6. Areas of Planning Interest

Development pressure within the Pilbara is considerable, for port and resource development projects along with the urban centres required to support ongoing operations. The potential for significant expansion of existing towns across the Pilbara has been identified, with recognition that careful planning and installation of critical infrastructure is required to ensure that short-term development pressure is used to generate growth that is sustainable in the long-term (Government of Western Australia 2009; WAPC 2012).

Areas encompassing Onslow, Karratha and Port Hedland have been identified as Areas of Planning Interest within the Pilbara, being areas of existing infrastructure where strong growth is anticipated. A coastal landform vulnerability assessment for each area has been completed at a tertiary sediment cell scale, allowing greater resolution of issues than the broader compartment scale assessment across the Pilbara (Section 5). The broader Areas of Planning Interest all contain existing urban centres and consequently there is a range of planning information relevant to each site. This includes Local Planning Strategies, sub-regional plans, townsite structure plans, local strategic plans or outline development plans (Astron & Coastwise 1998; Port Hedland Land Use Master Plan Steering Committee *et al.* 2007; DoP 2010a, 2011a, 2011b; EPA 2010b; BHP Billiton 2011; RPS 2011; Shire of Ashburton 2011; Taylor Burrell Barnett: TBB 2011; Town of Port Hedland: ToPH 2011a, b; WAPC 1998a, 2002b, 2003b, 2012). Further information on relevant planning documents at regional and local scales is contained in a summary document prepared by the Department of Planning (2010b) and in the recent *Pilbara Planning & Infrastructure Framework* (WAPC 2012). It is relevant to note that recognition of potential rapid growth in the Pilbara is relatively recent, and hence not considered in the scope of most planning documents older than a few years. In many cases, historic urban expansion through the Pilbara has been conducted via State agreements with resource companies; with infrastructure, including company-built town sites, being transferred after a designated period of operations.

The Areas of Planning Interest encompassing Onslow, Karratha and Port Hedland cover a number of locations of interest (Figure 1-1; Figure 6-8; Figure 6-16; Figure 6-17; Figure 6-45). Clustered into related sections of coast, these include:

- Onslow (Ashburton North and Onslow town site)
- Karratha area
    - Cape Preston (including Gnoorea)
    - Dampier
    - Karratha
    - Cleaverville and Anketell coast (includes Cape Lambert)
    - Point Samson (including Cossack)
- Port Hedland
    - Islands
    - Hedland Harbour
    - Old Hedland
    - Beebingarra

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

- Identification and grouping of the relevant tertiary sediment cells;
- Analysis of geomorphic processes;
- Description of planning context;
- Determination of the levels of susceptibility, instability and vulnerability across the tertiary cells within a group. This included the identification of the landforms most at risk and other coastal constraints related to environmental forcing;
- Advice for coastal management; and
- Identification of relevant further studies.

Throughout this Section describing the Areas of Planning Interest, location names within the text are based on the following sources:

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

6.1. COASTAL PLANNING, HAZARDS AND RISK

The Pilbara experiences extreme climatic and oceanographic conditions, with natural coastal hazards, particularly impacts of tropical cyclones, requiring risk mitigation. However, the approach of using setbacks to provide effective hazard avoidance is often impractical as the influence of marine conditions may extend several kilometres landward. This is directly relevant for many existing coastal town sites with established infrastructure and utilities in the Northwest.

The recent revision of SPP 2.6 (WAPC 2013) acknowledges the constraints for existing town sites to use horizontal setbacks to mitigate erosion and inundation hazards exacerbated by sea level rise. An adaptation hierarchy has been recommended, following the preferential sequence of AVOID-RETREAT-ACCOMMODATE-PROTECT. Existing town sites with freehold land holdings that are adjacent or even seaward of present-day hazard lines, may render avoidance as largely impractical. The strategy of retreat is heavily tied to the scale of management, and for small land holders it is likely to represent a significant economic loss. As a consequence, development applications on the basis of accommodation or protection strategies are considered likely to occur widely. This requires decision-making authorities active in the Pilbara to develop improved policy and enhanced knowledge of techniques for coastal hazard risk mitigation.

Risk mitigations may include, but are not limited to, development and implementation of warning systems and evacuation plans, establishment of critical infrastructure at areas of lowest risk, definition of site specific building guidelines and provision of coastal protection works. Following risk-management principles, the criteria used for hazard mitigation will vary between applications and should be evaluated on a case-by-case basis. However, the absence of fixed criteria does not provide justification for neglecting natural hazard mitigation where development setback cannot be achieved practically. This section is intended to support more detailed risk assessments in the Pilbara region.

Information on erosion hazard assessment, erosion hazard mitigation options and descriptions of land use sensitivity to adaptation have not been included in this report. This task was determined to be a large report in its' own right, and therefore is not a part of this project.

6.1.1. Decision Making and Information

At a simple level, decision-making in the Pilbara that affects coastal hazard risks for development can be separated into:

- Development site definition – including land ownership, zoning and building envelopes. These issues are usually addressed by the State government through planning approval, with local government input and referral to State agencies including the Department of Transport (Maritime) and the Department of Water. Development choice and purpose are land owner decisions, who in some instances may be a governmeny body;
- Infrastructure requirements – including building design criteria and associated service connections. These issues are largely addressed through local government building approvals process, although they may also be determined by conditions on planning approval. Useful information is available from Commonwealth and non-government agencies such as Australian Standards and the Australian Building Codes Board, but this is not directly bound by legislation;
- Hazard management – such as protective works, warning systems, evacuation plans and post-event clean-up. These aspects are addressed by both local and State government, with particular input from the Fire and Emergency Services Authority (WA). Hazard management issues are occasionally referred to FESA as part of planning approval. General guidance on hazard management (see "Emergency Management Australia" below) and funding for both disaster mitigation and post-disaster clean-up is available through the Federal government as part of the Natural Disaster Resilience Program.

The overall situation is one of multi-agency decision-making, using a dispersed knowledge-base, and therefore presents challenges the jurisdictional framework. Crossovers between planning, building approval and hazard management are significant and therefore rely upon inter-governmental and inter-departmental coordination and communication. Without this, there is a tendency for each agency to require a hazard management technique that is optimal for their jurisdiction, rather than providing an optimal suite of tools to minimise total risk. The most prevalent example is the use of infilling to resist inundation, which may transfer flood waters to adjacent land and shifts the hazard focus of hazard from flooding to stability of the edge treatment.

A similar problem of complexity exists for the dispersed knowledge-base used to support decision-making in areas affected by coastal hazards. Supporting information is provided through a wide range of sources, from local government planning schemes through to detailed descriptions of building specifications for flood risk mitigation. *It is worth acknowledging that the significance of the documents for decision-making purposes is almost directly opposite the level of detail provided with respect to hazard mitigation* (Figure 6-1). In this context, it is noted that much of the relevant supporting information is not legally binding. Instead, it is required that higher level documents make reference to the supporting information, typically specifying a classification or criteria to be met. Without such reference, the broad range of available information provides opportunity for ambiguity, division of expert opinion and consequent legal dispute.

Figure 6-1: Schematic of Information Supporting Decision-Making

Useful sources of supporting information, particularly for flood hazard management are described below. The knowledge-base for the Australian region has largely been developed for runoff-flooding, with significant recent advances following flooding in Queensland and New South Wales associated with TC Yasi. Detailed information regarding coastal flooding risk mitigation is available from the United States, where the impact of hurricanes on low-lying coast and barrier islands of the Gulf and Atlantic coasts forms a strong parallel to conditions in the Pilbara.

Floodplain Management in Australia

A summary of Australian floodplain management practices is outlined in ARMCANZ (2000) *Floodplain Management in Australia*. This identifies requirements for planning and governance related to flood hazard, risk assessment processes and general practices for flood mitigation. Flood criteria are not nominated, but the need to assess impact of 2 to 1000 year ARI events is recommended, with recognition of the consequences of larger events.

Emergency Management Australia (EMA)
A series of flood management manuals were developed as part of a program for addressing emergency management issues in Australia. These provide general guidance with respect the definition of flood hazard, warning systems, flood preparedness and post-event management. They contain limited information regarding hazard mitigation at a Lot level and are focused on runoff flooding rather than coastal inundation.

Guidelines that are relevant to the Pilbara include:

- EMA (2009a) Manual 20 – Flood Preparedness
- EMA (2009b) Manual 21 – Flood Warning
- EMA (2009c) Manual 22 – Flood Response

Australian Building Codes Board (ACBC)
Following inundation in the wake of TC Yasi, Australian flood management practices were reviewed and several deficiencies highlighted. One of the outcomes was development of improved guidelines for buildings in floodprone areas, with recent release of a draft document *Construction of Buildings in Flood Hazard Areas* (ACBC 2012). Whilst this document is focused on runoff flooding, its recommendations and provisions should also be considered in the coastal zone. Information included is prescriptive (e.g. piled foundations should be used where erosion may occur) but contains little structural detail how the recommendations may be achieved.

Federal Emergency Management Agency (FEMA) USA
Long-term private land ownership on very low-lying foreshores has provided a challenge to coastal management in the southern and eastern parts of United States that has largely been avoided in Australia through development setback. As a consequence, FEMA has developed a series of documents regarding construction in the coastal zone. The flagship document is the *Coastal Construction Manual* (FEMA 2011), which has had a series of revisions. This document is largely prescriptive, similar to the recent ABCB (2012) draft, but is supported by an extensive raft of smaller documents that provide detailed structural guidance. The most extensive set of guides are included as appendices to the 2005 edition of the *Coastal Construction Manual* (FEMA 2005).

6.1.2. Pilbara and State Planning Context

The most recent strategic planning advice for most of the Areas of Planning Interest is included within the *Pilbara Planning & Infrastructure Framework* (WAPC 2012) report. This incorporated supporting documents of the *Pilbara Framework – Regional Profile* (WAPC 2009a); the *Regional Hot Spots series* for Onslow (WAPC 2008), Karratha (WAPC 2010a) and Port Hedland (WAPC 2011); and the *Pilbara Infrastructure Priorities* (WAPC 2010b). A *Pilbara Infrastructure Implementation Report* planned that will use these reports to provide a Pilbara infrastructure implementation plan that is intended to have a twenty-year timeframe.

Results of the coastal landform vulnerability analysis at sediment cell scale have been considered in the context of available planning documents and with respect to the objectives of the *Coastal Zone Policy for Western Australia* (Western Australian Planning Commission: WAPC 2001). Three of the major infrastructure objectives are:

- Recognition of the dynamic nature of coastal environments and the consequences for coastal development and use.
- Avoidance or mitigation of the impacts of natural hazards through intelligent siting and design of infrastructure, based on ongoing scientific research.
- Location of new industrial and other infrastructure development away from the coastal zone and concentration in existing nodes, wherever practicable.

These objectives provide a framework for management of the coast, which has been further described through State Planning Policies (e.g. WAPC 2006, 2013) and departmental policies such as the *Coastal Protection Policy* (DPI 2006). The general approach is to use coastal setbacks as a primary means of natural hazard mitigation, where possible, and to focus coastal use such that adaptive or defensive measures may be minimised. For the purpose of advice contained in this assessment, coastal planning criteria contained within these policies have been used as a benchmark with which to identify coastal management constraints. This approach is necessarily a simplification of the planning process, and hence any study recommendations should be recognised as advice, rather than requirements.

Coastal planning criteria relevant to the Pilbara coast from State government policies (WAPC 2003a [superceded], 2006, 2013) are summarised below:

- *Statement of Planning Policy 2.6 – State Coastal Planning Policy* (SPP 2.6: WAPC 2013) provides setback guidelines considering a planning time frame of 100 years, with no requirement for coastal defence or emergency management. The policy states that the setback datum in areas prone to tropical cyclonic storm inundation (north of latitude 30°S) will be determined by a storm surge evaluation of a category 5 tropical cyclone tracking to maximise its associated storm surge, according to Schedule F.4. The extent of the setback should be defined on a case-by-case basis including allowances for S1 (acute erosion), S2 (chronic erosion or accretion), and S3 (sea level rise) where relevant. Due regard for SPP 2.6 and other State planning policies is required for all coastal areas of Western Australia.
- *State Planning Policy 3.4 – Hazards and Disasters* (SPP 3.4: WAPC 2006) encourages local governments to adopt a systematic approach to the consideration of natural hazards and disasters when performing their statutory or advisory functions. In relation to severe storms and cyclones, the policy refers to the Building Code of Australia for the ability of structures to withstand cyclonic winds and rain. In relation to coastal erosion, SPP 3.4 simply refers to SPP 2.6. SPP 3.4 also states that where storm surge studies have been undertaken and show that inundation may occur, new permanent buildings should be constructed to take account of the effects of storm surge (including wind and wave set-up). There is no further detail describing approaches, methods or techniques as to how this should be done. In areas where storm surge studies have not been undertaken, but evidence is available to demonstrate the likelihood of inundation, any development proposals should be supported by studies that demonstrate inundation will not occur. The policy does not specify under what storm conditions inundation should not occur. It further refers to SPP 2.6 for assistance in determining setbacks in coastal locations.

The existing policies do not provide a seamless set of criteria for coastal planning and management. Specifically, there are no criteria to define requirements for alternative forms of natural hazard mitigation where coastal setbacks are impractical, with each planning application to be considered on a case-by-case basis, following the AVOID-RETREAT-ACCOMMODATE-PROTECT hierarchy suggested in the revised SPP 2.6 (WAPC 2013). This situation is significant for almost the entire Pilbara coast and is directly relevant for the existing coastal town sites in the Areas of Planning Interest, which have established infrastructure and utilities.

The potential for rapid growth of the urban centres within the Areas of Planning Interest provides opportunity for planning that is essentially 'green field' in character as the supporting infrastructure network, such as roads and services, is not in place. However, future development must connect to existing infrastructure, much of which is located in areas currently prone to relatively high likelihood of coastal hazards. Acceptance of present-day hazard levels applied to increased area and density of both infrastructure and population represents an increased coastal hazard risk. Furthermore, proposed coastal infrastructure (including ports, marinas, waste water systems and desalination plants) may have the capacity to increase coastal dynamics and exacerbate threats to existing infrastructure. On the coastal floodplains prevalent across the Pilbara, the widely-used practices of infilling (raised floors) or impoundment (levees) are common mechanisms for transferring risk, as they reduce floodplain storage and increase flood levels across the wider area.

Previous planning studies have highlighted the significance of both coastal and runoff flooding on coastal sites throughout the Pilbara region. These have stimulated a range of flooding assessments, principally at a local town site scale, with occasional more regional evaluations (GEMS 2009). The majority of such assessments have been undertaken with limited consideration of projected mean sea level change or the consequent evolution of coastal landforms.

The *Pilbara Planning & Infrastructure Framework* (WAPC 2012) recommended the investigation and mapping of the effects of projected sea level rise for the main coastal settlements of Onslow, Karratha are Port Hedland be conducted. This work:

> *"...will be critical in informing the preferred location of future development areas in these centres and required fill levels, which will affect the economic viability of development proposals."*

Studies have been completed for Onslow (MP Rogers & Associates 2011), Karratha (JDA *et al.* 2011a, b) and Port Hedland (Cardno 2011) and have been considered in this document. Two of these studies applied an erosion allowance of 90m to account for projected sea level rise, based upon application of the Bruun ratio. This approach is not consistent with a landform assessment approach (Section 2).

6.1.3. Risk Frameworks

Although tropical cyclone impacts may be devastating, such occurrences are extremely infrequent. In many cases, design to tolerate possible worst case conditions may be impractical, and hence criteria are selected within a risk framework, combining likelihood with impact. Importantly, a risk-based approach also requires recognition of the events which exceed design conditions, which is particularly important for engineered situations (ARMCANZ 2000; Balmforth *et al.* 2006).

There are a range of processes used to define hazard criteria, according to the information available and the objects to which the criteria are applied. One approach to describe different criteria, developed for coastal flooding is the SOURCE-PATHWAY-RECEPTOR model (Hofstede *et al.* 2005; Sayers & Meadowcroft 2005), where:

- SOURCE refers to metocean parameters such as waves, tides and surges;
- PATHWAY involves the possible mechanisms by which impacts may occur, such as wave overtopping, levee failure or storm surge flow up river channels;
- RECEPTOR refers to the people, buildings or land that may be affected by flooding.

A fully developed risk assessment requires analysis of all components of risk management, including flood processes, physical structures, human management and economic provisions (Figure 6-2).

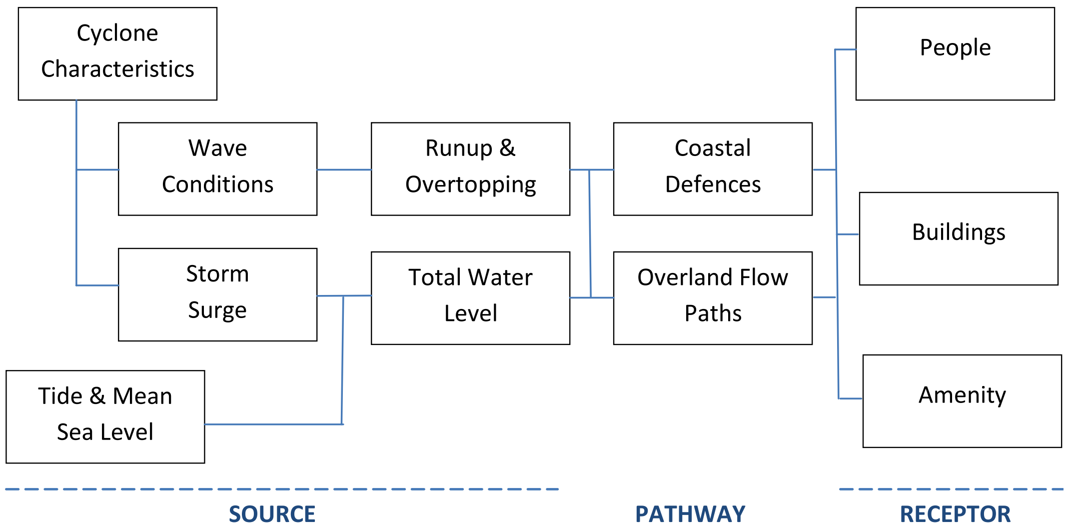


Figure 6-2: Example of Source-Pathway-Receptor Factors for Inundation

Although most commonly applied to inundation, the SOURCE-PATHWAY-RECEPTOR framework also applies to consideration of erosion hazard. Obvious PATHWAY distinction occurs between acute storm-driven erosion, chronic shoreline change and response to sea level rise, as applied in SPP 2.6 (WAPC 2013).

Historically, there has been a rough link between the three types of decision-making described in Section 6.1.1 and the division into SOURCE-PATHWAY-RECEPTOR factors. For example, setting of a 100-year ARI total flood level or erosion distance only considers a SOURCE factor. Estimation of hydrodynamic loads for infrastructure criteria requires evaluation of PATHWAY factors. Emergency management mainly considers RECEPTOR factors, as all possible events must be considered. A consequence of this division is that decisions based upon SOURCE factors only, including SPP 2.6 (WAPC 2013), neglect other risk factors and therefore may contain a highly uncertain representation of hazard likelihood. This high level of uncertainty has justified the use of simplified techniques of analysis on the basis that they are suitably conservative, with a corresponding need to modify hazard criteria according to the analysis technique applied (Oumeraci 2005; Figure 6-3).

A limitation with assessment of risk using only SOURCE factors is that opportunities for risk mitigation may be less easily recognised or distinguished. An example that is widely applied is the definition of a finished floor level across a coastal area that includes a constant freeboard, ostensibly for wave action. By distinguishing the water level and wave components, significantly less fill material is required if the wave action is dealt with at the coastal margin, provided overtopping waters are directed through suitable drainage paths. This approach was identified for coastal hazard assessment at Coral Bay, where inundation was distinguished from the more readily engineered wave effects (GEMS 2005).

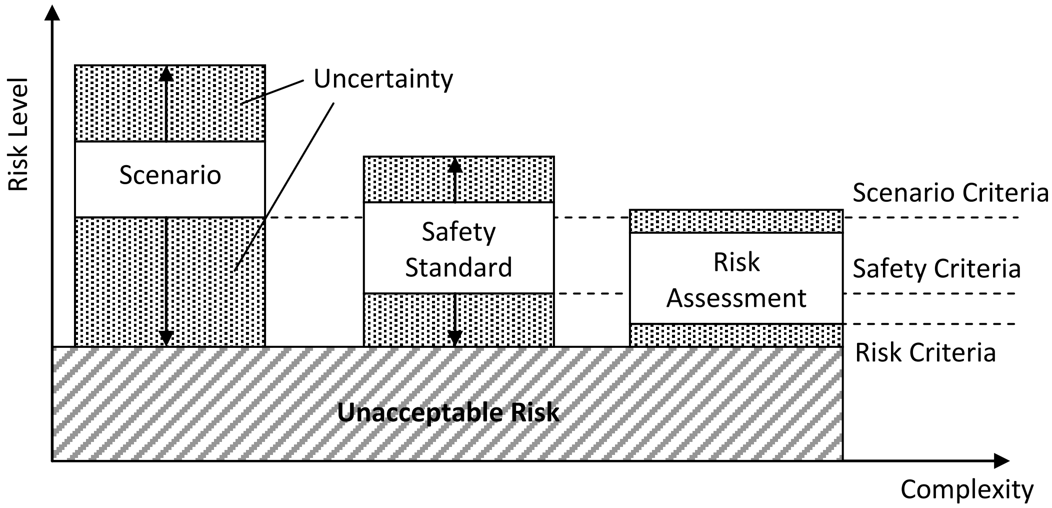


Figure 6-3: Schematic Relationship of Scenario, Safety and Risk Criteria Adapted from Oumeraci (2005)

The revised SPP 2.6 includes improved recognition of PATHWAY factors, such as breaching, bypassing and dune erosion. Further, the recommended adaptation hierarchy suggests that PATHWAY and RECEPTOR factors may be considered as part of adaptation to sea level rise where AVOID or RETREAT options are impractical. The importance of using an appropriate risk framework including RECEPTOR factors when considering ACCOMMODATE or PROTECT options is particularly well illustrated for linear defences (e.g. levees). On one hand, the potential for catastrophic damage if the defence is overwhelmed is only captured if a full range of events are considered, whilst on the other, the potential for loss of life and property may be significantly reduced if a warning system allows flood preparation and evacuation, often in time ‘bought’ by the defence.

Following emergency management principles, the inclusion of RECEPTOR factors into the framework is a means of significantly reducing risk, particularly that of threat to people. Provision of cyclone shelters, dissemination of evacuation plans, implementation of effective warning systems and on-ground emergency management are all integral parts of reducing community risk (EMA 2009b).

6.1.4. Erosion versus Inundation

The SPP 2.6 (WAPC 2013) includes identification of an inundation-based horizontal setback datum as part of the calculation of coastal setback allowances. The policy caters for both erosion and inundation, for site development where there is sufficient space to use *coastal setback as the primary means of mitigating risk*. However, for the majority of town sites along the Northwest Shelf coast, there is limited opportunity to use a significant development setback. In such locations, a wider range of risk management techniques may need to be applied.

Both inundation and erosion hazards are developed through a combination of acute and more gradual processes. For the Pilbara, over planning time scales, inundation is generally dominated by the acute processes, whereas erosion is more strongly affected by gradual processes. This distinction is important for the management approach, with gradual erosion more readily managed through avoidance or maintenance of adequate buffers (Dekker *et al.* 2005; Larson *et al.* 2009). Despite this general tendency, which is reflected in hazard policy definitions, the potential for acute erosion may remain an important consideration, particularly where it may destabilise coastal barriers.

When interpreting SPP 2.6 risk criteria, it is important to recognise that there is a general need for a more precautionary approach when considering horizontal setbacks than vertical levels. Buildings subject to erosion ('*damage to land*') are highly likely to experience structural failure, whereas low levels of episodic inundation cause comparatively minor *building damage* (Figure 6-4; Dale *et al.* 2004). This difference between *damage to land* and *building damage* is significant, as the two have different planning horizons. Typically land is considered to have a planning horizon of 100 years, whereas houses typically have a life-cycle of 30-50 years. The shorter time frame more readily accommodates adaptive response, through rebuilding or modification, whereas erosion loss requires construction of more significant coastal defences.

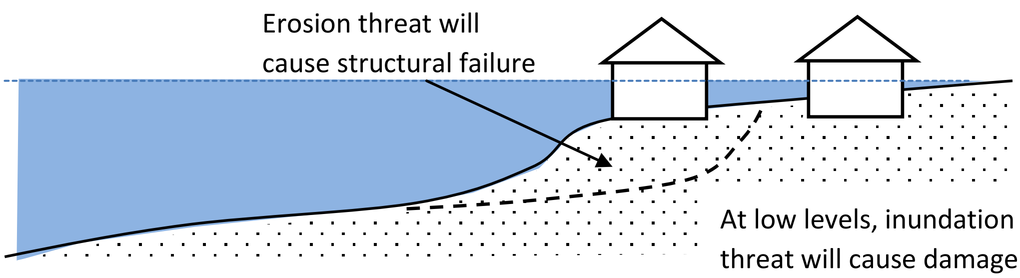


Figure 6-4: Schematic Illustration of Erosion and Inundation Threats

The threat to housing through inundation alone (i.e. without being affected by erosion) is determined by the structural capacity of the building to withstand a certain depth of inundation, and the corresponding wave and current stresses. Future performance of a building (after Local Government approval) is therefore subject to increased risk due to both building deterioration and rising mean sea levels. Risk could be significantly reduced through a program of condition assessment and maintenance, say tied to adaptation drawn from review of sea levels at approximately decadal intervals. Similar programs have been recommended for Queensland in response to wind damage caused by TC Larry and TC Yasi.

6.1.5. Implications of Climate Variability and Change

Both building and planning horizons extend over decades and therefore must consider the implications of changing climate conditions, including both climate variability and anthropogenic climate change. For either pathway of change, coastal management must either make allowance within present-day decisions, or facilitate adaptation to change in future years. Following the principles of adaptive management (NCCOE 2012a, c), the appropriate management pathway is determined by the severity of potential impact and the time frame required for change detection and adaptation. In situations where the defensive capacity is not developed sufficiently rapidly, changing environmental conditions may reach an unacceptable hazard levels for an extended period (Figure 6-5).

Whether adaptation is done immediately or in the future, environmental change provides impetus for monitoring suitable to facilitate management decisions regarding capacity building. For the Pilbara, this is complicated by the potential difficulty of relating perceptible changes, which are typically driven by change in mean ambient conditions or low-moderate cyclone impacts, and the change to hazard level, which is generally determined by severe tropical cyclone impact. This limitation commonly results in budgetary inertia towards capacity building, with such activity more commonly occurring in the wake of a disaster, whether local or more further afield.

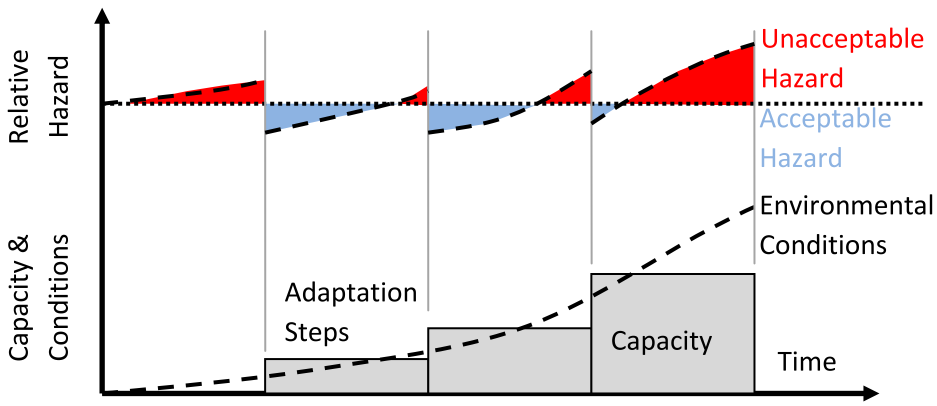


Figure 6-5: Schematic of Hazard Sequence Associated with Adaptation Steps

Responses to environmental change are likely to vary for each particular site or development. Consequently, a process of establishing environmental sensitivity is recommended when identifying whether to incorporate allowance for change or to use adaptation. A detailed assessment framework is described by the National Committee for Coastal and Ocean Engineering (NCCOE 2012a) which is applicable to assessment of either climate change or variability. However, an attempted application of this framework to the Pilbara identified that the available projections for change to tropical cyclones in the Australian region are presently limited (Damara WA 2009b). As a consequence, change analysis is limited to selecting possible scenarios.

The relative severity of a selected climate change scenario affects both the range of adaptation options considered and their timing (Figure 6-6). Severe scenarios for change provide a more extensive adaptation sequence, but will suggest incorrect timing of responses and may thereby provide undue emphasis upon remotely possible outcomes – such as abandoning existing town sites. Mild scenarios for change do not allow identification of the full sequence of adaptation actions, but may provide the subtlety required for local coastal management.

Postulated climate changes that may affect coastal inundation include:

- Sea level rise;
- Changes to storm generation, including the geographic distribution;
- Changes to storm climatology, including intensity, speed and paths.

Sea level rise associated with climate change has been exhaustively assessed through the Intergovernmental Panel on Climate Change (Meehl *et al*. 2007), which forms the basis for the present WAPC recommendations for sea level rise allowance in planning (DoT 2010a). This mechanism is largely independent of inter-annual variability of mean sea level processes, which is strongly related to El Nino-Southern Oscillation climate fluctuations (Haigh *et al*. 2011).

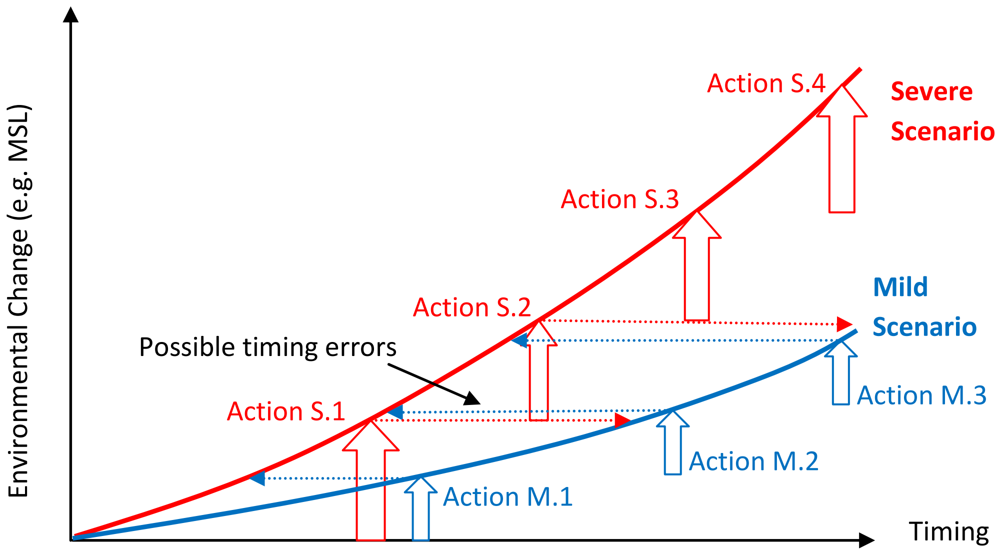


Figure 6-6: Effect of Scenario Selection upon Identified Adaptation Sequence

For the Pilbara region, the most severe storms are tropical cyclones. The knowledge base regarding how such systems will respond to climate change is still a matter of scientific conjecture (Box 6-1). A general approach is to consider changes of intensity and frequency that may be in the order of 10-15%.

Box 6-1: Climate Change Effects on Australian Tropical Cyclones

The following summary is extracted directly from Damara WA (2009b).

Assessment of the impacts of climate change upon tropical cyclone formation and behaviour has been a serious research question for the last two decades, with limited resolution of some of the key scientific issues. The most comprehensive available statement regarding the likely interaction between cyclones and climate change is available from the World Meteorological Organisation (WMO 2006).

Since the development of early theory regarding cyclogenesis and subsequent interpretation of corresponding environmental data sets (Gray 1979; McBride 1981; McBride & Keenan 1981), further research has been undertaken regarding the physics of tropical cyclone formation (Holland 1997; Emanuel *et al*. 2004; Camargo *et al*. 2008). Whilst the theory has advanced, there remains some uncertainty, which is amplified when the relationships between environmental conditions and cyclone formation are projected into scenarios of potential climate change (Emanuel 1986; Love 1988; Landsea 2000; Leslie & Karoly 2007; Camargo *et al*. 2008). Theoretical modelling of projected climate change at a cyclonic scale has suggested that a 3-10% increase of tropical cyclone intensity is likely in most ocean basins for a 2.2-2.7% increase of sea surface temperature, with an approximate 6 hPa decrease of MPI for the South Indian Ocean region (Knutson *et al.* 2001).

The difficulty of addressing the impacts of climate change on cyclone formation and behaviour are complicated through the restricted scales generally available to global ocean-atmosphere modelling. As a consequence, cyclone formation is typically described by a set of proxy conditions, under which cyclone formation is considered possible. Early, relatively low-resolution modelling suggested that cyclone-like vortices were predicted with much greater frequency than actual cyclone formation (Evans 1990; Walsh & Pittock 1998; Walsh & Ryan 2000). Recent improvements have occurred, particularly through the inclusion of shear and finer resolution modelling (Landsea 2000; Emanuel *et al.* 2004; Abbs *et al.* 2006), although uncertainty remains with regards to the relative dominance of various parameters, which apparently varies from region to region. This suggests that a regional modelling approach may provide better results than global assessment. Questions regarding the focus of modelling efforts and parameterisations are noted to be an existing topic of research, complicated by the unreliability of historic databases (Landsea 2000; WMO 2006).

The most recent efforts to understand the behaviour of tropical cyclones off Western Australia have suggested that regional behaviour is markedly different to that occurring off Eastern Australia. For example, the parameterisation developed by Abbs *et al.* (2006) shows a reasonable prediction for east-coast Australia, but clearly underestimates the frequency of cyclones for Western Australia. Consequently, studies grouping the Australian region as a whole may be inclined towards providing a relatively poor representation.

Box 6 1: Climate Change Effects on Australian Tropical Cyclones (Continued)

Results for Australian tropical cyclone modelling are described in CSIRO & BoM (2007): *Three recent studies have produced projections for tropical cyclone changes in the Australian region. Two suggest that there will be no significant change in tropical cyclone numbers off the east coast of Australia to the middle of the 21st century (Walsh et al. 2004; Leslie et al. 2007). The third study, based on the CSIRO simulations (Abbs et al. 2006), shows a significant decrease in tropical cyclone numbers for the Australian region especially off the coastline of Western Australia.*

And further:
Each of the above studies finds a marked increase in the severe Category 3-5 storms. An increase of 60% and 140% in the intensity[1] *of the most extreme storms for 2030 and 2070, respectively, was found using a model with a 15 km grid spacing (Abbs et al. 2006). Walsh et al. (2004) found an increase of 56% by 2050 using a 30 km model. Leslie et al. (2007) used a 50 km model and reported an increase of 22% by 2050, and a change in the latitudinal extent of tropical cyclones, with more storms forming closer to both the equator and the poles; a poleward extension of tropical cyclone tracks; and a poleward shift of over 2 degrees of latitude in the tropical cyclone genesis region. A poleward shift of 0.7 degrees of latitude (around 70 km) in the average tropical cyclone genesis region on both coastlines and a shift of almost 3 degrees latitude in the average decay location for east Australian cyclones were found for the year 2070 (Abbs et al. 2006).*

Two high-resolution modelling studies specifically for the Western Australian region were presented at the Australian Meteorological and Oceanographic Conference in February 2008.
- Leplastier *et al*. (2008) presented results based on the work of Leslie & Karoly (2007), which applied wind shear as the controlling process for cyclone formation.
- Camargo *et al* .(2008) presented results based on the theory of Emanuel *et al*. (2004) which applies Maximum Potential Intensity (MPI) as the controlling process for cyclone formation.
These studies have been 'tweaked' such that the historic period is 'calibrated' in terms of cyclone numbers. However, both the zones of generation and the model simulation of the extreme observed events provide less than perfect simulation of historic conditions.

6.1.6. Inundation Risk Management

The low-lying coastal floodplains prevalent along the Pilbara coast, and the potential for extreme conditions associated with tropical cyclones determines that both coastal and runoff flooding are major hazards for the region. Historically, flood hazard management has been influenced by the landform complexity, the low density of development and the small residential population. These characteristics have enabled development in focal areas that have lower risk of flooding with corresponding recognition that dispersed infrastructure is required, and occasional periods of isolation. During Pilbara growth in the 1960s and 1970s the low density of many developments also allowed the concept of minimum total risk to be

[1] Review of Abbs *et al.* (2006) suggests that these figures refer to frequency rather than intensity. Abbs *et al.* (2006) report simulation of tropical cyclone-like vortices, suggesting a net reduction in the frequency of events, but an increase of intensity, with a mean decrease of 6 hPa.

continued, where high sensitivity infrastructure was located at areas of lowest practical risk, commonly identified on the basis of geomorphology. This includes growth of Karratha at the 'foot' of the ridge behind the town, and construction of South Hedland.

Extreme flood events in the Pilbara during the 1970s and 1980s indicated that the practice of choosing the 'best' local site for coastal infrastructure did not necessarily provide an acceptable level of protection. Coupled with the emergence of numerical modelling for flood hazard, this encouraged the use of probabilistic assessments, where maximum likelihoods for inundation events were identified. Where existing conditions did not reach the nominated standard, infrastructure provisions were required, such as infilling, construction of levees or structural fortification. During this phase, the low density of development enabled adaptation to change, including recognition of assessment error, without significantly transferring risk to adjacent land or facilities.

The recent significant pressure for expansion in the Pilbara has challenged historic development practices, particularly the key approach of hazard avoidance by choosing the 'best' local sites for focal nodes. Instead, an undeclared aim has been to maximise the available area for development, which places increased importance on the definition of acceptable flood hazard criteria to define planning envelopes. An important further step that is not always taken is to consider hazard variation within these envelopes, to enable minimisation of total risk, rather than have risk clustering at a critical threshold. Further, higher development density may constrain opportunities for adaptation if flood hazards are revisited, due to structural, climate or policy change. An example is provided by the recent change in recommended sea level rise allowance (DoT 2010a), although similar adjustments have previously occurred when flood recurrence estimates were updated, or when criteria were revised following a severe storm impact.

Inundation Hazard Assessment

The landforms and structure of the Pilbara coast form a topographically complex system with a blend of low-lying floodplains and moderate relief relict rocky landforms. Emergent geologic features at the coast and islands provide areas of both sheltering and storm surge focus. This landform and bathymetric complexity produces highly varied exposure to coastal flooding and considerable interaction between catchments due to breakout flows and convergence in coastal lagoons. The implications for flooding assessments include:

- Coastal flooding assessment may require fine resolution assessment to distinguish local topographic effects, which may produce an order of ±1m variation from regional assessments. Alternatives include adoption of conservative flood criteria, or interpretation of regional flood assessments based upon on-site (sub-scale) characteristics;
- Wave effects, including runup and overtopping may occasionally be significant, particularly in the presence of rocky landforms or coastal defences, and are generally reduced across mildly graded topography;
- Runoff flooding assessments commonly require a more regional, rather than catchment-scale approach, to quantify the interactions with adjacent catchments;

- Interaction between coastal and runoff flooding may be complex within the coastal fringe, generally with greater potential for superposition for small catchments (rapid response) or those with large upland contribution to flow (sustained response).

The sporadic nature of extreme flood events and high spatial variability determines that modelling (numerical or analytic) is an appropriate tool for assessment. However, such evaluation is highly sensitive to the underlying model processes and assumptions, requiring careful validation to produce meaningful results. *Any model should capture the major water level processes at the site, and recognise the potential influence of other processes*. Importantly, description and validation of flood processes are generally limited in the Pilbara by the existing and historic monitoring framework, with comparatively sparse stream gauges, tide gauges and post-flood surveys. Ongoing review of inundation hazard levels is appropriate, which may include identification of mean sea level trend, characterisation of any morphological change, confirmation of previously modelled synoptic climate and post-event validation of tropical cyclone flooding, such as wrack-line surveys reported by Nott & Hubbert (2005).

Details of prior hindcasting and modelling of extreme water levels for planning purposes and infrastructure design are included for Onslow (Section 6.2.2), Karratha region (Section 6.3.2) and Port Hedland (Section 6.4.2). The majority of studies focus on rainfall runoff or direct-impact tropical cyclone-induced coastal flooding, with limited evaluation of tsunami hazard.

Runoff Flooding

Techniques for assessment of runoff flooding in Australia were partly standardised through the regional analysis of rainfall records and analysis techniques in *Australian Rainfall & Runoff* 2nd Edition (Pilgrim 1987). However, the original data sets and approaches have progressively been updated, refined and supplemented with flow gauge records, giving a body of literature regarding runoff estimation that is relevant to the Pilbara region (Ruprecht 1996; Ruprecht & Ivanescu 2000; Durrant & Bowman 2004). This literature has informed the most recent revision of Australian Rainfall & Runoff, with the 3rd Edition shortly due for completion.

Coastal Flooding

Coastal flood hazard in the Pilbara is developed through a combination of processes, which are most simply separated into a combination of tides, atmospheric surges and mean sea level variation (Pugh 1987). For much of the Pilbara region, tides are the dominant phenomenon, with a range from 3m at Onslow to 7.6m at Port Hedland (NTF 2000). Whilst atmospheric surges are typically small, there are rare occasions when extreme surges up to 5m have been identified, associated with tropical cyclones (Nelson 1975; Nott & Hubbert 2003). Mean sea level variations are typically smaller, although they play a clear role in the incidence of water level exceedance within typical ‘tidal’ conditions, along with sub-annual and inter-annual tidal modulations.

The potential for tropical cyclones to cause large storm surges is often the basis for assumption that the most severe weather events also give the most significant flood risk, prompting hazard assessment within the context of the Bureau of Meteorology (BoM) tropical cyclone record (http://www.bom.gov.au/cyclone/). However, whilst this information is valuable, the primary focus of the BoM summary relates to extreme winds, and therefore requires further interpretation when evaluating flood hazard. While the low barometric pressure and strong winds associated with tropical cyclones may cause large storm surges if they blow onshore, extreme response is spatially limited (≈50-100km), varies significantly according to the storm pathway, and is highly modulated by the coincident tide level.

The relatively large tidal range and potential for extreme surge provides opportunity for different processes to contribute to high water levels. A notional attribution of water level contributions based upon water level thresholds is suggested by Figure 6-7. This suggests that different techniques or assumptions for assessing flood hazard may be appropriate within these different bands. For example, for Karratha in the 7 to 10mCD band, it may be reasonable to assume onshore winds and storms that pass close by; whereas a more extensive range of storms should be evaluated for the 5.5 to 7mCD band.

Tsunami or Extreme Local Wave Runup	>10m CD	HAT + Smax
Extreme Tropical Cyclone +High Tide	7-10m CD	HAT + Smod / MSL + Smax
High Surge + Moderate Tide or Moderate Surge + High Tide	5.5-7.0m CD	HAT + MDLmax
High Tide; Moderate Surge + Tide or High Surge + Low Tide	4.5-5.5m CD	MHWS
High Phase Tide or Moderate Tide Phase + High MSL	3.7-4.5m CD	MHWN
Tide Phase + MSL Variations	2.8-3.7m CD	MSL

Figure 6-7: Notional Attribution of Water Level Components for Karratha

There is no standard methodology for assessment of tropical cyclone flooding frequency (Box 6-2). This provides a challenge to decision-makers to use modelling outputs effectively in real-world applications. Possible steps towards the use of estimates include:

(1) Definition of standard modelling techniques;
(2) Allowance for model uncertainty in criteria (Figure 6-3); and
(3) Recognition of the possible need for adaptation.

It is acknowledged that allowance for model uncertainty (Step 2) cannot practically apply the potential model output ranges suggested by Table 6-1. In most cases, reasonable information and adequate practice by competent practitioners will reduce this uncertainty, which facilitates using adaptation (Step 3) as a trade-off for allowance (Step 2). However, as this trade-off represents a balance between risk averse and risk tolerant management, it should therefore be considered carefully, taking into account the potential effect of under-estimation and ease of adaptation. A error is almost certainly unavoidable, planning applications should recognise that typically adaptation may be at least as large as projected climate change scales.

Table 6-1: Water Level Assessment Techniques

Assessment Classification	Assessment Type	Information Required	Uncertainty of 100yr ARI est.[1]	Decision Making Use
Primary	Numerical	Water level Observations	-2 to +5m[2]	Regional planning / Site selection
	Empirical	Bathymetric cross-section	-2 to +5m[2]	
	Parametric	Cyclone parameters	-1 to +5m[2]	
Secondary	Oceanographic	Bathymetry	-1 to +2m	Development / Structure Siting
	Inundation	Topography	-1 to +2m	
Tertiary	Tidal inundation	Tidal characteristics	-0.5 to +1m	Structural / Risk assessment
	Morphodynamic	Sediment mobility	-0.5 to +1m	

Note: 1. This uncertainty reflects the potential range of assessment results due to flexibility within the techniques, variation of observation data sets to provide validation and effects of process interpretation from observations.
2. Very large differences can be generated where the period of observation used for extrapolation contain none or few significant cyclone surge events.

Uncertainty estimates are based upon the range of levels reported for individual WA sites. This includes all sources of uncertainty, such as knowledge-base, effects of modelling a subset of processes and influences of model application, including scale, boundary conditions and scenario selection. For the Pilbara region, the quality of validation is also a source of uncertainty, as there are few well recorded historic events, both due to sparse instrumentation and the failure of many gauges under extreme impacts. This limitation typically results in underestimation of extreme water levels (Resio *et al*. 2009), although it may result in exaggeration if potential far-field responses (e.g. Ekman setup, wave response, shelf waves) are incorrectly attributed to local effects (e.g. pressure response, wind setup).

Inundation processes included within modelling are rarely comprehensive, with their selection usually on the basis of available budget and study scale (Table 6-2). This sometimes results in a chain of assessments Regional → Intermediate → Coastal → Engineering, where logical divisions occur according to output relevance and management options. For example, it is common to separate Intermediate and Coastal inundation studies because the determination of wave runup and overtopping is intrinsically related to the choice of coastal defence system. An example of a regional assessment is provided by the ACE-CRC web-tool Canute (Haigh *et al*. 2013) which uses a simplified set of physics and coastal structure to estimate coastal flooding recurrence.

Box 6-2: Tropical Cyclone Inundation Frequency Assessment

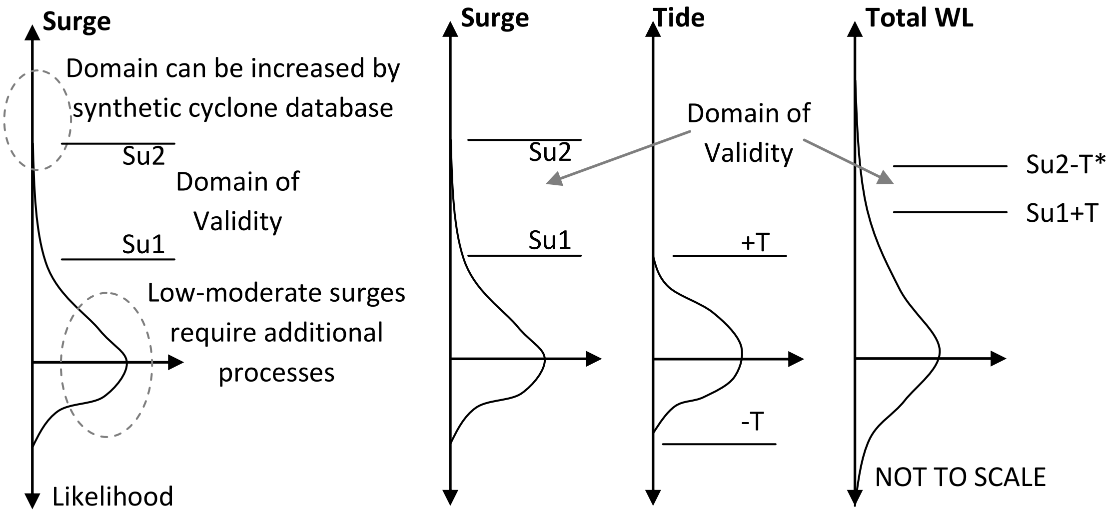
There is a diversity of techniques available for tropical cyclone inundation assessment. Each is based upon one or more aspects of coastal structure, meteorological characteristics and water level records. The techniques effectively vary in the manner with which inundation processes are represented, and therefore will reflect a bias according to whether that process is more or less active in any particular case. For example, wave setup on a discontinuous (jagged) coast is limited, as the variation in wave breaking produces alongshore gradients and rip currents. Hence, simulation of wave setup using a one-dimensional cross-shore model, such as suggested by Longuet-Higgins (1962) and Longuet-Higgins & Stewart (1963, 1964) would likely produce exaggerated results.

The origins of storm inundation assessment were mainly developed from mid-latitudes, particularly north Atlantic and North Sea studies. Long-term tide gauge records and spatial coherence of storm surges enabled the development of *Historical Analysis* techniques (Scheffner 2002), which were extended through tide-surge integration techniques (Pugh & Vassie 1980). However, it was recognised that monitoring by dispersed tide gauge networks could not adequately capture the spatial variation of extreme water levels due to tropical storms (Jelesnianski 1966). This prompted programs of monitoring and evaluation to derive distinct techniques for tropical cyclone inundation modelling, with the US Army Corp of Engineers particularly active in definition of early empirical models, based largely upon continental shelf structure and system intensity (Reid 1956; Bretschneider 1966, 1972; Trajer 1973; USACE 1975). This phase of evaluation identified that the largest surges were generally associated with systems tracking almost normal to the shore. The earliest models were subsequently refined, including factors such as approach speed, system radius and direction (Jelesnianski 1966, 1972, 1978). More detailed evaluation of individual water level processes was undertaken, with the three main components being identified as pressure effect, wind setup and wave setup (Harper *et al*. 1978; USACE 1984; DNRM Queensland 2001). Other processes, including surge-tide interaction, resonant effects and shelf waves were identified as less important for US Atlantic and Gulf coasts (Jelesnianski 1966), and therefore have been commonly neglected in widely available models.

The majority of simple water level assessments, including one-dimensional cross-shore models SBEACH (Larson & Kraus 1989; Larson *et al.* 1990; Rosati *et al.* 1993) and LITPROF (Hedegaard & Deigaard 1988; DHI Software) only use simplified representations of the three most common processes. This form of inundation assessment is termed Synthetic Data Interpretation (SDI) which populates a range of storms through selected parameters, such as central pressure and scale (USACE 2006). Performance of the SDI approach highlighted the potential sensitivity of water level estimates to parameter selection, prompting increased integration of observational data to define storm parameters. Initial techniques developed to resolve this issue included track shifting of observed events, or empirically fitting model variation with to observational statistics.

From the early 1990s, improvements in numerical modelling (Hubbert *et al*. 1991; Westerink *et al*. 1994; Bode & Hardy 1997) and meteorological databases (Lourensz 1981) enabled hydrodynamic modelling to be combined through Monte Carlo assessment. In this way, the meteorological database could be used to synthesise an artificial database of tropical cyclones, with modelled surges used to generate a statistical distribution. This technique is the fundamental basis for the approach widely-considered 'present best practice' for describing the meteorological characteristics (Scheffner *et al*. 1996; Harper *et al*. 2009; Hardy *et al*. 2010). The synthesis approach is constrained where there are few examples of storms from critical paths, or when tropical cyclones experience extra-tropical transition (Harr 2004). There is less agreement regarding specification of model scale, boundary conditions and tide-surge integration, with the model approach potentially determining drastically varying results (BOMSSU & GEMS 1995; Blain 1996). Furthermore, numerical models can only accurately represent a selected sub-set of the water level processes.

The effects of sub-sampling from a tropical cyclone database should be considered carefully. This may neglect events from a critical path, or fail to capture low-moderate surges, and therefore provide a limited domain of model validity (Figure Box 6-2a). This domain may be further reduced if tide and surge distributions are integrated following the model, rather than as part of the Monte Carlo process (Figure Box 6-2b). Typically the upper limit of the surge model (Su2) is considered infinite, as small probabilities only provide small error to total water level likelihood.



(a) Domain of Validity ***(b) Tide-Surge***

Figure Box 6-2: Domain of Validity and Tide-Surge Integration

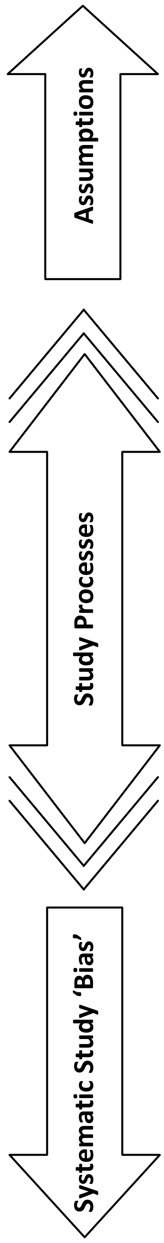
Despite a relative convergence of 'best-practice' techniques for tropical cyclone surge modelling, almost all preceding techniques remain in common practice, due to the need to provide cost-effective analysis. The results of different techniques have significantly varied degrees of precision (Table 6-1), although all are highly affected by the level of validation and quality of information used. Fallah *et al*. (1976) and Resio *et al*. (2009) provide two examples rom the USA which illustrates the change in methods over time.

An important aspect for the interpretation of inundation studies in the Pilbara is that sub-scale processes provide a systematic bias to study outcomes. An awareness of factors which have not been considered may be used to help on-ground hazard management, typical including coastal interactions, overland processes and receptor characteristics.

The SPP 2.6, in both existing and previous forms (WAPC 2003a, 2013), identifies a single storm event scenario occurring at a fixed tidal level as the recommended base case for inundation (Box 6-3). This approach is deliberately simple, allowing analysis to be cost-effective for small land developers. As compensation for this simplicity and the associated high uncertainty, SPP 2.6 (WAPC 2013) recommends the relatively severe inundation criterion of 500 year average recurrence interval. The SPP 2.6 Guidelines provide additional information regarding processes that should be considered in the evaluation, including wave runup, breaching or bypassing of barriers and overtopping for rocky or armoured coasts.

Table 6-2: Components of Tropical Cyclone Inundation Assessments

Processes	Factors	Scales: Regional	Intermediate	Coastal	Engineering
Meteorological	Cyclone Characteristics	✓			
	Wind & Pressure Fields	✓			
	Surface Stresses	✓			
Shelf Processes	Shelf Structure	✓			
	Wind Setup	✓			
	Seiches				
	Shelf Waves				
Hydrodynamic	Density Structure				
	Bathymetry	✓	✓		
	Bed Friction	✓	✓		
	Circulation	✓	✓		
Coincident Water Level Phenomena	Tidal Characteristics	✓	✓	✓	
	Mean Sea Level Change				
	Non-cyclonic Forcing			✓	
Surface Waves	Wave Field Generation	✓	✓		
	Wave Propagation	✓	✓		
	Nearshore Effects		✓	✓	
Coastal Interaction	Topography		✓	✓	
	Wave Runup		✓	✓	✓
	Vegetation			✓	
	Sediment Transport			✓	
	Coastal Change			✓	
	Barrier Breaching			✓	✓
Overland Processes	Overland Propagation			✓	✓
	Frictional Damping			✓	✓
	Fluvial Interaction			✓	
Receptors	Receptor Value				✓
	Management Response				✓
	Susceptibility to Impact				✓
	Structural Characteristics				✓



Details within this table are indicative only, with ticks marking those factors ***commonly*** *included in modelling at different scales. Every study contains a unique suite of factors and process representations. In general, there is a transition of processes with study scale, with regional or intermediate scale modelling neglecting coastal, overland and receptor factors. These provide systematic biases to the study, which may be relevant for hazard study interpretation.*

Box 6-3: Extracts from SPP 2.6 regarding cyclone prone areas

Selection of a storm event:

WAPC (2003a) Clause F.4: *Category 5 cyclone tracking to maximise its associated storm surge.*

WAPC (2013) Clause 5: *The selection of the storm event for determining the allowance for the current risk of erosion and inundation is dependent on the coastal zone (Figure E1). The allowance for the current risk of inundation should be based on a tropical cyclone storm event for zones one, two and three; and a mid-latitude depression or extra-tropical low storm event for zone four.*

Storm events will vary for each location and should be reviewed on a case-by-case basis. The path for the storm event should be determined so as to maximise the associated erosion and inundation. To assist in the determination of tropical cyclonic storm events the relative scales, central pressures and worst-case paths derived from historic records area available for the majority of locations.

F.4 Development in Cyclone Prone Areas (WAPC 2003a)

Any development located to the north of latitude 30 degrees should be set back from the foreshore to afford protection from the impact of cyclonic storms. The extent of the setback should be defined on a case-by-case basis including S1, S2 and S3 where relevant. The storm surge that accompanies coastal cyclones can inundate large areas a significant distance inland from the high water mark. The setback should be defined with regard to the amount of existing foreshore protection (natural or man made) and to local topography including waterways, as storm surge can induce back-flooding. Development should be set back from any areas that would potentially be inundated by the ocean during the passage of a Category 5 cyclone tracking to maximise its associated storm surge.

S.4 Inundation – Current Risk of Storm Surge Inundation (WAPC 2013. Clause 4.10)

The allowance for inundation should be the maximum extent of inundation calculated as the sum of S4 Inundation plus the predicted extent of sea level rise. Where inundation is limited by a coastal barrier (natural or manmade) consideration should be given to the stability of the barrier over the planning period.

The allowance for the current risk of inundation should be the maximum extent of storm inundation, defined as the peak steady water level plus wave run-up. Where inundation is halted by a coastal barrier (natural or manmade) consideration should be given to whether the barrier may be breached or bypassed during a storm event over the planning period.

Where a continuous barrier dune is present the capacity of the dune to provide protection from inundation should be assessed based on the cross-sectional area of the dune. If the dune reserve, the cross-sectional area of the dune above the peak steady water level, is less than 100 cubic metres, it should be assumed that the dune will be removed during storm activity and the maximum extent of storm inundation should be calculated without the dune.

On low permeability/impermeable coasts where wave run-up can result in wave overtopping, the coastal foreshore reserve width for this coastal process should be the maximum extent of wave overtopping.

The majority of existing townsites within the Pilbara have either or both runoff and coastal flood hazard. The recommended sequence for flood assessment when planning in affected urban and industrial zones, based upon Australian and international practice, involves:

1. Determine infrastructure elements, including key infrastructure providing essential services;
2. Consider a full range of potential flood levels, nominally up to the ‘probable maximum flood’;
3. Define spatial extent of maximum risk criteria for infrastructure elements (planning envelopes);

4. Determine 'best' available locations for key infrastructure, based upon ability to provide essential services through the range of flood levels;
5. Identify options for effective adaptation to varied flood conditions, likely involving definition of development exclusion areas for floodways and potential mitigation works;
6. Define spatial extent of non-essential infrastructure; and
7. Identify building design criteria suitable for flood-proofing.

Important aspects of Steps 4-7 are described in the risk mitigation section below.

The sequence considered crosses a range of planning and design issues, and therefore is cross-jurisdictional. Adequate assessment requires a framework that integrates between levels of government and different departments. In practice, this may most effectively be resolved through local planning strategies, although it may vary from case to case.

Flood Risk Mitigation Options and Adaptation

Many parts of the Pilbara are presently located within areas of flood risk, with the hazard to low-lying coastal areas projected to increase under sea level rise scenarios. The SPP 2.6 (WAPC 2013) acknowledges that existing freehold land-owners may be constrained in the use of setback to respond to projected sea level rise, as in some cases boundaries are defined based on present-day flood hazard. To this end, the policy allows consideration of adaptation as a variation to the general case. A preferential hierarchy is defined, following the sequence of 'Avoid-Retreat-Accommodate-Protect'. This hierarchy of strategies should be considered in the context of the seven steps to planning in flood-affected areas as described above.

To 'Avoid' inundation risk is to locate development on existing land which is above a threshold defined as having *negligible* inundation likelihood, adopted in SPP 2.6 as 500 year average recurrence interval plus projected sea level rise. For existing Pilbara townsites, this approach is difficult to apply, as this criterion is often well above existing infrastructure, and in some cases, would imply relocation outside of existing town boundaries or into rocky hills. The constraints to using the 'Avoid' strategy indicate that alternate nundation risk mitigation and adaptation options are likely to be required for many parts of the Pilbara.

The relative importance of minimising overall risk through site selection increases, when the 'Avoid' strategy is not appropriate. A common approach is the identification of infrastructure classes, such as emergency, key, general and peripheral; each of which has a different level of importance. Hazard criteria and planning envelopes should be established for each infrastructure class, with the more important facilities located preferentially in areas of lower hazard. This corresponds to Planning Steps 3, 4 and 6 listed above.

'Retreat' is the strategy of relocating infrastructure to higher ground over time, to offset the increased hazard caused by changing conditions. Consequently, this is an adaptive strategy, particularly for projected sea level rise, but does not mitigate present-day flood risk.

'Accommodate' refers to strategies that reduce the ultimate risk from flooding by modifying the impacts of a flood event, rather than changing the likelihood of an event occurring. Available techniques vary widely, including fiscal measures (e.g. flood insurance), human management (e.g. evacuation planning) through to structural measures (e.g. flood proofing, building on stilts, or blow-out panels). The SPP 2.6 Guidelines contain a list of options that 'Accommodate' flood hazard. These techniques are widely used in the Pilbara, but as they are not clearly codified in the planning or building approvals processes, their use is haphazard and has generally not been considered in the evaluation of hazard thresholds.

The strategy to 'Protect' against flood hazard refers to the installation of structures that physically prevent the effects of erosion or inundation impacting upon a development. This strategy has seen increasing use throughout the Pilbara in recent years, including using fill to raise floor levels and containment to reduce the impacts of erosion. The practicality of using 'Protect' strategies to reduce risk is constrained in very low-lying areas due to both expense and the difficulty of integrating isolated developments with existing services, including roads and drainage.

Issues regarding the use of 'Protect' strategies have been addressed in the USA and Europe (USACE 1996, Hofstede *et al*. 2005). This includes the potential transfer of flood risk (due to less space for floodwaters to move through), the potential for exacerbated impact associated with structural failures and concentrated impact above the threshold of protection provided by the structures.

For either 'Accommodate' or 'Protect' strategies, imposed changes may affect the relative differences between various economic and safety considerations. These can be, at a simple level, distinguished by three criteria:

- Human safety, when there is threat to well-being. This may correspond to an evacuation level, structural failure, or a threshold causing isolation in locations that are not capable of withstanding the possible maximum flood;
- Onset of damage, generally considered to commence once a residence starts to get wet; and
- Structural failure, which occurs once hydrodynamic loads exceed the structural capacity of the building.

Commonly these criteria are considered closely related, with minimum freeboard and structural capacity commonly providing additional capacity (and therefore less frequent criteria) above the nominated design flood level. However, structural works to 'Accommodate' or 'Protect' may bring the safety or economic criteria closer together, and therefore the relative impact of each criterion may need to be considered separately.

The effect of human safety is most commonly addressed in the Pilbara through existing emergency management plans that have been developed for many townsites (FESA 2004). In the context of individual developments, this requires consideration of the available warning systems, and potential constraints to exit pathways, including wave action (EMA 2009a, 2009b).

Human Safety including Risk of Isolation
Isolation provides a significant risk to residents, as the difference between a 3m surge or a 5m surge can merely be a change in cyclone path of a few kilometres. Consequently, where isolation may increase the threat to human life, evacuation of low-lying premises should be undertaken before building isolation occurs. If 'Queenslander' style buildings are used, there is a large difference between the commencement of flooding on a building and the onset of damage. The risk of building isolation is often commonly determined road levels. Pedestrian access is generally considered possible through water of depth up to 0.3m, although this is likely to be further constrained under cyclonic conditions due to extreme winds and possible impact of waves. 'Site wetting' may not always be possible to use as a guide, requiring evacuation to occur on a site-by-site basis prior to the level of water reaching 0.3m on the lowest point of an evacuation route.

Consideration should be included for existing road infrastructure and non-sealed tracks, with high elevation connection away from flooded areas. The increase in flooding likelihood with sea level rise should also be considered.

Key evacuation centres and health facilities (eg. schools and hospitals) should be located beyond any inundation hazard to provide a refuge in the event of road closure or townsite isolation.

Most areas of the Pilbara townsites and camping facilities will require an evacuation plan to be developed and distributed to occupants at risk.The difficulty of operating under strong winds and the potential absence of visual flooding clues determines that an emergency warning system is necessary in some areas such as Onslow, which in practical terms should be part of a town-wide system.

Onset of Damage
The criterion for onset of flood damage varies between Local Governments, generally above the 100 year ARI criteria with some also incorporating an allowance for sea level rise over 100 years. In many locations, such as Onslow townsite, there is a significant difference between the requirements for evacuation and the onset of damage. Under such conditions, residents may be more likely to decide to 'wait out' the flood in isolated buildings, which increases risk to human safety compared to evacuation at an earlier time.

For events above the onset of damage threshold, no guidance is provided by local or State government policies relevant to flood management. However, following the approach of considering a full range of possible flood events (ARMCANZ 2000), it is generally appropriate to minimise the incremental damage with larger flood events (i.e. flood-proofing). Basic structural elements to reduce cost of repairs following a flood event include:

- Installation of flow through paths, to prevent build up of floodwaters;
- Use of waterproof or flood resistant floor surfaces on ground floor of buildings;
- Raising of electrical connections well above floor level.

Extensive further information regarding structural modifications suitable for flood-proofing is available from the US Federal Emergency Management Authority (FEMA) building design guidelines (FEMA 1981, 2005, 2011).

The general principles of flood hazard mitigation are distinguished by FEMA for three zones:

Flood Zone Class A	Low level flooding, wave action < 0.4m
Flood Zone Class A Coastal	Low level flooding, wave action 0.4-1.0m
Flood Zone Class V	Wave action > 1.0m

Different building requirements listed in Table 6-3 for 'erosive flooding' from oceanic water which includes wave attack (V Zone), which is a threat to life and is destructive to buildings, and for 'wetting flooding' (A Zone) which under the 100 year ARI cyclonic event is short-lived and only produces property damage.

Table 6-3: FEMA Building Requirements for Defined Flood Zones
BFE – Base Flood Elevation typically corresponds to 100 year ARI occurrence. Higher flood levels may be designated by State or community

	V Zone Guidance	Coastal A Zone Guidance	A Zone Guidance
General Requirements			
Design	**Requirement:** building and foundation must be designed, constructed, and anchored to prevent flotation, collapse, and lateral movement due to simultaneous wind and water loads	**Requirement:** building must be designed, constructed, and anchored to prevent flotation, collapse, and lateral movement resulting from hydrodynamic and hydrostatic loads, including buoyancy	**Requirement:** building must be designed, constructed, and anchored to prevent flotation, collapse, and lateral movement resulting from hydrodynamic and hydrostatic loads, including buoyancy
Materials	**Requirement:** structural and non-structural building materials at or below the BFE must be flood resistant	**Requirement:** structural and non-structural building materials at or below the BFE must be flood resistant	**Requirement:** structural and non-structural building materials at or below the BFE must be flood resistant
Construction	**Requirement:** building must be constructed with methods and practices that minimise flood damage	**Requirement:** building must be constructed with methods and practices that minimise flood damage	**Requirement:** building must be constructed with methods and practices that minimise flood damage
Siting	**Requirement:** all new construction shall be landward of mean high tide; alteration of sand dunes and mangrove stands that increases potential flood damage is prohibited **Recommendation:** site new construction landward of the long-term erosion setback and landward of the area subject to erosion during the 100-year coastal flood event.	**Requirement:** encroachments into the SFHA are permitted as long as they do not increase the BFE by more than 1 foot *(some communities may allow encroachments to cause a 1-foot rise in the flood elevation, while others may allow no rise)*; encroachments into the floodway are prohibited. **Recommendation:** site new construction landward of the long-term erosion setback and landward of the area subject to erosion during the 100-year flood event.	**Requirement:** encroachments into the SFHA are permitted as long as they do not increase the BFE by more than 1 foot *(some communities may allow encroachments to cause a 1-foot rise in the flood elevation, while others may allow no rise)*; encroachments into the floodway are prohibited.

	V Zone Guidance	Coastal A Zone Guidance	A Zone Guidance
Foundation			
Structural Fill	**Prohibited**	**Allowed**, but **not recommended**; compaction required where used; protect against scour and erosion *(some coastal communities require open foundations in A zones)*	**Allowed**; compaction required where used; protect against scour and erosion *(some coastal communities require open foundations in A zones)*
Solid Foundation	**Prohibited**	**Allowed**, but **not recommended**; *(some coastal communities require open foundations in A zones)*	**Allowed**; *(some coastal communities require open foundations in A zones)*
Open Foundation	**Required**	**Not required**, but **recommended**; *(some coastal communities require open foundations in A zones)*	**Allowed**; *(some coastal communities require open foundations in A zones)*
Non-structural Fill			
Non-structural Fill	**Allowed** for minor landscaping and site drainage as long as the fill does not interfere with the free passage of flood waters and debris beneath the building or cause changes in flow direction during coastal storms that could result in building damage	**Allowed** (Placement of non-structural fill adjacent to buildings in coastal AO zones is not recommended) **Recommended;** same as V zone	**Allowed**
Structural Elements			
Lowest Floor Elevation	**Not Applicable**: bottom of lowest horizontal structural member must be at or above the BFE	**Requirement:** top of floor must at or above BFE **Recommendation:** elevate bottom of lowest horizontal structural member to or above BFE (see next category below); orient member perpendicular to wave crest	Requirement: top of floor must at or above BFE
Lowest Horizontal Structural Member	**Requirement:** bottom must at or above BFE **Recommendation:** orient perpendicular to wave crest	**Allowed** below BFE *(state or community may regulate to a higher elevation - DFE)*, but **not recommended** **Recommendation:** bottom must at or above BFE	**Allowed** below BFE (*state or community may regulate to a higher elevation (DFE))*, but **not recommended** **Recommendation:** bottom must at or above BFE
Freeboard	**Not required, but recommended**	**Not required**, **but recommended**	**Not required**, **but recommended**

	V Zone Guidance	Coastal A Zone Guidance	A Zone Guidance
Enclosures Below the BFE			
Enclosures Below the BFE	**Prohibited**, except for breakaway walls, open lattice, and screening *(some coastal communities prohibit breakaway walls)* **Recommendation**: if constructed, use open lattice or screening instead of breakaway walls	**Allowed**, but not recommended; if an area is fully enclosed, the enclosure walls must be equipped with openings to equalize hydrostatic pressure; size, location, and covering of openings governed by regulatory requirements **Recommendation:** if enclosure is constructed, use breakaway walls, open lattice, or screening *(some coastal communities prohibit breakaway walls)* *(if an area below the BFE in an A-zone building is fully enclosed by breakaway walls, the walls must allow equalization of hydrostatic pressure)*	**Allowed;** if an area is fully enclosed, the enclosure walls must be equipped with openings to equalize hydrostatic pressure; size, location, and covering of openings governed by regulatory requirements *(some coastal communities prohibit breakaway walls)* *(if an area below the BFE in an A-zone building is fully enclosed by breakaway walls, the walls must allow equalization of hydrostatic pressure)*
Use of Space Below BFE			
Use of Space Below BFE	**Allowed only** for parking, building access, and storage	**Allowed only** for parking, building access, and storage	**Allowed only** for parking, building access, and storage
Utilities			
Utilities	**Requirement:** must be designed, located, and elevated to prevent flood waters from entering and accumulating in components during flooding	**Requirement:** must be designed, located, and elevated to prevent flood waters from entering and accumulating in components during flooding	**Requirement:** must be designed, located, and elevated to prevent flood waters from entering and accumulating in components during flooding

	V Zone Guidance	Coastal A Zone Guidance	A Zone Guidance
Certification			
Structure	**Required**: registered engineer or architect must certify that the design and methods of construction are in accordance with accepted standards of practice for meeting the design requirements described under GENERAL REQUIREMENTS	**Recommendation;** same as V zone	**Recommendation;** same as V zone
Breakaway Wall (also see enclosures below the BFE)	**Required:** either of the following: (1) walls must be designed to provide a safe loading resistance of between 10 lb/ft^2 and 20 lb/ft^2 OR (2) a registered engineer or architect must certify wall collapse at BFE without affecting elevated sections (*some coastal communities prohibit breakaway walls*) (*if an area below the BFE in an A-zone building is fully enclosed by breakaway walls, the walls must allow equalization of hydrostatic pressure*)	Not required, but **recommended** *(some coastal communities prohibit breakaway walls)* *(if an area below the BFE in an A-zone building is fully enclosed by breakaway walls, the walls must allow equalization of hydrostatic pressure)*	**Not required** *(some coastal communities prohibit breakaway walls)* *(if an area below the BFE in an A-zone building is fully enclosed by breakaway walls, the walls must allow equalization of hydrostatic pressure)*
Openings in Below-BFE Walls (Also see enclosures below the BFE)	**Not Applicable** *(walls below BFE must be designed and constructed as breakaway walls that meet the minimum requirements of the NFIP regulations)*	**Required:** unless number and size of openings meets regulatory requirements, registered engineer or architect must certify that openings are designed to automatically equalize hydrostatic forces on walls by allowing the automatic entry and exit of flood waters	**Required:** unless number and size of openings meets regulatory requirements, registered engineer or architect must certify that openings are designed to automatically equalize hydrostatic forces on walls by allowing the automatic entry and exit of flood waters

Structural Failure
The consideration of structural failure is important, as the cost of repair increases significantly when there is building failure. A range of pathways to structural failure may need to be considered in design, including:

- Wind loading;
- Flooding (hydrostatic and hydrodynamic);
- Scour and erosion (waves and currents);
- Overtopping of adjacent structures, including duneds if present; and
- Battering by debris (wind or flood driven).

Criteria set for hazard mitigation of each of these pathways are typically unequal, as any criterion is normally intended to capture the risk associated with exceedance events and is often affected by the cost to mitigate. For example, wind load criteria typically have higher ARI than wave criteria. Hydrodynamic loads associated with 100, 500 and 1000 year ARI inundation may be evaluated to ensure adequate performance of structures and supporting sub-structures under an extrement inundation event.

For buildings designed to the cyclone wind code (AS 1170.2), but not specifically designed for hydrodynamic loads, failure is likely to occur approximately 0.3m above the base of building slabs. The risk of failure is further enhanced by structural deterioration, suggesting the need for a program of building inspection, maintenance and potentially adaptation to changing conditions.

Modifications to accommodate potentially higher sea level rise include:

- Installation of stronger vertical supports (during construction);
- Installation of flow through paths, to prevent build up of floodwaters (during construction);
- Provision of 'blowout' panels that are capable of withstanding wind load, but not hydrodynamic loads, thereby reducing stresses on major structural elements (during construction);
- Construction of external walling on the property boundary suitable to baffle wave action (may be retro-fitted);
- Construction of high strength walling on the lower part of the building to resist hydrodynamic pressures (may be retro-fitted).

The general principles of flood hazard mitigation building requirements for 'wetting' flooding and 'erosive' flooding are described by FEMA and included in Table 6-3 above.

A further element of consideration for structural hazard is the relative susceptibility of structure types to sustained or instantaneous wave loads. Historical observations of extreme water levels, such as TC Vance at Exmouth in 1999, typically peak for only 1-3 hours. This may reduce the limit the damage caused to some structure types, particularly where fatigue or incremental damage may occur (van der Meer 1988). However, this is not generally relevant to the structural elements of buildings.

6.2. ONSLOW

The Area of Planning Interest containing Onslow is in the west Pilbara, which contains Onslow town site and Ashburton North, the approved location for a Strategic Industrial Area 12 km southwest of Onslow. The Onslow area is located between the Ashburton and Cane Rivers, to the west and east respectively and is dominated by an expansive area of mudflats which act as an overflow pathway for the river systems during extreme runoff events.

The Onslow coast has a mixture of sandy and rocky features, with low-lying rock headlands providing structural controls that define three tertiary sediment cells in the area (Figure 6-8), including Beadon Point, upon which the town site of Onslow is located. Two tertiary compartments are present in the area (Figure 1-1), being the convex sandy deposit of the Ashburton delta and the arcuate sandy beaches to the east. Connectivity along the coast is provided through natural bypassing at the headlands and sediment transfer between the coast and mudflats (Figure 6-13 to Figure 6-15).

Historically, there has been a net eastward sediment transport, with a progressively decreasing quantity away from the Ashburton River. This has resulted in net accretion along much of this section of coast, intermittently reversed through short-term erosion due to some tropical cyclones. The abundance of sediment and the control by rock headlands has historically provided a relatively stable coastal situation. Disruption of the alongshore transport through coastal infrastructure is likely to affect the downdrift supply and therefore may have implications for coastal dynamics to the east.

6.2.1. Geomorphic Processes

The wider Onslow area is geomorphically complex, with significant influence from both coastal and fluvial processes, acting upon a mixture of lithified and sedimentary features. Environmental conditions are highly irregular, with a mild prevailing climate, but potential for extremes, particularly associated with tropical cyclones (Nelson 1975; Silvester & Mitchell 1977; Ruprecht & Ivanescu 2000; DHI 2010).

The overall morphology is that of a breakout coastal floodplain, which is eastward and therefore downdrift from the major sediment supply from the Ashburton River (Damara WA 2010a; URS 2010b). This ongoing, albeit irregular sediment supply is sufficient to facilitate vertical growth of coastal dunes, with occasional severe storm erosion and dune overwash (Nott & Hubbert 2005). Relict coastal limestone features act to control the shoreline position, but have fixed position and capacity, providing a generally narrow coastal dune structure, with any excess material bypassing the low-lying coastal headlands. A wider dune field of up to 800m width has developed on Sunset Beach (also called Onslow Back Beach).

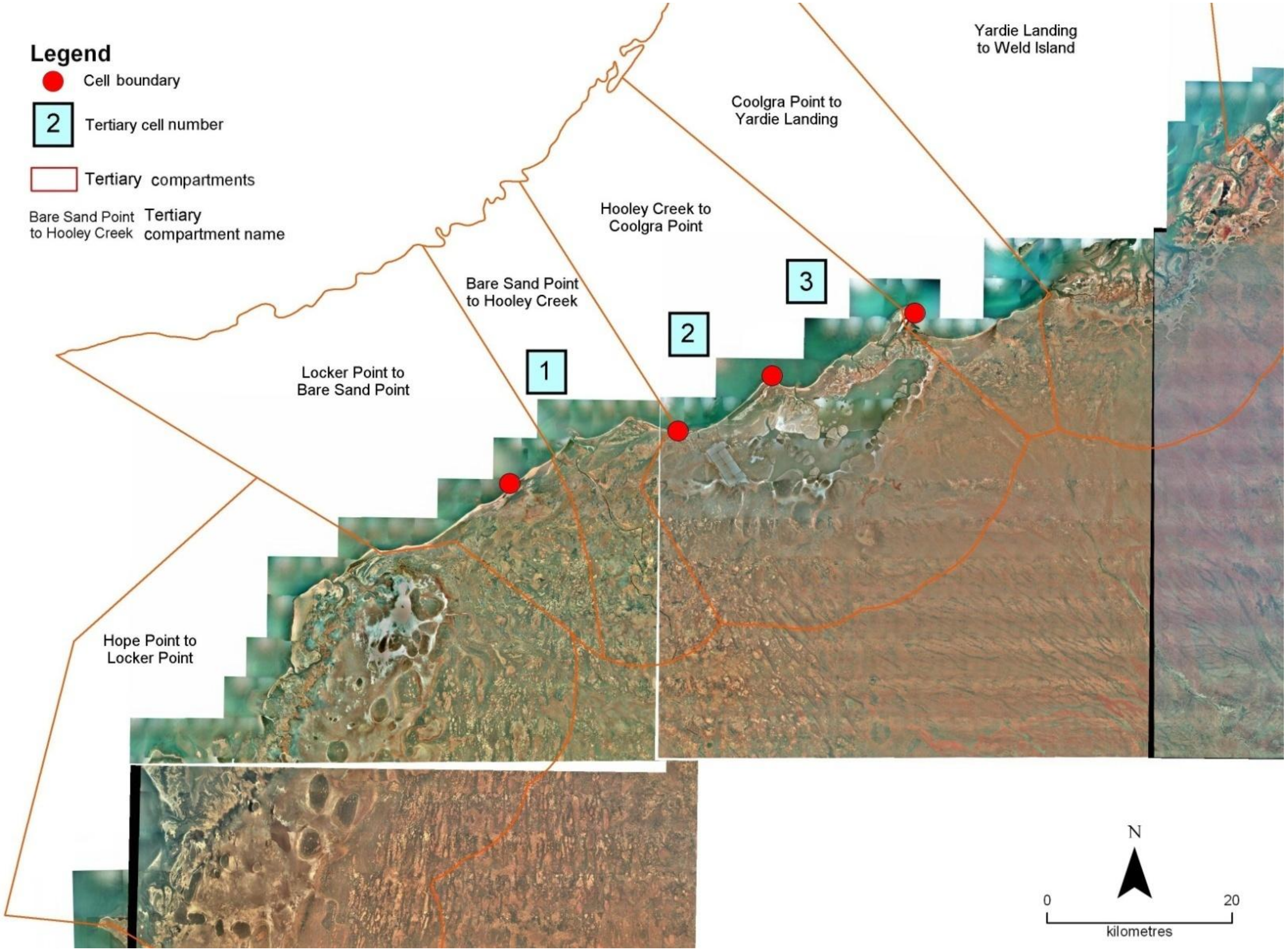


Figure 6-8: Onslow Tertiary Sediment Cells (Cells 1-3)

Coastal dynamics at Onslow Town Beach have been largely determined by human actions, particularly management of the small craft harbour at Beadon Creek (Crawford 1995). Construction of a training wall for the tidal creek entrance resulted in dramatic accretion on its western side, with corresponding retreat further west, adjacent to the town site (Figure 6-9). A seawall to protect against further erosion was installed, with later significant upgrade (HGM 2000; MP Rogers & Associates 2002). Beadon Creek harbour continues to experience sedimentation, although the rate is relatively low (HGM 1999; BMT JFA & Oceanica 2011).

The breakout floodplain is low-relief, with extensive areas of mudflats and salt flats. Sediment supply to the floodplain is limited, restricted by the coastal dune barrier and the occasional nature of significant runoff flows. Local exceptions are provided by the tidal creek systems, which facilitate sediment exchange between the coast and floodplain (Damara WA 2010a). Extensive modification of the breakout floodplain through construction of solar salt ponds has been coincident with significant sedimentation within the Beadon Creek tidal network since its isolation, although there is insufficient record to determine if this is a cause-and-effect relationship, or is the result of natural variability. Creek expansion of up to 10m per year has been identified on the Hooley Creek tidal network, immediately east of the Ashburton North site (Damara WA 2011a).

The low-lying nature of the area, including much of Onslow town site makes it potentially susceptible to flooding hazards from storm surge, runoff flooding or tsunami (GEMS 1999, 2000a; Simpson *et al*. 2007; GA & FESA 2010). Under moderate to high flooding conditions, access from the town site may be cut off by inundation of the mudflats. This affects emergency management for Onslow, parts of which may be directly affected by flooding during extreme events. The threat of runoff flooding for much of the area has been reduced through construction of the salt pond levees (Gulf Holdings 1990; Onslow Salt 1995), although this has produced an alternative hazard associated with levee failure and has locally increased the level of runoff flooding outside the ponds.

6.2.2. Planning Context

Onslow was established as a town site in 1883, with maritime facilities located inside the Ashburton River Mouth and the town site to the east. Repeated flooding of the area and movement of the river channel prompted relocation of landing facilities from 1894 and movement of the town site itself in the 1920s. Onslow sea jetty was destroyed during initial construction in 1897, rebuilt and then later abandoned in favour of a jetty at Beadon Point.

The existing Onslow township is located between Beadon Point and Beadon Creek. Dredging works and construction of a training wall in 1968 provided a fishing craft harbour within the creek entrance, which is managed by the Department of Transport and periodically dredged (Crawford 1995). Concern regarding the stability of the shoreline, and potential cyclone impacts on the township resulted in the construction of a seawall in front of the town. This structure was damaged during TC Vance in 1999, with an upgraded 900 m seawall completed in 2002. This structure provides erosion protection, but does not resist inundation, with parts of the town site below the estimated 100 year storm surge level.

Figure 6-9: Aerial Photography Onslow Townsite (1963-2007)

Previous industrial development at Onslow included construction of extensive salt ponds, a loading jetty and navigation channel for Onslow Salt in 1998 (Gulf Holdings 1990; EPA 1991a, 1995 a & b, 1997 a & b).

The capacity for a small further industrial expansion southwest from Onslow was identified in *Northern Strategic Industry Areas Environmental, Social and Economic Study* (SMEC 2004), which briefly considered land tenure, morphology, coastal hazards, groundwater hydrology, flora and fauna, cultural heritage, social infrastructure and industrial infrastructure. The area targeted for development was subsequently significantly expanded westward through the *Onslow Strategic Industrial Area: Expansion Study* (WorleyParsons 2005). On the basis of this work, the area of Ashburton North has undergone extensive evaluation for its capacity to site the Ashburton North Strategic Industrial Area, incorporating an LNG and DomGas plant, with associated port works for supply and materials offloading (Chevron Australia 2010; DSD 2010). The proposal was granted conditional environmental approval in September 2011 (EPA 2011a), with planning for further expansion to service additional fields underway (TBB 2011).

Recent town planning for Onslow has built around the anticipated industrial growth of the adjacent areas. This has included preliminary planning for development of further residential and transient workforce accommodation, and identification of potential growth corridors (WAPC 2008a, 2009a [Map 23], 2012 [Map 9]). The uncertainty surrounding potential impacts of coastal hazards, specifically in the context of potential high scenarios for projected sea level rise, has prompted reanalysis of coastal flooding extent and erosion (MP Rogers & Associates 2011) which is intended to refine previous planning. Comparison of the growth plan with available contours suggests that much of the planned residential growth has been directed towards higher land. However, this approach has not been followed for isolated industrial areas, which have been sited according to proximity of existing infrastructure, including Onslow Salt operations and Beadon Creek harbour.

Present-day zoning for Onslow is provided by the *Shire of Ashburton Town Planning Scheme No. 7* (DoP 2010a [Map 3 and 4]). This includes defined areas for strategic industrial development and special control areas related to coastal hazards, which incorporate those areas subject to erosion or inundation. Conditions relating to the special control areas relate to potential incompatibility of the proposed land use with flood or storm surge effects, and require consideration of minimum floor levels (+5mAHD for 'dune ridge' and +4mAHD for remaining storm surge hazard area). These levels were recommended by the Department of Marine Harbours (1988) considering peak steady water level on highest astronomical tide, increasing from the previous +3mAHD contour (Taylor & Burrell 1982; or 3m above HAT [Table 6-4]). The minimum development levels were established after the development of the town and are above extensive low-lying portions of the town, including the road network. Previous plans for Onslow have recognised the need for special control areas (Taylor & Burrell 1982; DPUD 1994; WAPC 2000, 2002b) but are likely to be outdated due to the dramatic increase in the projected town site growth.

Inundation Assessments

Inundation through either coastal flooding or runoff is a significant hazard across the low-lying floodplains within the Shire of Ashburton. Major events have previously caused extensive damage to coastal infrastructure and on two occasions caused relocation of Onslow townsite. The potential severity of extreme events is suggested by wrack lines up to +8mAHD that have been dated at 700 years before present (Eliot & Dodson 2010; Dodson & Eliot 2011; Section 4.2.2). Flooding during tropical cyclones in 1958 and 1961 was observed to reach 1.5m and 2.5m above high water mark (Nelson 1975; Hopley & Harvey 1976). Similar levels of flooding were observed during TC Vance (Nott & Hubbert 2005).

Analysis of coastal flooding hazard at Onslow was first conducted as part of Australia-wide and regional applications of basic surge models built around shelf structure (Trajer 1973; Hopley & Harvey 1976; Silvester & Mitchell 1977). The capacity of these initial models to represent hazard likelihood was recognised as limited due to minimal meteorological data, poor representation of inner shelf and nearshore surge processes and a very small sample set of extreme events. Subsequent accumulation of meteorological data and availability of more advanced modelling techniques has enabled progressive refinement of flood assessments. However, there still remains a small set of extreme observations available for validation and in most cases only a restricted sub-set of water level processes were simulated.

Modelling of extreme water levels (typically 10 to 1000 year ARI) has been undertaken for planning purposes and infrastructure design at Onlow townsite, Onslow Salt facilities and the proposed port at Ashburton North, approximately 10km west of Onslow (Table 6-4). The majority of studies have involved assessment of direct-impact tropical cyclone-induced flooding, with some evaluation of tsunami hazard. Analyses of tide gauge records at Onslow suggest that there is potential for moderate surge events to be under-represented, as surges in the order of 1.0m have been generated by tropical cyclones moving shore-parallel, through formation of shelf waves (Hopley & Harvey 1976; Hubbert *et al.* 1991; Damara WA 2008; Eliot & Pattiaratchi 2010).

Despite the number of inundation assessments, the information-base to support hazard assessments is poor, with only one probabilistic study that is based upon relatively modern comprehensive surge modelling (GEMS 1999). Subsequent studies are either directly derivative (GEMS 2000a; MP Rogers & Associates 2011) or based upon highly simplified surge assessment techniques (LWI 2010; GHD 2010b). The most recent evaluation (MP Rogers & Associates 2011) recommends a development minimum floor level of +6.4m AHD, which incorporates a tropical cyclone water level of +5.0m AHD, a sea level rise allowance of 0.9m and a development freeboard of 0.5m. The study used a 1D model (SBEACH) that suggested a rise of 0.8m from nearshore to the coast, which roughly corresponds to the previous 2D modelling results (GEMS 2000a).

Table 6-4: Inundation Assessments in the Onslow Region

Assessment	Application	Hazard Levels	Model Basis
Tropical Cyclones			
Hopley & Harvey (1976)	Australia-wide	100 yr *Port Hedland* Surge: 2.78m	Shelf structure
Silvester & Mitchell (1977)	Australia-wide	Maximum surge: 2.8m Average surge: 1.0m	Shelf structure
Taylor & Burrell (1982)	Onslow	Development required above 10 foot contour (+3mAHD). If based on Kelly Line this would be 3m above HAT (+1.55mAHD) to a total of +4.55mAHD.	
Department of Marine & Harbours (1987)	Onslow Salt	100 yr: +4.5mAHD [conservative] 100 yr of +4mAHD used for planning Suggested all developments must be above +3mAHD.	Tide gauge data
Department of Marine & Harbours (1988)	Onslow	100 yr: +3.25mAHD 100 yr PSWL: +4.75mAHD (surge + HAT)	Tide gauge data
Steedman Science & Engineering (1990)	2km north of Beadon Point	Modelled at -4.5mAHD. 100 yr surge: 2.4m 100 yr PSWL: +2.4mAHD	
GEMS (1999)	Onslow Salt	*<Not Available>*	TC direct-hit
GEMS (2000a)	Onslow (Beadon Point)	Along Town Beach area, therefore likely to include setup. 100 yr PSWL: +3.9 to +4.5mAHD 200 yr PSWL: +4.3 to +5.1mAHD	TC direct-hit
Damara WA (2009b)	Onslow	Surge variation with shift in tropical cyclone intensity and frequency	100 yr surge (existing): 4.2m
LWI (2010)	Ashburton North	At shoreline, includes wave setup 100 yr: +4.1mAHD (Surge 3.26m) 200 yr: +4.7mAHD (Surge 3.86m)	TC direct-hit
GHD (2010b)	Onslow	*At -8.5mAHD* 100 yr surge: 2.2-2.9m (at 0.39mAHD tide) 100 yr: +4.5 to +5.2mAHD (includes 0.4m SLR, wave setup, wave runup) *At +1.5mAHD* 100 yr surge: 3.0-3.9m (at 0.39mAHD tide) 100 yr: +5.3 to +6.2mAHD (includes 0.4m SLR, wave setup, wave runup)	TC direct-hit
MP Rogers & Associates (2011)	Onslow	Used GEMS (2000a) findings. 100 yr: +5mAHD 100 yr finished floor level: +6.4mAHD (PSWL +5mAHD plus 0.9m SLR + 0.5m freeboard)	TC direct-hit
Tsunami Modelling			
Simpson *et al.* (2007)	Onslow	>6m inundation in areas.	
Burbidge *et al.* (2008)	Western Australia-Wide	Reported for *Exmouth in 50m water depth*: 500 yr wave height: 0.5 to 1m 1000 yr wave height: 0.8 to 1.8m 10000 yr wave height: 2 to 7m	
Geoscience Australia & FESA (2010)	Onslow	Maximum runup height for worst Magnitude 9.0 to 9.3 tsunamis is 11-16m.	
LWI (2010)	Ashburton North	100 yr: +3.6mAHD 500 yr: +5.6mAHD 1000 yr: + 6.6mAHD	

Reliance upon a single modelling study to describe inundation hazard is not uncommon for the smaller townsites across northern Western Australia. However, experience gained in more frequently studied locations has demonstrated that even relatively minor amendments of the supporting information may drastically affect model outcomes, with adjustment of the 100-year ARI flood level by 1-2m not uncommon (CMPS&F 1999; Damara WA 2010b). Factors that may affect the results include observations used for model validation, the synoptic climatology, fundamental model processes, ocean-coast representation and interactions with tide or mean sea level.

6.2.3. Landforms and Sediment Cells

Landform mapping has been completed for the wider Onslow region by the Geological Survey of Western Australia (Figure 6-11 with key in Figure 6-10), which reflects the geological complexity. The relative stability of each landform type has been identified (Table 6-5; Figure 6-12) which provides a general progression from low stability near the coast towards higher stability landward. The extensive area of coastal instability is mainly a consequence of the low relief of landforms across the coastal floodplain.

The landform analysis has been grouped into three tertiary sediment cells for the wider Onslow Area, being:

1. Rocky Point to Hooley Creek
2. Hooley Creek to Beadon Point
3. Beadon Point to Coolgra Point

The major features, when described at this scale are outlined in Table 6-6.

Aerial imagery for the Rocky Point to Hooley Creek area (Figure 6-13) shows the dynamic nature of the Ashburton River delta, which has been described in greater detail (Damara WA 2010a). Large fluxes of water and sediment have the capacity to rework the deltaic channel system over short time scales and have caused large-scale channel migration over longer-time scales with an extensive network of palaeochannels, many of which are active as modern breakout flow paths.

Imagery for Hooley Creek to Beadon Point (Figure 6-14) illustrates the focus for change occurring on tidal creek entrances, with major changes to the entrance spits, closure of one breach through the dunes and expansion of the Hooley Creek system. This may be partly explained by the construction of salt ponds, but much of the change occurred prior to their installation (Damara WA 2011a). Erosion at the tip of Beadon Point occurred largely during TC Vance (March 1999) and has exhibited slow recovery, despite a rapid recovery and general advance of the dune field along Sunset Beach.

Observed coastal change between Beadon Point and Coolgra Point (Figure 6-15) is largely limited to Onslow Town Beach, in response to human interventions of groynes, seawalls, Beadon Creek training walls and channel dredging (Section 6.2.1). The coast further to the east is rock controlled, apparently with limited available sediment. Beadon Creek tidal network has been isolated from the coastal lagoon through construction of salt pond levees. Extensive depositional fans throughout the tidal network suggest that the wider area of the creek is subject to significant accretion following reduction of tidal and runoff flows.

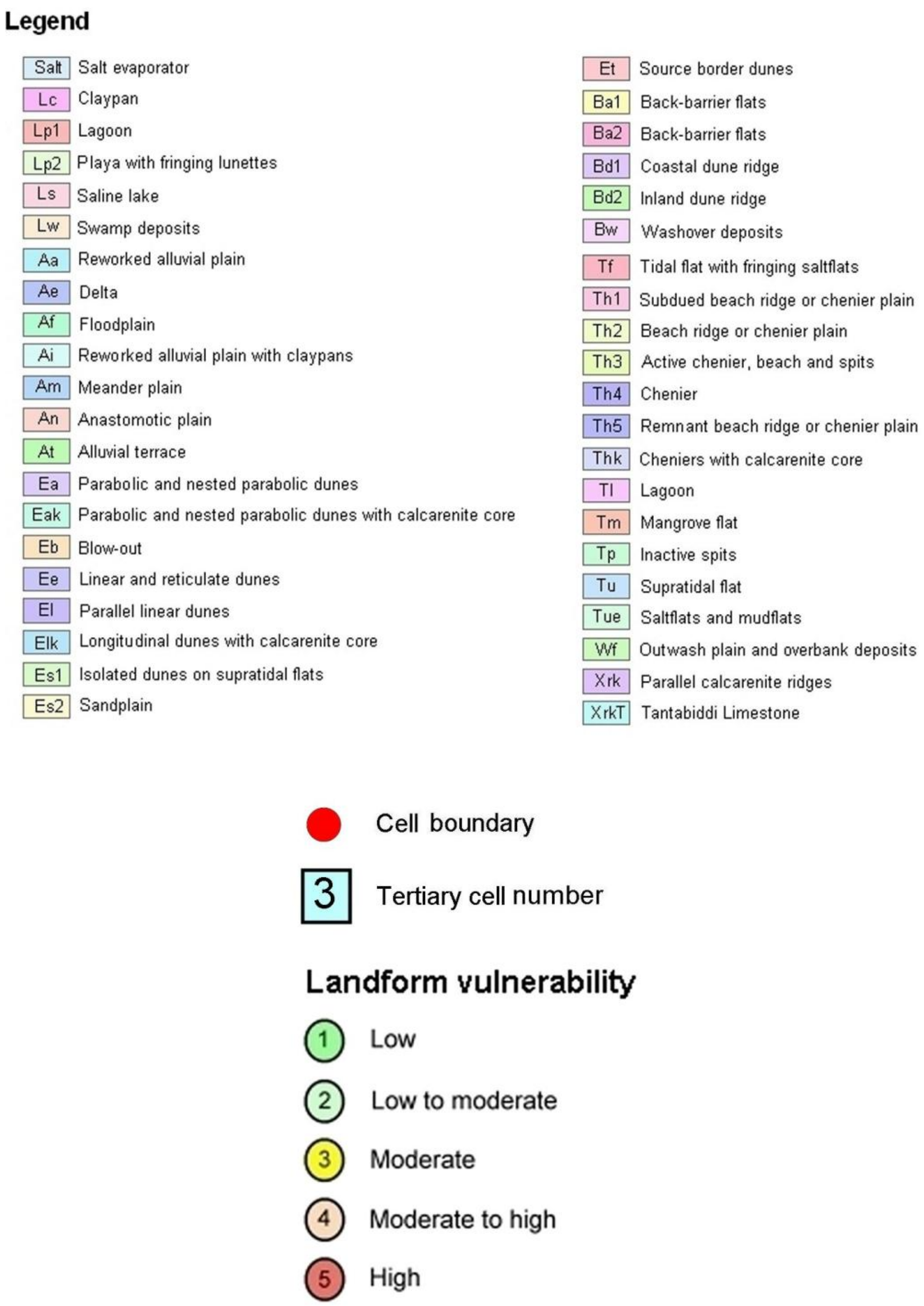


Figure 6-10: Onslow Landform and Vulnerability Map Legend

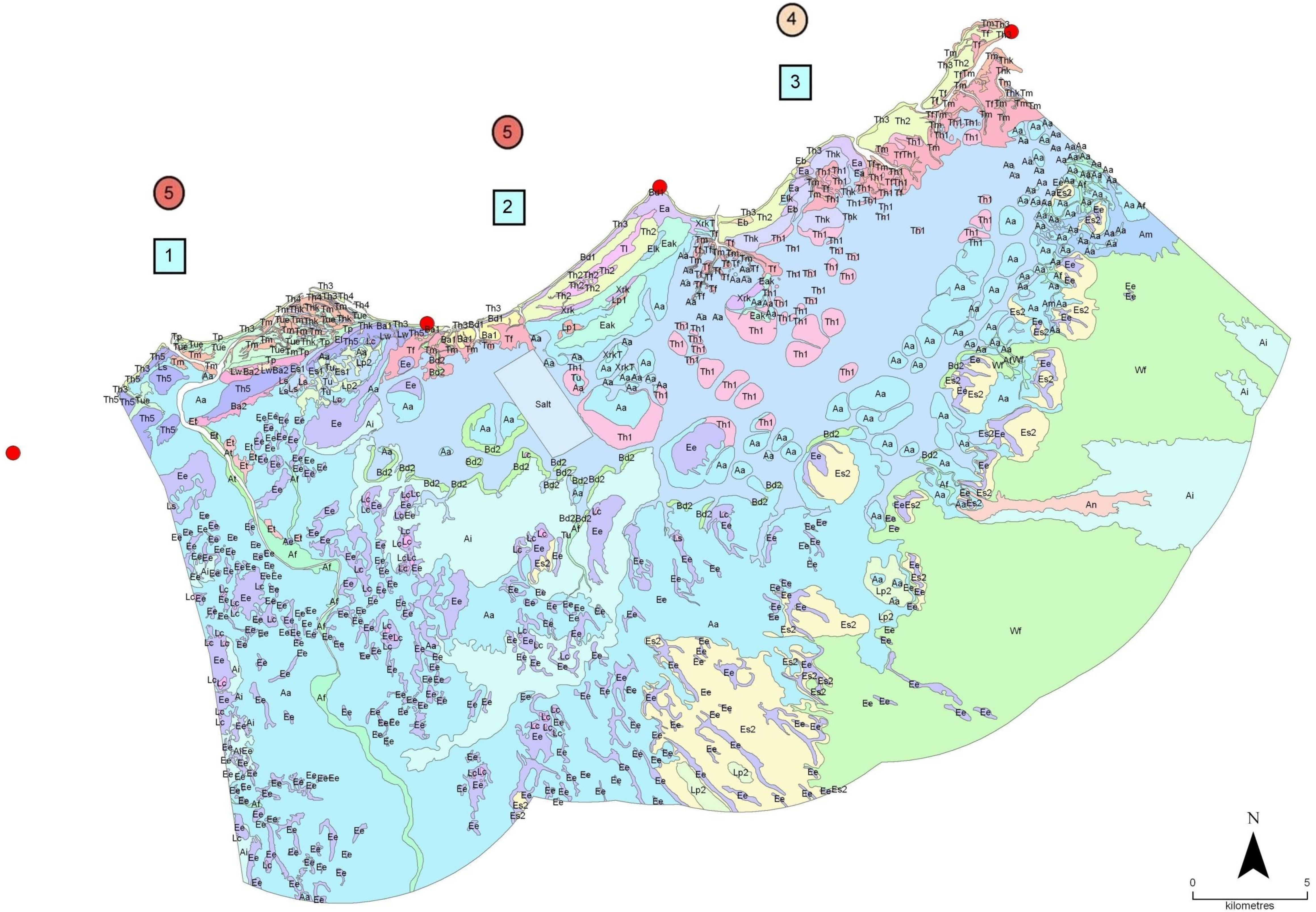


Figure 6-11: Onslow Area Vulnerability and Landforms
Legend in Figure 6-10

Table 6-5: Landforms of the Onslow Area and their Relative Instability (After: Gozzard 2012a). See Table 2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Salt evaporator (Salt)	Salt evaporator	High (Unstable)
Claypan (Lc)	Small, circular, oval or irregularly shaped deflation depressions; bare, sealed surfaces; soils are reddish brown non-cracking clays	High (Unstable)
Lagoon (Lp1)	Shore-parallel linear units behind the main body of dunes immediately southwest of Onslow; bare surfaces, subject to inundation during extreme high tides and storm surge events; soils are salt-encrusted silts and clays	High (Unstable)
Playa with fringing lunettes (Lp2)	Bare, circular, oval or elongated depressions fringed by quartz sand lunettes, soils are dark reddish brown non-cracking clays with some silt and poorly sorted sand	High (Unstable)
Saline lake (Ls)	Elongate depressions on the supratidal flats; comprise extensive saline to hypersaline flats with residual pools as remnants of flood events; soils are highly saline clays	High (Unstable)
Swamp deposits (Lw)	Elongate drainage foci subject to inundation within older beach ridge or chenier plains of the deltaic foreland of the Ashburton River delta; soils are dark reddish brown, light to medium, non-cracking clays	High (Unstable)
Reworked alluvial plain (Aa)	Older fluvial deposits associated with major river systems; gently undulating terrain of low relief; subject to local flooding; dominance of reworking by eolian or alluvial processes varies from place to place; soils are dark reddish brown loams and clays	Moderate
Delta (Ae)	Small delta at the confluence of a tributary and the Ashburton River; soils are dark reddish brown loams	Moderate
Floodplain (Af)	Channel bedloads of poorly sorted sand and gravel and overbank deposits of dark reddish brown silt and clay; subject to inundation	Moderate
Reworked alluvial plain with claypans (Ai)	Older fluvial deposits associated with major river systems; gently undulating terrain of low relief; innumerable claypans of various sizes; subject to local flooding	Moderate
Meander plain (Am)	Floodplain with widely spaced, migrating alluvial stream channels; scalded surfaces and claypans; subject to sheetflow; soils are reddish brown non-cracking clays	Moderate
Anastomotic plain (An)	Floodplain with moderately spaced alluvial channels forming a unidirectional integrated reticulated network; subject to sheetflow and overbank flooding; scalded surfaces; soils are reddish brown non-cracking clays and loams	Moderate
Alluvial terrace (At)	Low terraces marginal to the Ashburton River slightly above river level; subject to inundation; soils are dark reddish brown clays	Moderate
Parabolic and nested parabolic dunes (Ea)	Small-scale, low, stabilised parabolic dunes; soils are non-coherent pale brown or pink well-sorted calcareous quartz sands	High (Unstable)
Parabolic and nested parabolic dunes with calcarenite core (Eak)	Small-scale, low, stabilised parabolic dunes; soils are non-coherent pale brown or pink well-sorted calcareous quartz sands; occurs as a veneer over an undulating calcarenite core	High (Unstable)
Blow-out (Eb)	Small-scale active parabolic dunes; soils are loose pale brown or pink calcareous sands	High (Unstable)
Linear and reticulate dunes (Ee)	Dunes up to 15 m high; hummocky uneven crests with gently to moderately inclined slopes steepest on the western sides; soils are well-sorted deep red quartz sands	Moderate
Parallel linear dunes (El)	Relatively narrow, but extensive, high-relief dune terrain comprising one or two parallel ridges; represents a former chenier ridge and spit complex	High (Unstable)

Landform	Description	Relative Instability
Longitudinal dunes with calcarenite core (Elk)	Low to medium relief, parallel dune ridges developed transverse to the coast; soils are pale brown or pink calcareous sands which occur as a veneer over an undulating calcarenite core	High (Unstable)
Isolated dunes on supratidal flats (Es1)	Small, low-relief, oval or circular, isolated mounds of pale brown calcareous sand on the supratidal flats	High (Unstable)
Sandplain (Es2)	Level to gently inclined sandy plains between linear and reticulate dunes and extending westwards away from the dunes as a veneer over alluvial and sheetwash deposits; soils are well-sorted deep red sands	Moderate
Source border dunes (Et)	Dark red, fine- to medium-grained sand derived from adjacent floodplain deposits of the Ashburton River; some local sand ridges, some of which are unstable; overlies alluvial deposits	Moderate
Back-barrier flats (Ba1)	Gently sloping flat ground on the landward side of the coastal dune ridge composed predominantly of sand washed over or through the barrier during tidal surges; remnant washover fans may be present	High (Unstable)
Back-barrier flats (Ba2)	Gently sloping flat ground associated with a remnant beach ridge or chenier plain landward of the present coast	High (Unstable)
Coastal dune ridge (Bd1)	Relatively narrow shore-parallel fringe comprising irregular, low-relief sand hummocks rarely exceeding 5m in height; soils are well-sorted pale brown calcareous quartz sand, locally rich in heavy minerals	High (Unstable)
Inland dune ridge (Bd2)	Relatively narrow dune ridge comprising one or two low ridges occurring locally on the landward side of the supratidal flats; formed during summer cyclones sweeping sediment across the flats; soils are pale brown calcareous sands	High (Unstable)
Washover deposits (Bw)	Small area of washover fans landward of an active chenier on the deltaic foreland of the Ashburton River delta; soils are pale brown calcareous sands	High (Unstable)
Tidal flat (inter and supra) with fringing saltflats (Tf)	Intertidal and supratidal halophyte mudflats of brown, black and grey muds and silts with grey, brown and red, mottled clayey and silty sands all heavily salt-impregnated with some minor authigenic gypsum	High (Unstable)
Subdued beach ridge or chenier plain (Th1)	Low-relief, flat, circular to ovoid 'islands' on the intertidal and supratidal flats with characteristic banding of alternating vegetated and non-vegetated beach ridges or cheniers	High (Unstable)
Beach ridge or chenier plain (Th2)	Linear belts of medium-relief, continuous parallel sand ridges, some of which are disrupted by reworking; soils are pale brown calcareous sands	High (Unstable)
Active chenier, beach and spits (Th3)	Narrow, elongate and arcuate shell and sand spits and beach ridges parallel to the coast; soils are highly calcareous, white or pale grey shelly sands to loamy fine sands	High (Unstable)
Chenier (Th4)	Arcuate belts of discrete elongated shell and sand spits and low beach ridges parallel to the coast, stranded on the coastal mudflats and mangal flats at the seaward edge of deltaic foreland of the Ashburton River delta	High (Unstable)
Remnant beach ridge or chenier plain (Th5)	Medium-relief, undulating chenier plains landward of the active shore composed of several parallel individual chenier ridges rarely exceeding 20 m in height; soils are pink or pale brown loose calcareous sands	High (Unstable)
Cheniers with calcarenite core (Thk)	Low-relief, attenuated linear and en-echelon chenier ridges of calcarenite; may be in part overlain by unconsolidated pink or pale brown loose calcareous sands	High (Unstable)
Lagoon (Tl)	Shore-parallel linear lagoon within the main body of dunes southwest of Onslow; comprises an extensive salt flat with a joining series of interconnected seasonal pools and shallow tidal creeks; soils are highly saline clays	High (Unstable)
Mangrove flat (Tm)	Flat to gently inclined surface vegetated by dense thickets of *Avicennia marina* up to 4 m high on an organic-rich muddy substrate	High (Unstable)
Inactive spits (Tp)	Narrow, elongate and occasionally arcuate, inactive shell and sand spits and beach ridges; soils are highly calcareous, white or pale grey shelly sands to loamy fine sands	High (Unstable)

Landform	Description	Relative Instability
Supratidal flat (Tu)	Unvegetated, low gradient mudflat; only inundated during extreme high tides and storm surge events; soils are calcareous silts and sands with authigenic silt and gypsum	High (Unstable)
Saltflats and mudflats (Tue)	Bare, extensive, level plains with salt-encrusted surfaces subject to inundation by peak tides; soils are red to dark brown light to medium clays that are strongly alkaline and highly saline	High (Unstable)
Outwash plain and overbank deposits (Wf)	Extensive level plains subject to sheetflow and occasional overbank flooding; surfaces often scalded and microrelief often moundy and hummocked on more sandy sites; no surface mantles; soils are red sands and sandy silts	Moderate
Parallel calcarenite ridges (Xrk)	Medium- to high-relief, continuous, parallel, linear calcarenite ridges; occasional veneer of unconsolidated pale brown calcareous sand; represents lithified chenier ridges	Low (Stable)
Tantabiddi Limestone (XrkT)	Low-relief, subdued, parallel, calcarenite ridges; correlated with the Tantabiddi Member of the Bundera Calcarenite; Last Interglacial in age	Low (Stable)

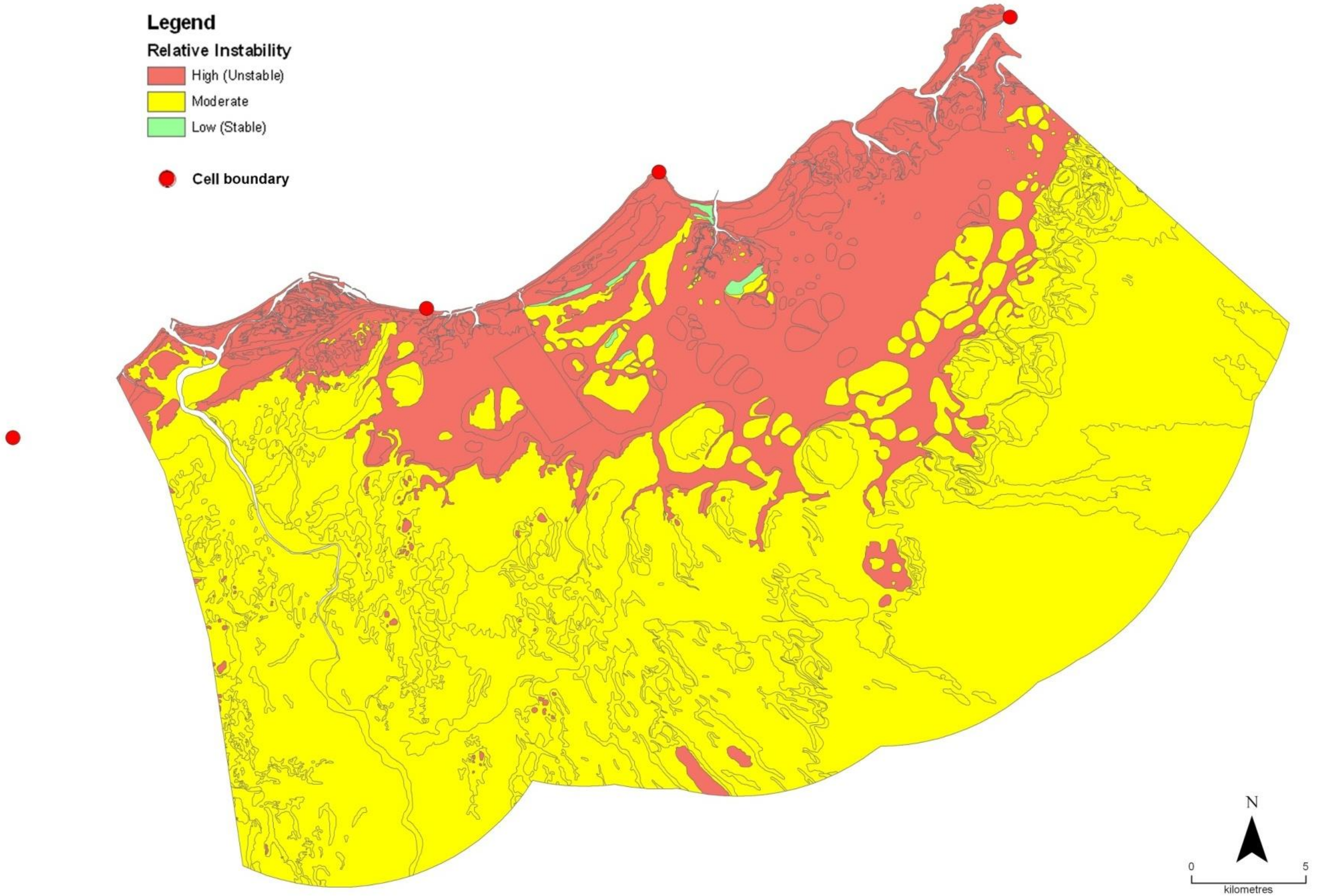


Figure 6-12: Onslow Area Landform Instability

Table 6-6: Onslow Area Tertiary Sediment Cell Description

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
Onslow	3. Beadon Point to Coolgra Point	The sediment cell is the eastern part of the Hooley Creek to Coolgra Point Compartment. The inner-continental shelf widens to the east offshore between Hooley Creek and Coolgra Point and the barrier island chain along the NNW facing coast splits into two components. The offshore component includes Thevenard Island, which is surrounded by a shallow island fringe up to 4km wide, and the Rosily Islands as well as reefs. Within the compartment, the inner-shelf is wide. Water depth is <10m approximately 12km from shore; 20m approximately 40km from shore; and 50m approximately 45km from shore.	Close to shore and within the 10m isobath are Direction Island and the Twin Islands. Water depth is <5m for approximately 4km from shore. The substrate comprises 50-75% reef or pavement particularly in the east. Reaches of rock pavement are separated by tidal channels. The perched beaches merge to seaward with the unconsolidated sediments of the inshore waters.	Three shallow, zeta-form embayments constitute the sandy NNW facing shore. They are linked by rock outcrops at their headlands, in places to beachrock outcrops. The perched beaches merge to landward with a high dune ridge. The curve of each zeta-formed embayment and the dune ridge it contains is broken by tidal creeks. There are four tidal creeks per 10km of shore. These are connected to a network of tidal creeks draining mudflats to landward.	In each of the embayments a moderately high and wide frontal dune ridge either abuts or overlies rocky terrain. The seaward face of the frontal dune is steep. Active dunes are located adjacent to the mouths of tidal creeks, with substantial activity on the eastern shores of the channels. The dunes and underlying topography impound a floodplain basin extending for approximately 30km along the coast and for 12km landward. The natural components of the basin, away from the salt ponds, are inundated tidally through the tidal creeks and by flooding from the Ashburton River, and to a lesser extent the Cane River. Further landward, the basin merges with the residual mounds and palaeochannels characteristic of the floodplain.
	2. Hooley Creek to Beadon Point	The sediment cell is the western part of the Hooley Creek to Coolgra Point Compartment. The NNW facing coast is in the lee of a formerly embayed coast, now apparent as a chain of barrier island s and reefs. The islands include Thevenard Island, which is surrounded by a shallow island fringe up to 4km wide, and the Rosily Islands. Within the cell, the inner-shelf is wide. Water depth is <10m approximately 12km from shore; 20m approximately 40km; and 50m approximately 45km from shore.	Water depth is <5m for approximately 4km. The substrate comprises 25-50% reef or pavement. The sandy beaches merge to seaward with the unconsolidated sediments of the inshore waters which are mainly sourced from the Ashburton River. In particular, sediments are moved alongshore as migratory spits immediately seaward of a beachrock platform between Casugrina Point and Hooley Creek.	The curve of a NW facing, zeta-form embayment and the dune ridge it contains is broken by three or four tidal creeks between Casugrina Point, in the adjacent western cell, and Beadon Point. There are approximately three tidal creeks per 10km of shore. The shape of the embayment is controlled by rock outcrops on the west bank of the Hooley Creek mouth and at Beadon Point. Between these outcrops the sandy beach abuts a high dune ridge fronted by a low foredune.	A moderately high and wide frontal dune ridge either abuts or overlies rocky terrain. The seaward face of the frontal dune is commonly scarped and a 8m high wrack line has been found near the lookout on Sunset Beach (Table 4-4). The dunes and underlying topography impound a floodplain basin extending for approximately 30km along the coast and for 12km landward. The natural components of the basin, away from the salt ponds, are inundated tidally through the tidal creeks and by flooding from the Ashburton River. Further landward, the basin merges with the residual mounds and palaeochannels characteristic of the floodplain.

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
	1. Rocky Point to Hooley Creek	At a broad scale the coast between Locker Point and Coolgra Point faces NNW and is in the lee of a remnant barrier chain along a formerly embayed coast. The sediment cell incorporates part of the Locker Point to Bare Sand Point Compartment and the coast between Bare Sand Point and Hooley Creek. Water depth is <10m at approximately 15 km from shore; 20m approximately 20-30km from shore; and 50m approximately 35km from shore. Several small islands are located in State Waters. The largest, Thevenard Island is surrounded by a subtidal shelf up to 4km wide.	The NNW facing coast includes the shallow waters immediately offshore of the Ashburton River mouth. The curve of the embayed shoreline is broken by three small cuspate landforms, including the unconsolidated sediments comprising former deltas of the Ashburton River. The water depth is <5m for approximately 2-4 km from shore. A number of reefs are also apparent and the inshore substrate is on up to 50% reef or pavement.	The sandy shore faces NW and comprises the landward margin of the active delta of the Ashburton River that dominates the cell. Pulsatory sediment supply by flood discharge results in the formation of transitory shoals and spits that migrate along the coast in both directions. Commonly, the intertidal shore is perched on rock pavements and platforms.	The Ashburton River has undergone several phases of avulsion, as evidenced by a floodplain with numerous deltas, foredune plain insets, palaeochannels, abandoned shorelines marked by high dune ridges and lithified cheniers. It is an area of long-standing and ongoing dramatic geomorphic change. In the vicinity of the active delta sandy beaches are backed by low chenier ridges and sand spits breached by river outflow or cut by tidal creeks. Overwash fans are common along the ridge. Away from the active delta sandy beaches are backed by high perched frontal dunes including mobile sand sheets.

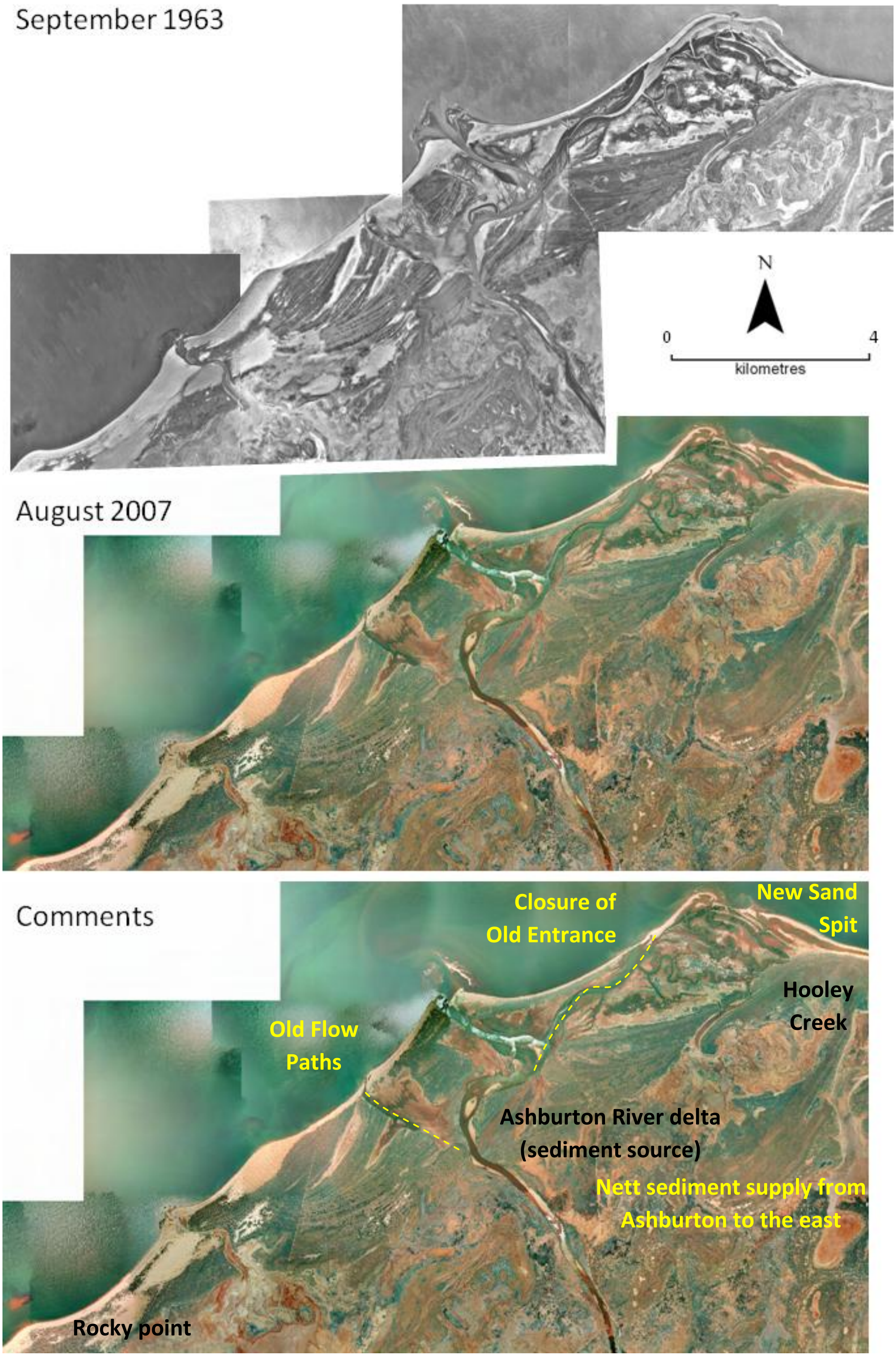


Figure 6-13 : Aerial Photography Onslow Cell 1 (1963-2007)

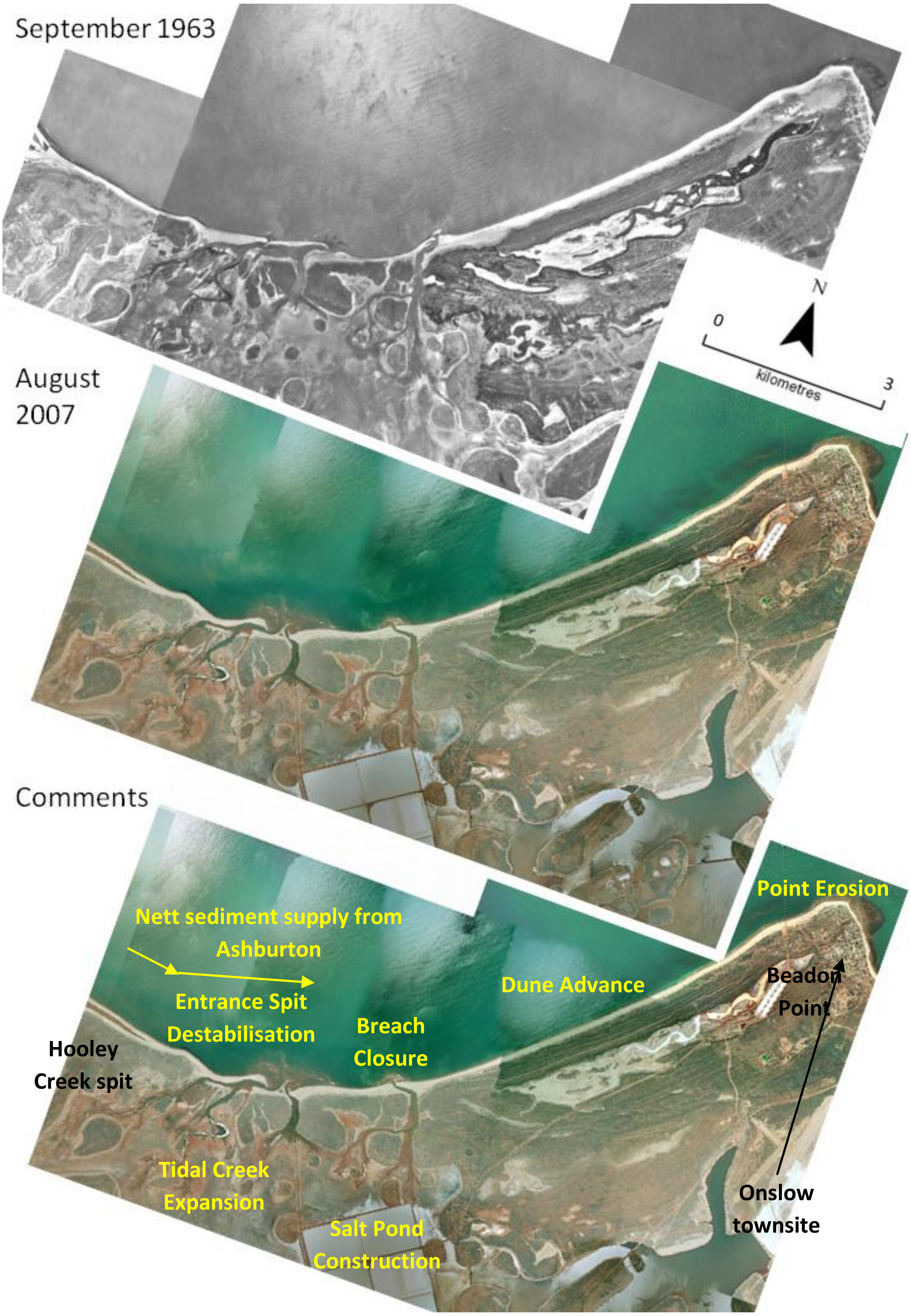


Figure 6-14: Aerial Photography Onslow Cell 2 (1963-2007)

Figure 6-15: Aerial Photography Onslow Cell 3 (1963-2007)

6.2.4. Coastal Susceptibility, Instability and Vulnerability

Coastal landform vulnerability has been assessed at a sediment cell scale for the wider Onslow area using the combination of instability and vulnerability described in Section 2 (see classifications in Table 2-7, Table 2-11, Table 2-12 and Figure 2-20). Overall, all three cells are vulnerable due to the dominance of low-relief coastal floodplain landforms and multiple tidal channel networks, with slightly lower instability in the eastern cell (Beadon Point to Coolgra Point) essentially due to the greater presence of rocky substrate (Table 6-7 and Table 6-8; Figure 6-11).

The relative ranking of susceptibility and instability across the three sediment cells has a systematic transition that is characteristic of the connectivity of the three tertiary cells to the updrift sediment supply of the Ashburton River. The dynamic nature of the Ashburton delta provides considerable instability and susceptibility for onshore landforms, but also provides a large supply of sediment, which enables formation and post-event recovery of sedimentary coastal landforms west of Hooley Creek (Cell 1). Eastward, the supply of sand to the shore reduces, resulting in progressively reduced prevalence and increasing isolation of sedimentary features. Consequently, the intertidal zone of Hooley Creek to Beadon Point (Cell 2) has susceptible and unstable landforms. East of Beadon Point, the sediment supply is sparse, exposing rocky substrate, which has high stability.

Table 6-7: Onslow Area Tertiary Sediment Cell Vulnerability Rankings

Area	Sediment Cell	Cell Boundaries	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 (Shoreline)	Hinterland Topography or Supratidal Mudflats	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
Onslow	3	Beadon Point to Coolgra Point	3	4	4	4	15	**H**	2	4	3	5	14	**M**	4	**M-H**
	2	Hooley Creek to Beadon Point	4	4	5	4	17	**H**	3	4	3	5	15	**H**	5	**H**
	1	Rocky Point to Hooley Creek	3	3	4	5	15	**H**	3	5	2	5	15	**H**	5	**H**

Table 6-8: Onslow Area Tertiary Sediment Cell Vulnerability Implications
Susceptibility and Instability Rankings should not be used independently.

Area	No.	Cell	From Lat.	From Long.	To Lat.	To Long.	Susceptibility		Instability		Vulnerability		
							Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Onslow	3	Beadon Point to Coolgra Point	115.10958	-21.630912	115.24799	-21.56993	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
	2	Hooley Creek to Beadon Point	115.01793	-21.68474	115.10958	-21.630912	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
	1	Rocky Point to Hooley Creek	114.85485	-21.735729	115.01793	-21.68474	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

The high ranking of coastal landform vulnerability across the Onslow area indicates that any coastal development is subject to significant management constraints that should be addressed with caution. In particular, treatment of storm surge and runoff flooding hazards requires careful consideration, as management of one threat may exacerbate the other hazard. This is particularly significant for areas adjacent to tidal channel networks, which are highly dynamic and may episodically switch between expansionary or contracting behaviour.

The existing historic pattern is for high, albeit irregular sediment supply west of Hooley Creek resulting in ephemeral but predominantly accretionary coastal formations near the Ashburton delta; dune field accretion along Sunset Beach subject to occasional erosion; gradual accretion along Onslow Town Beach and effectively a static situation between Beadon Creek and Coolgra Point. The consideration of downdrift sediment supply is required for any facilities between Ashburton Delta and Beadon Creek (Figure 6-13; Figure 6-14), as any interruption may potentially reduce the limited beach buffer in front of Onslow town site.

Behaviour of the tidal creek systems within the Onslow area is obscured by the installation of salt ponds, which is very recent in geomorphic terms. However, for the period prior to the levee construction and those channels which have not been isolated by the ponds, tidal creek expansion has historically been high, which suggests net marine encroachment. For those channels isolated by the levees, sedimentation has apparently been enhanced.

Potential change to the wider Onslow area may result due to variability of the Ashburton River sediment supply, major avulsion of the river channel, or projected sea level change. **Variability of the sediment supply** is a greater management constraint closer to the Ashburton River, as it is effectively smoothed out further eastward. Nevertheless, design for any facility within the Onslow area should cater for variability of supply, which may affect sedimentation or post-erosion recovery rates. **Major avulsion of the river channel** is presently most likely to occur within the delta itself. This would result in a large short-term variation (either increase or decrease) in downdrift sediment supply. Alternative landward pathways are possible, as evidenced by the extensive palaeochannel networks between the Ashburton and Cane Rivers (Figure 4-14). This effectively requires blocking of extreme flows through the main channel, such that increased breakout flows can cause channel cutting. Blocking may occur naturally, say at the delta through littoral transport, or artificially, due to bridge or road construction. The anticipated response of the coastal floodplain to **sea level rise** is suggested by Semeniuk (1994) with parallels drawn from other coastal lagoons where there is a lower availability of sediment. As sea level rises, sediment exchange through tidal channel networks becomes increasingly landward, resulting in channel expansion and increased marine incursion, with available sediment deposited across the floodplain. Where supply is limited or if sea level rise accelerates, sediment transfer to the floodplain may not be able to keep pace. This either drowns the lagoon or produces a local sediment demand leading to increased breaching and potential collapse of coastal barriers.

The historic pattern of tidal channel expansion has been coincident with a mean sea level rise of approximately 0.15m over the 20^{th} Century, suggesting increased marine incursion and indicating a transfer of coastal sediment on to the coastal lagoon flats. However, the relative supply of sediment to the floodplain and the likely evolutionary pathway for the floodplain landforms has not been established.

Impoundment of a significant portion of the coastal lagoon within the salt pond levees dramatically reduces the area of the floodplain which is prone to sedimentation under a sea level rise scenario. This effectively reduces the risk of coastal barrier breaching, but is offset by a requirement to repeatedly adapt and strengthen the levee systems, with progressively increasing threat posed by levee breaching.

The existing town site of Onslow is isolated from the floodplain through the construction of salt pond levees, and therefore is likely to experience limited local floodplain sediment demand, restricted to Beadon Creek's tidal catchment. Coastal change anticipated at the town site is expected to include profile adjustment (as per Bruun 1962) and a reduction in the availability of material bypassing Beadon Point, which will limit beach recovery after erosion events.

The most significant anticipated impact on Onslow associated with sea level rise is the increased incidence and extent of coastal flooding. In present day conditions, the town may be affected by water levels above 2.5m AHD, which is estimated to be the 25 year recurrence interval (GEMS 2000a; level not revised by MP Rogers & Associates 2011). Under a 0.8m sea level rise, 2.5m AHD would be equivalent to the 1 year recurrence interval, representing a dramatic increase in the frequency of flooding and if no action were taken, would cause the low-lying parts of the town to evolve towards a tidal channel network.

6.2.5. Advice

The connectivity of alongshore transport within sediment cells requires consideration for any coastal development (Figure 6-11; Figure 6-13 to Figure 6-15). Any facility located between the Ashburton River and Beadon Creek should be designed or managed to minimise downdrift impacts affecting Onslow town site or Onslow Salt.

Considerations of assessing and mitigating risk and hazard for Onslow should follow the risk framework in Section 6.1, including separate considerations for erosion and inundation. Detailed information on erosion risk management has not been included in Section 6.1.

Various parts of the wider Onslow area are subject to coastal flooding, runoff flooding or a combination of the two. Any approach used for hazard mitigation should be cognisant of the potential transfer of risk to adjacent sites or other processes. This may include drainage focusing or deflection of floodwaters. An example of transfer between processes is where raising ground levels to reduce the risk of coastal flooding acts to constrain a runoff floodway and cause increased flood levels upstream of the restriction. A parallel may occur on coastal floodplains where levee construction prevents landward propagation of surge waters, allowing more rapid development of coastal surge components that may enable higher total water levels. Any planning or potential mitigation works for areas prone to flooding should incorporate the requirements within the *Better Water Management Plan* (WAPC 2008b) at the relevant scale. Flood hazard mitigation advice should be sought from the Department of Water with additional advice from the Department of Transport coastal engineers for works with a coastal component.

Application of emergency management principles should apply to flood hazard mitigation, considering isolation of residential properties, ensuring key facilities are located in areas of low risk and providing a suitable evacuation plan. The potential for the access road and air field to be flooded at relatively moderate levels provides a major constraint for Onslow town site (Simpson *et al.* 2007).

A portion of Onslow town sites' coastal defence is incidentally provided by the salt pond levees, which effectively isolate the town from flood runoff and reduce the potential for collapse of the coastal dune barrier under projected sea level rise. However, these facilities are third-party owned and managed, which provides a constraint upon effective risk management for the Shire, who are not responsible for levee upkeep and adaptation.

The presence of levee structures provides an additional hazard of levee failure. Following risk management principles, the potentially catastrophic (i.e. rapid rather than devastating) failure of such linear defence structures requires application of higher risk criteria (Oumeraci 2005).

6.2.6. Further studies

The following studies have been identified as being useful to the management of Onslow coast:

- *Coastal System Stability Assessment*. One-off identification of key coastal change indicators, relative to baseline assessment of Ashburton River channel, coastal barrier dune and tidal creek systems.
- *Coastal Adaptation Study*. One-off study to outline possible risk mitigation measures, monitoring and triggers.
- *Inundation Review*. Confirmation of previously modelled synoptic climate and comparison of model performance against tide gauge records for low-level flooding every 5-10 years. Post-event flood surveys on an opportunistic basis.
- *Coastal Change Evaluation*. Collation of geotechnical information, evaluation of sediment availability and foreshore beach survey analysis, every 3-5 years if new information has been collected as part of other projects.
- *Building Design Criteria and Auditing*. One-off revision of building design requirements, with ongoing education and auditing programs to assist land owners.

These studies are outlined in more detail below.

The potential for drastic modification to existing landform structure exists on the Onslow coast, through either avulsion of the Ashburton river channel or collapse of the coastal dune barrier along any part of the extensive coastal lagoons. In the present day, these possibilities are remote, but they may require greater consideration in the long term, particularly in the face of potential climate change. This requires preparation of a simple baseline, and identification of indicators of change in risk, including dramatic tidal creek expansion or significant channel constriction within the Ashburton River.

Existing coastal studies for Onslow include inundation and erosion assessments. These provide a basic measure of “worst-case” events that may affect Onslow townsite and are arguably focused towards “100 year events”, with restricted ability to describe less extreme variations in water level or coastal change. This limitation is important in the context for providing risk-based coastal management and planning adaptation (Section 6.1), as Onslow is already affected by less-severe events, with active risk mitigation measures including an evacuation warning system and a foreshore seawall. The existing town site is strongly challenged by projected sea level rise, with limited ability to use ‘Avoid’ or ‘Retreat’ management pathways in the Avoid-Retreat-Accommodate-Manage risk mitigation hierarchy. This places greater importance on assessment of risk likelihood and the associated economic consequences of risk accommodation or acceptance. A coastal adaptation study that identifies possible adaptive measures for risk mitigation, with associated monitoring and triggers would facilitate planning for Onslow and its facilities.

Inundation risk is presently described by a study of direct cyclone impacts (GEMS 2000a), which has been extrapolated to include the influence of sea level rise (MP Rogers & Associates 2011). The base study provides a restricted representation of less extreme events, and therefore does not give a real representation of inundation likelihood, particularly including the effects of sea level rise. Ongoing review of inundation hazard levels is appropriate, which may include identification of mean sea level trend, confirmation of previously modelled synoptic climate and post-event validation of tropical cyclone flooding, such as the wrack-line surveys reported by Nott & Hubbert (2005).

The existing evaluation of coastal change is based upon a simplified evaluation of potential coastal erosion, based upon historical aerial imagery and SBEACH modelling (MP Rogers Associates 2011). This does not consider the presence of rock, or the relative availability of sediment supply from the Ashburton River, and assumes that the foreshore seawall is maintained and adapted as required. Refined erosion risk assessment for sites in the Onslow region may involve collection of information collected by field survey or geotechnical investigations. Useful information is expected to be obtained from the ongoing coastal monitoring that is proposed as part of the Ashburton North port site. The dependence of Onslow upon the foreshore walling for erosion mitigation suggests that active management is advisable, with ongoing assessment, maintenance and adaptation.

The presence of many low-lying areas within Onslow town site and the difficulty of raising fill the whole town area to limit inundation risk. Refinement of building design criteria and ongoing auditing may be positive actions for the reduction of economic losses in the event of a flood. There is limited guidance for this approach within Australian practice, but a large body of information is available from other nations including the United States (FEMA 2011). It is recommended that affected building owners be provided access to information describing flood proofing and awareness, including EMA (2009a) and FEMA (2009).

6.3. KARRATHA AREA

The Karratha Area of Planning Interest is located in the centre of the Study Area. The Karratha area includes eight tertiary compartments (Figure 1-1) with 15 focal tertiary sediment cells (Figure 6-16 and Figure 6-17). Throughout the wider area, rock features, including geological strike ridges and previous shorelines provide significant structural control upon more mobile sedimentary features. These are fed episodically by supply from the Pilbara river systems, and respond to tidal and wave action, with ambient conditions generally providing onshore drift, balanced by dispersion during occasional tropical cyclones. Coastal conditions are seasonally variable and typically tide-dominated, but may vary dramatically during storm events.

The Karratha Area of Planning Interest has been separated into five smaller areas based on grouping of similar geomorphology and processes. The five areas include:

1. Cape Preston and Regnard Bay– Tertiary Cells 4 to 7 from James Point to Pelican Point;
2. Dampier –Tertiary Cell 8 from Sharp Peak to Dampier;
3. Karratha – Tertiary Cells 9 to 11 from Nickol Bay W to Fields Creek;
4. Cleaverville and Anketell Coast – Tertiary Cells 12 to 15 from Fields Creek to Cape Lambert; and
5. Point Samson – Tertiary Cells 16 to 18 from Cape Lambert to Butcher Inlet E.

Cape Preston is located on a basalt formation, declining in height to the north, which provides a sharp change in coastal orientation to the coasts to both the east and west. Coastal limestones and corals are built upon this formation, in turn overlain by sand masses and mangroves. Mobile sediments are typically captured by rock masses either as perched coast, or where the rock acts as natural groynes. This constrained coastal structure facilitates beach recovery after erosion events, but limits capture of excess material during periods of high supply, and makes the coastline susceptible to changes in sea level or prevailing wave direction (GEMS 2008c).

Sediment supply to the Cape Preston area is largely from west to east, with intermittently high but more commonly low sediment supply from the Fortescue River. Preston Spit forms a major accretive feature southwest side of the Cape, with sand shoals to the east indicating occasional bypassing. The low lying nature of the Erramurra Creek floodplain suggests that a limited amount of bypassed material enters western Regnard Bay, with the majority anticipated to travel along the steep coastal contours between Cape Preston and North East Regnard Island.

Development of port facilities at Cape Preston (described by LeProvost Environmental 2008) has been underway since 2010, with the major breakwater completed in 2011.

East of Preston Point is a floodplain coast, with Erramurra Creek, McKay Creek, Devil Creek and Yanyare River debouching into Regnard Bay. The coast is perched on an extensive subtidal rock platform, with relict emergent features providing chains of barrier island and headland control for Forty Mile Beach and Gnoorea.

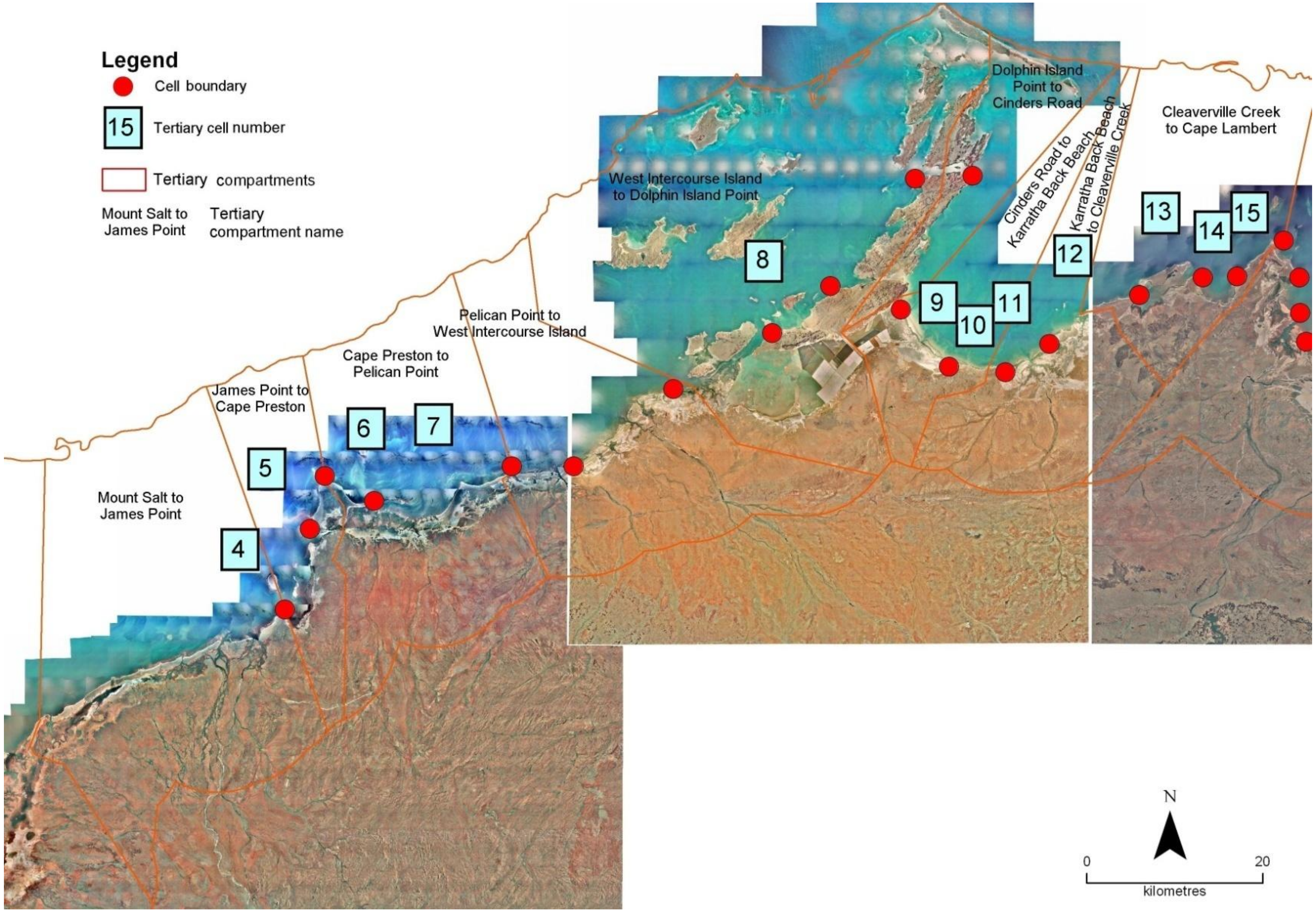


Figure 6-16: Karratha Tertiary Sediment Cells West (Cells 4-8)

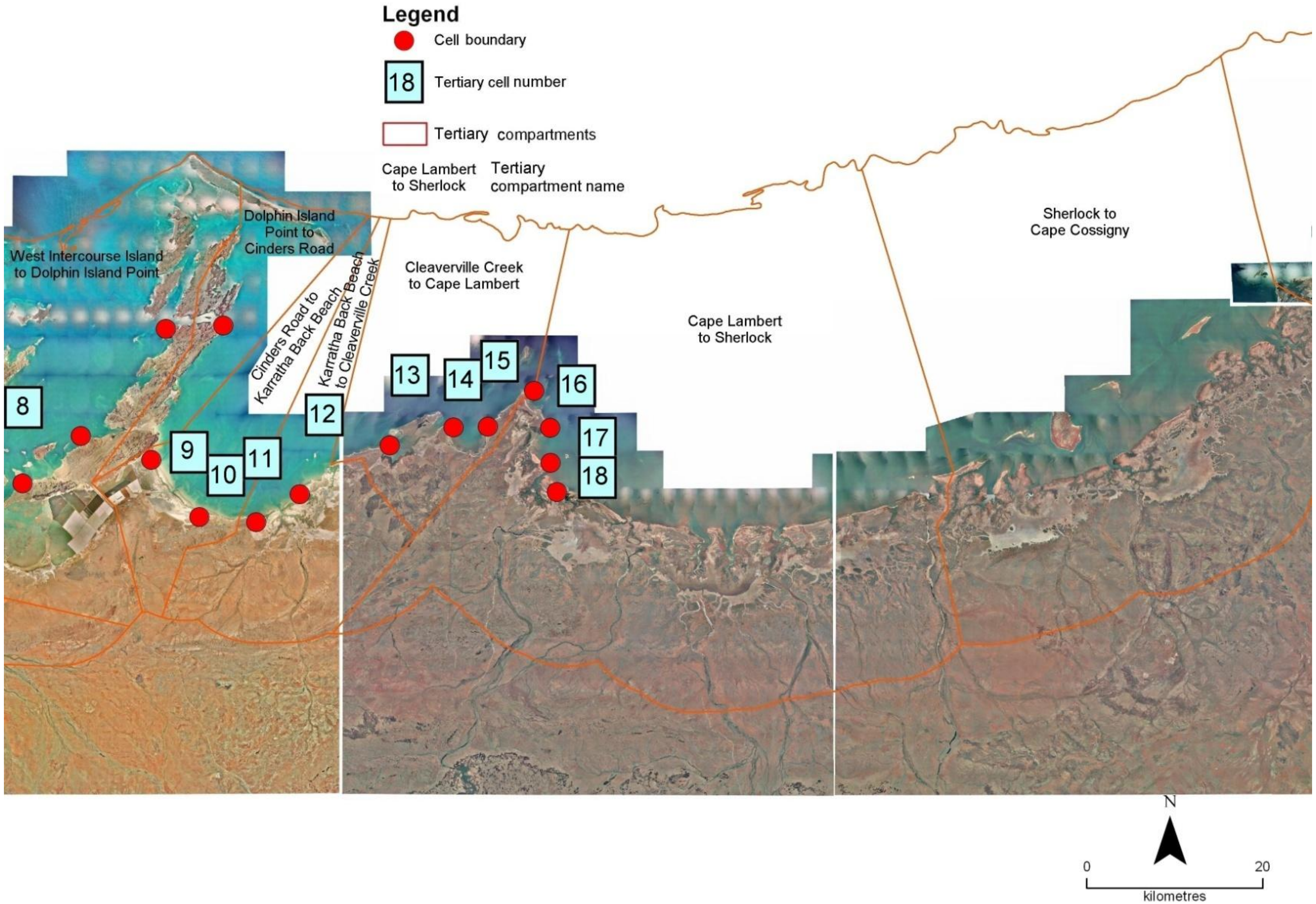


Figure 6-17: Karratha Tertiary Sediment Cells East (Cells 9-18)

The **Dampier** coast is located along the western side of the Burrup Peninsula strike ridge, which runs approximately in a northeast direction. Further expressions of the Precambrian geological formation occur as islands and offshore shoals. The older base is overlain in parts by Pleistocene limestone which forms several of the outer islands and is common on the modern coast (Jones 2004). These rocky features are in turn overlain by mobile sediments, with a mixture of gravel, sand, silt and clay reflecting the degree of shelter and the focusing of tidal currents provided by offshore features.

Sediment supply to the Dampier area is limited, with the Maitland River providing a low supply of material, with the finer fraction dispersed via tidal currents and the coarser material distributed in Regnard Bay. As a consequence, West Intercourse Island marks a distinct change from sandy to rocky coast. Sedimentary features within Mermaid Sound reflect the level of local sheltering, with silty seabed, muddy inlets including King Bay, through to small coarse sand perched beaches held in place by rock headlands. Modification of the coast has been undertaken, including construction of causeways, revetments, reclamation and extensive bunding of the mudflats south of Dampier town site to form salt ponds (Damara WA 2011b).

Karratha coast is located within the lee of the Burrup Peninsula, with partial shelter provided by Legendre, Hally and Delambre Islands. Rocky formations along the Burrup and east of the Nickol River effectively confine Nickol Bay, which has a shallow seabed gradient, declining to the northeast. The coastal margin is a mixture of rocky foreshore and low lying coastal mudflats, the latter which constrain Karratha townsite to the west and east (JDA *et al.* 2011b Attachment 3). These mudflats are structurally different in character: the western mudflats are sandwiched between an onshore storm-built dune ridge and an outer mangrove fringe, with a broad subtidal terrace and relict lithified ridge; in contrast the eastern mudflats have less apparent structural control with an outer mangrove fringe and sandy subtidal terrace. Sediment supply to the Karratha coast is apparently limited, with the Nickol River providing a relatively low input due to its small catchment.

Structural modification along the Karratha coast is largely associated with Dampier Salt works, including extensive bunding across the western mudflats and dredging of a bitterns channel. A small boat ramp with a rock armour breakwater is located to the east of Karratha.

Cleaverville and Anketell Coast is the northern expression of a Precambrian formation, which runs in a northeast direction. The formation possesses an extensive terrace, which may be intertidal or subtidal. Coastal landforms perched on this terrace vary according to its width, with perched beach and coastal dune where the terrace is wider along Cleaverville, and perched pocket beaches or rock cliffs where the terrace is narrow, including the north side of Dixon Island. West of Cleaverville, the terrace is occupied by mangrove flats, although the shoreward landforms suggest an origin that is consistent with other parts of this coast, responding to terrace width and the height of the rock formation.

On sections where the rock formation is low, tidal networks across the lower topography have been established, including a small tidal creek network west of Cleaverville and a larger tidal estuary to the east, which includes Bouguer Passage and extensive tidal flats across

Antonymyre. The latter tidal structure exhibits geomorphic markers from several different eras, with a series of rock terraces: at the western entrance to Bouguer Passage, in line with the eastern tip of Cleaverville, and along the mangrove fringe (Oceanica & Damara 2011).

Sediment transport along the Cleaverville and Anketell coast is partly disconnected from the shore by the rock terrace. However, sand is present offshore from the terrace, which is mobilised by moderately strong tidal currents and occasional strong wave action from the north. These mechanisms generally provide a net southwest sediment transport, although strongly modified at a local scale by the tidal networks. Sediment supply from Rocky Creek and several smaller creek systems is apparently limited by their small local catchments. Relict spits are present along the majority of coastal rock outcrops, although these typically appear inactive. Modern spits are present on the south side of Bouguer Passage, and to the east of Nickol River deltaic mudflats.

Existing coastal development along this section of coast is largely restricted to the Rio Tinto jetty and facilities at Cape Lambert, plus a boat ramp at Port Walcott Yacht Club. The Cape Lambert jetty includes a reclamation area built to the east of the Cape, which is mainly used as a stockpile area.

Anketell Point was earmarked as a possible industrial development area in early planning for the Pilbara (SMEC 1998). However, until recently, this was limited to zoning a section on the mainland and a part of Dixon Island as reserved for industrial use. The site is presently undergoing engineering assessment for development of a government-managed multi-user facility, principally intended for second-tier iron ore miners. These agencies were invited to undertake detailed investigations for a collaborative development plan and seek a role as port construction proponents. Anketell Point Industries has submitted a PER for construction of primary port facilities (API 2011; EPA 2012a), with Dampier Port Authority providing a masterplan to guide the wider development (DPA 2010).

The **Point Samson** coast, from Cape Lambert to Butcher Inlet is the western portion of an arcuate segment of low-lying floodplain coast that extends approximately sixty kilometres from Cape Lambert to West Moore Island, presenting a dramatic change in character from the coast west of the Cape. Over this wider length, seven small rivers, including the regulated Harding River, drain into a highly connected sequence of supratidal lagoons, which in turn are connected to the ocean through a series of tidal creeks. A relict barrier system is present on the seaward side of the lagoon, in several places inter-fingered with mangroves. Extensive subtidal terraces are present along much of this coast, cut with tidal channels and forming mobile sandbars.

As a whole, the wider section of coast is highly dynamic, and therefore provides a major constraint to development. However, the western section, herein referred to as the Point Samson Coast, has two local rock ridges running perpendicular to the prevailing swell direction. These create a stepped coastal plan form, with headlands at Point Samson and Cossack that have historically provided relative coastal stability and the opportunity for shallow-draft navigation.

Sediment transport along the Point Samson Coast and further east is locally complex, with tidal creek systems able to switch their net direction of sediment transport between periods of relative runoff and tidal dominance. This facilitates the formation of ephemeral sandbars, which have affected navigation at both Cossack and Point Samson. It is considered likely that the net direction of wave-driven transport is eastward, although actual transport is limited by the rocky material of the relict barrier system.

The Point Samson coast includes one of the oldest European ports in the Pilbara, at Cossack, on the Harding River. This site was progressively damaged by riverine flooding, coastal flooding and channel sedimentation, ultimately making the site unusable for progressively deeper draft vessels supplying the area. Recent plans to re-establish Cossack as a historic precinct with some residential development (Department of Housing and Works *et al.* 2006) identified stringent constraints to development due to a lack of suitable secure land, and poor emergency access.

Point Samson is a small townsite located to the east of Cape Lambert, originally built up around a deep water jetty built after the decline of facilities at Cossack. The jetty was damaged by tropical cyclones in 1925 and 1989, and removed in 1991. A fishing boat harbour with a dredged basin and protective breakwaters was constructed on the south side of the townsite.

6.3.1. Principal Geomorphic Processes

There are distinct variations in the geomorphic character across the wider Karratha coast, which forms the basis of the five smaller areas of interest.

1. Cape Preston and Regnard Bay Coast – Rock-controlled coast, with high sediment supply from the Fortescue River, and low sediment supply to Regnard Bay;
2. Dampier Coast – Rocky shoreline, with low sediment supply;
3. Karratha Coast – Low-lying sedimentary coast, structurally controlled by rock outcrops;
4. Cleaverville and Anketell Coast – Mixture of rocky coast and tidal lowlands;
5. Point Samson Coast – Low-lying floodplains, with relict barrier system and tidal creeks.

These differences in morphology determine that each section of coast is likely to respond differently to weather systems or environmental change, discussed in detail in Section 6.3.4. Influences that have been considered, on the basis of historic and projected climate include: seasonal and inter-annual variations of prevailing weather systems and tides; extreme water levels and waves potentially associated with tropical cyclones; and projected sea level rise.

6.3.2. Planning Context

The coast considered within this Section is in the Shire of Roebourne, with overarching planning and management described by the planning scheme (DoP 2011a) and the *Karratha Area Development Strategy* (WAPC 1998a). The present planning scheme is based on a report by Landvision (2000) with working papers unable to be located. However, it appears inundation risk areas in the present scheme were carried forward from prior planning schemes combined with the KADS (WAPC 1998a). The KADS may be replaced by the final

Pilbara Planning and Infrastructure Framework (WAPC 2012). Preparation of a coastal management plan for the Shire is presently underway, with several previous drafts developed (Shire of Roebourne 2005, 2007) following a previous plan which was used in draft form for an extended period of time (DCE 1985). A coastal management plan was developed for the smaller scale area of Gnoorea Beach, principally to address recreational use issues (Astron & Coastwise 1998).

Three Native Title claims in the Pilbara region have achieved consent, with the Thalanyji people to the west (including Onslow), the Ngarluma to the east (including Anketell Point and Cape Lambert) and the Guruma within the central Pilbara.

European settlement in the Karratha region commenced in the 1860's, principally associated with pastoral leases, with Roebourne being the first gazetted townsite in 1866. The region was supported by a port at Cossack from 1872, which experienced damage from tropical cyclones, river flooding and harbour siltation. Major port services were shifted to Point Samson after construction of a deep-water jetty, which was gazetted as a town in 1910 (WAPC 2009a).

The post-war resources boom saw expanded development across the Karratha region, with associated coastal infrastructure for port facilities and residential settlements. Company town sites in Dampier, Karratha and Wickham were established from 1966 to 1970, principally associated with iron ore mining. Discovery and exploitation of hydrocarbons offshore from the region saw significant expansion of Karratha town site, largely associated with the Northwest Shelf Gas Project, including plant and services on the Burrup Peninsula. A series of subsequent resource development projects have occurred in the Pilbara region, with progressively growing demand upon the existing coastal infrastructure.

Most coastal facilities developed through the 1970s and 1980s have experienced significant subsequent expansion along with associated town site growth. However, limited space for expansion and potential conflict with existing users was identified as a constraint. The state government assessed the opportunity for increased diversification through a number of industrial estates (SMEC 2004), with potential ports at Cape Preston and Anketell Point identified within the Karratha region. Commercial proponents for each port development were sought, with an ERMP submitted for Cape Preston (LeProvost Environmental 2008) and a PER for Anketell Point (API 2011). In each case, the State Government has reserved the capacity to extend the facilities to provide a multi-user port. The majority of these developments, including infrastructure expansions at Dampier Port and Cape Lambert, have incorporated local planning and environmental documents, to facilitate the development approvals process.

The most recent resource and development boom has prompted more strategic consideration of planning for the Pilbara by the State government (WAPC 2009a, 2012). This has included assessment of infrastructure requirements, with the intent to facilitate growth of Pilbara town sites (coastal townsites in Table 6-9); and identification of a future Marine Park for the Dampier Archipelago. Draft management plans for State and Commonwealth Marine Parks have been prepared (CALM 2005; DSEWPC 2012) along with a bioregional plan for the wider Northwest Australian region (DSEWPC 2011). Marine Park gazettal will have implications for planning and management of coastal facilities across the Karratha region.

Present-day zoning for Karratha area is provided by the *Shire of Roebourne Town Planning Scheme No.8* (DoP 2011a; Table 6-9). This includes defined areas for strategic industrial development, townsite development and special control areas related to inundation due to storm surge risk for the area from North West Coastal Highway to the coast. Conditions relating to the special control area (Clause 7.5) require consideration of the 100 year storm surge level. No non-industrial development is generally permitted within this area, but Council may consider submissions which discuss the sensitivity of the proposal to risk and protection measures. No surge levels are provided in the scheme, deferring to relevant authorities for most recent projections of surge and sea level rise. There is no advice pertaining to erosion risk or terrestrial flooding risk for the coastal townsites. Special development requirements have been developed for Point Samson (Shire of Roebourne 2009).

Table 6-9: Planning Documents for Coastal Townsites in the Karratha region

Coastal Townsite or Area	TPS Section and Map (DoP 2011a) Gazetted 2000	Other Planning Documents
Dampier - including potential boat harbour	Clause 5.7 (Dampier); Map 9	WAPC (1998a); Landvision (2000) describes prior TPS No.4 in 1993; URS (2007); Landcorp (2009) Slide 28; DPA (2010); WAPC (2012)
Karratha – including Dampier Salt expansions, airport and Mulataga	Clause 5.9 (Karratha); Clause 7.7 (Dampier Salt); Development Area 10 (Mulataga); Map 5 and Map 10	Landvision (2000) describes prior TPS No. 6 in 1987; Aurecon (2009); LandCorp & Shire of Roebourne (2009) Figure 9; WAPC (2009a) Map 19; WAPC (2010a); WAPC (2012) Map 4.
Point Samson	Clause 5.12 (Point Samson); Map 12	WAPC (1998a); Landvision (2000) describes prior TPS No. 7 draft in 2000; Shire of Roebourne (2009) *Development Requirements for Point Samson*; WAPC (2012)
Cossack - return to a living town	Clause 5.6 (Cossack); Clause 7.6; Development Area 23; Map 13	WAPC (1998a); Landvision (2000) describes prior TPS No. 7 draft in 2000; Department of Housing and Works *et al.* (2006) ; WAPC (2012)
Coastal link road from Mulataga to Cleaverville and Wickham	Area zoned parks, recreation and drainage in Maps 5 and 6.	WAPC (1998a) p55

Inundation Assessments

Coastal and runoff flooding have been recognised as providing major constraints to development of coastal infrastructure in the Karratha region. Both forms of inundation are capable of dramatic levels of inundation, often with design 100 year ARI levels in the order of 5m above typical day-to-day levels. Historically, coastal flooding hazard has been mitigated by developing away from the coast, and consequently engineering of runoff hazard has been the major focus for Karratha land development. However, the significant pressure for expansion in the Pilbara has placed pressure on the practice of avoiding coastal flooding, which is further challenged by the potential for sea level rise over long-term planning time frames.

Approaches to flood assessment require modification of common practices to accommodate the landforms and structure of the Karratha coast. The region has a topographically complex blend of low-lying floodplain and moderate relief relict rocky landforms. Emergence of geological features, particularly along the Burrup and Anketell Peninsulas and nearshore islands around Dampier, provides areas of both sheltering and storm surge focus. This landform and bathymetric complexity produces highly varied exposure to coastal flooding and considerable interaction between catchments due to breakout flows and convergence in coastal lagoons. The implications for flooding assessments include:

- Coastal flooding assessment requires fine resolution assessment, to distinguish local topographic effects, that may produce an order of ±1m variation from regional assessments;
- Runoff flooding assessments commonly require a more regional, rather than catchment-scale approach, to quantify the interactions with adjacent catchments;
- Interaction between coastal and runoff flooding may be complex within the coastal fringe, with greater potential for superposition for small catchments (rapid response) or those with large upland contribution to flow (sustained response).

The sporadic nature of extreme flood events and high spatial variability in the Karratha region determines that modelling (numerical or analytic) is an appropriate tool for assessment. However, such evaluation is highly sensitive to the underlying model processes and assumptions, requiring careful validation to produce meaningful results. Monitoring systems for flooding are generally limited in the Pilbara, with comparatively sparse stream gauges, tide gauges and post-flood surveys.

Hindcasting and modelling of extreme water levels has been undertaken for planning purposes and infrastructure design at Cape Preston, Dampier area, Karratha, Cleaverville, Dixon Island, Cape Lambert, Point Samson, Cossack and at a broader scale across the wider region (Table 6-10).

The basis for development in and near Karratha in the 1970s was initially the Kelly Line, a simple minimum level as 10 feet (3.05m) above Highest Astronomical Tide (JDA *et al.* 2011a). The Kelly Line at Karratha townsite is +5.55mAHD as HAT is +2.5mAHD. The Kelly Line was a simple approach, with a number of more or less scientific studies done through the 1960s and 1970s by the Public Works Department or University studies (Noye 1972; Trajer 1973;

Nelson 1975; Hopley & Harvey 1976; and Silvester & Mitchell 1977). Development levels were reassessed using modelling by Stark & McMonagle (1982).

Revision of inundation levels for KADS (WAPC 1998a) was undertaken through a series of studies by the Bureau of Meteorology Special Services Unit (BoMSSU & GEMS 1995a; BoMSSU 1996; BoMSSU & GEMS 1998). These were built around a model and associated methods described in Hubbert *et al.* (1990). It was recommended certain elements of the modelling should be refined, with a revised Greater Port Hedland Storm Surge Study conducted (GEMS 2000b). A series of studies were conducted between 2004 and 2008 that were used as the basis for the inundation investigations for the broader Dampier to Point Samson area within the Shire of Roebourne using this refined approach (GEMS 2009), with more detailed modelling of the Cleaverville, Anketell and Point Samson Coast (Tertiary Cells 12 to 18). The study considered tropical cyclone inundation according to previous SPP 2.6 requirements (WAPC 2003a) for worst track scenario with maximum surge coinciding with tide near MHWS, and incorporation of a 0.88m sea level rise. The study also included the revised modelling approach and measured levels followed the two tropical cyclone events (TC Clare and TC Daryl) in the 2005/2006 season at Cape Lambert (Damara WA 2006c, Oliver & Mocke 2007).

Further information on frequency and distribution of tropical cyclone events, along with wave, wind and inundation levels along the Pilbara was prepared by Damara WA (2009a). Damara WA (2009b) also provided further discussion and analysis of the impacts of climate change upon tropical cyclones in the Pilbara region using a simplified high-level assessment using parametric cyclone modelling. More complex repeated tropical cyclone modelling with possible climate change scenarios has been undertaken (Stroud & McConochie 2007) with the information not presently available in the public domain.

Table 6-10: Previous Water Level Assessments in the Karratha region

Application	Study	Recommendation or Hazard
Broader region		
Shire of Roebourne between Maitland River and West Moore Island. Focal study for 22 locations at Cleaverville-Anketell, Cape Lambert, Point Samson and Cossack	GEMS (2009)	100 yr PSWL range from +4.3mAHD to 5.2mAHD (Cossack) 1,000 yr PSWL range from +6.5mAHD to 6.9mAHD Included BoMSSU (1996) results converted to GIS layers
Australia-wide	Hopley & Harvey (1976)	100 yr ARI *Port Hedland* surge: 2.78m
Australia-wide	Silvester & Mitchell (1977)	Maximum surge: 2.10m Average surge: 0.6m
Site-specific from West to East		
Cape Preston	GEMS (2008c)	At four sites along the shoreline 100 yr ARI surge: 4 to 4.5m. 500 yr ARI surge: 4.7 to 5.1m. 1000 yr ARI surge: 4.8 to 5.3m.
Dampier	Chappell (1982)	Dated 'maximum' high level boulder beaches at: Pebbly Beach +8.3mAHD (400 and 2230 years) No-name Beach +5.8mAHD (1440 years) Refers to Woodside modelling report

Application	Study	Recommendation or Hazard
		100yr ARI PSWL: +3.8mAHD 500yr ARI PSWL: +4.5mAHD
Dampier	Metocean Engineers (2004)	100 yr PSWL: +3.8mAHD 400 yr PSWL: +4.01mAHD 1000 yr PSWL: +4.03mAHD
Karratha	1970s (described in JDA *et al.* 2011a)	+5.55mAHD Kelly Line. A simple minimum level as 10 feet (3.05m) above Highest Astronomical Tide of +2.5mAHD at Karratha.
Karratha	Stark & McMonagle (1982)	Incorporates tide with storm surge 100 yr ARI: +6.2mAHD 200 yr ARI: +6.7mAHD 500 yr ARI: +7.4mAHD
Karratha area, Dampier Salt and Mermaid Sound	BoMSSU (1996)	
Karratha	Damara WA (2009b)	Parametric cyclone modelling. Surge variation with shift in tropical cyclone intensity and frequency 100 yr surge (existing): 4.9m
Karratha	JDA *et al.* (2011a, b)	*Only tropical cyclonic surge* 100 yr at shore for existing: +5.5m AHD to +7.3mAHD For 2060 SLR (+0.3m): +5.7m AHD to +7.6mAHD For 2110 SLR (+0.9m): +6.1m AHD to +8.7mAHD Also considered joint probability with terrestrial flooding.
Cape Lambert	BoMSSU & GEMS (1995a)	
Cape Lambert	BoMSSU & GEMS (1998)	100 yr PSWL at Johns Creek: +5.3mAHD 100 yr PSWL at Cossack: +5.8mAHD 100 yr PSWL at Cape Lambert: +5.9mAHD
Cape Lambert	Buchanan & Treloar (2002)	No ARIs were defined for water level, only Hs
Cape Lambert	GEMS (2004)	
Cape Lambert	Damara WA (2006c)	Reviewed Cape Lambert water levels with comparison of data (TC Clare and Daryl), processes and model results.
Cape Lambert	GEMS (2006)	Revised results. 100 yr PSWL: 7.4mAHD 200 yr PSWL: 7.9mAHD
Cape Lambert	GEMS (2008d)	
Cape Lambert	GEMS & JFA (2010)	100 yr PSWL: +7.7 to +8.2mAHD 200 yr PSWL: +8.1 to +8.6mAHD 500 yr PSWL: +8.4 to +9.1mAHD
Tsunami Modelling		
Western Australia-Wide	Burbidge *et al.* (2008)	Reported for *Exmouth in 50m water depth*: 500 yr wave height: 0.5 to 1m 1,000 yr wave height: 0.8 to 1.8m 10,000 yr wave height: 2 to 7m
Shire of Roebourne between Maitland River and West Moore Island	GEMS (2009)	Map and GIS layer of 100 year wave on mean sea level, excluding tide
Karratha, Dampier	Geoscience Australia & FESA (2010)	Not available in the version of the report provided.

The most recent inundation assessment for Karratha townsite incorporated both fluvial and coastal flooding to a 500 year ARI with consideration of future scenarios (2060 and 2110) of sea level rise, increase in rainfall and increase in tropical cyclone frequency and magnitude (JDA *et al.* 2011a, b). The 500 year ARI levels have been incorporated to follow SPP 2.6 (WAPC 2013). Prior hydrologic and hydraulic investigations for Karratha townsite are documented in JDA *et al.* (2011a); including Ruprecht & Ivanescu (2000), JDA (2009, 2010b) and GHD (2009, 2010a).

Between 2000 and present there have been a number of private industry requests for coastal modellers to produce local scale storm inundation studies, particularly for Cape Preston, Cape Lambert and for Dampier Port Authority. These studies include (not exhaustive list) Metocean Engineers (2004), GEMS (2004, 2006, 2008b, 2008c, 2008d), Damara WA (2006), GEMS & JFA (2010). Other local investigations incorporating water levels were Chappell (1982), CMPS&F (1997) and Buchanan & Treloar (2002).

The majority of studies have involved assessment of direct-impact tropical cyclone-induced flooding, with some evaluation of tsunami hazard. Tsunami were considered by GEMS (2009) along the Shire of Roebourne and by Burbidge *et al.* (2008) and GA & FESA (2010) at the 50m contour for WA, both presented as a wave height above mean sea level.

6.3.3. Landforms and Sediment Cells

Landform mapping has been completed for the wider Karratha area by the Geological Survey of Western Australia (Figure 6-19 to Figure 6-23 with key in Figure 6-18), which reflects the geological complexity. The relative stability of each landform type has been identified (Table 6-11; Figure 6-24 to Figure 6-28) which shows low stability for non-rock landforms near the coast and alluvial landforms, with higher stability for high-relief rock structures and landforms further landward. The extensive area of coastal instability is mainly a consequence of the low relief of landforms across the coastal floodplain and alluvial channels between the rock controls.

The landform analysis has been considered in five groupings of tertiary sediment cells for the wider Karratha Area as specified above for the Cape Preston and Regnard Bay Coast, Dampier Coast, Karratha Coast, Cleaverville and Anketell Coast and the Point Samson Coast. The major features, when described at this scale are outlined in Table 6-12 .

Aerial imagery for **Cape Preston to Regnard Bay Coast** (Figure 6-29 and Figure 6-30) shows limited historical change at the vegetation line with most changes at, or below, the water line and on floodplains. Changes near Cape Preston have been described in greater detail by GEMS (2008c). The rocky points provide structural control, limiting potential long-term coastal movement, with the most significant change occurring on western-facing beaches and at entrances to tidal creeks. These images do not show the recent construction of the Cape Preston port.

Imagery for the **Dampier Coast** (Figure 6-31 and Figure 6-32) illustrates the shoreline has historically been relatively stable and is strongly controlled by underlying, alongshore and supratidal rock features; which has been described in greater detail by Damara WA (2011).

Very little coastal change is apparent to the vegetation line, with mild accumulation along the Hampton Harbour shore and slight erosion west of Parker Point. The majority of observed change is in response to human interventions, including boating facilities and coastal protection works. Erosion is occurring at coastal road embankments and at eastern areas of embayments associated with terrestrial runoff.

Observed change for the low-lying sedimentary **Karratha Coast** (Figure 6-33 to Figure 6-35) is difficult to identify from vegetation lines as the majority of change is vertical variation or modification to channel networks (further detail in JDA *et al.* 2011b Attachment 3). In western Nickol Bay (Cell 9; Figure 6-28) and the Nickol River delta (Cell 11; Figure 6-29) the extension of tidal creek channels and overwash channels are indicative of increased tidal exchange and suggest the mudflats may be deepening, with an increased capacity to capture sediment. The largest change is attributed to the Dampier Salt drainage channel; and infilling of secondary channels in the Nickol River delta. At Karratha townsite (Cell 10; Figure 6-29) there has been little change to Karratha town beach, with some localised lowering of the mud flats and loss of mangroves. Sand and gravel mining of the large barriers has occurred, with potentially significant implication for stability in the vicinity of Karratha airport. The barrier primarily provides protection against wave action rather than inundation, as it is already breached in several places by creek channels.

Aerial imagery for the **Cleaverville and Anketell Coast** (Figure 6-36 to Figure 6-39) shows limited change on the rock controlled coast with tidal lowlands. The majority of observed change is localised spit growth, modification of subtidal channels and tidal creeks. Cells 13 and 14 appear to demonstrate the embayment infill process; with Cells 12 and 13 showing a highly infilled floodplain that connects with adjacent tidal creeks during high water level or runoff events. Further detail for the Anketell area is included in Oceanica & Damara WA (2011). Coastal change in Cell 15 is largely limited to human interventions through reclamation and floodplain modification.

Observed change for the **Point Samson Coast** (Figure 6-40 to Figure 6-44) is consistent with interaction of low-lying sedimentary features with irregular rock formations. The rock provides a degree of control which restricts coastal mobility, giving limited change of the vegetation line and anchoring the position of tidal creeks. In contrast, sedimentary features such as mudflats, terraces and spits are highly dynamic, with a cycle of erosion during extreme events, followed by a general pattern of recovery, albeit sometimes significantly less than the erosion. The sequence for individual features is irregular, and includes migratory sandbars to the southeast of Point Samson. Tidal creek systems have been extensively modified between Cossack and Point Samson, including harbour construction and provision of low elevation causeways into Point Samson (Figure 6-40) and Cossack (Figure 6-42).

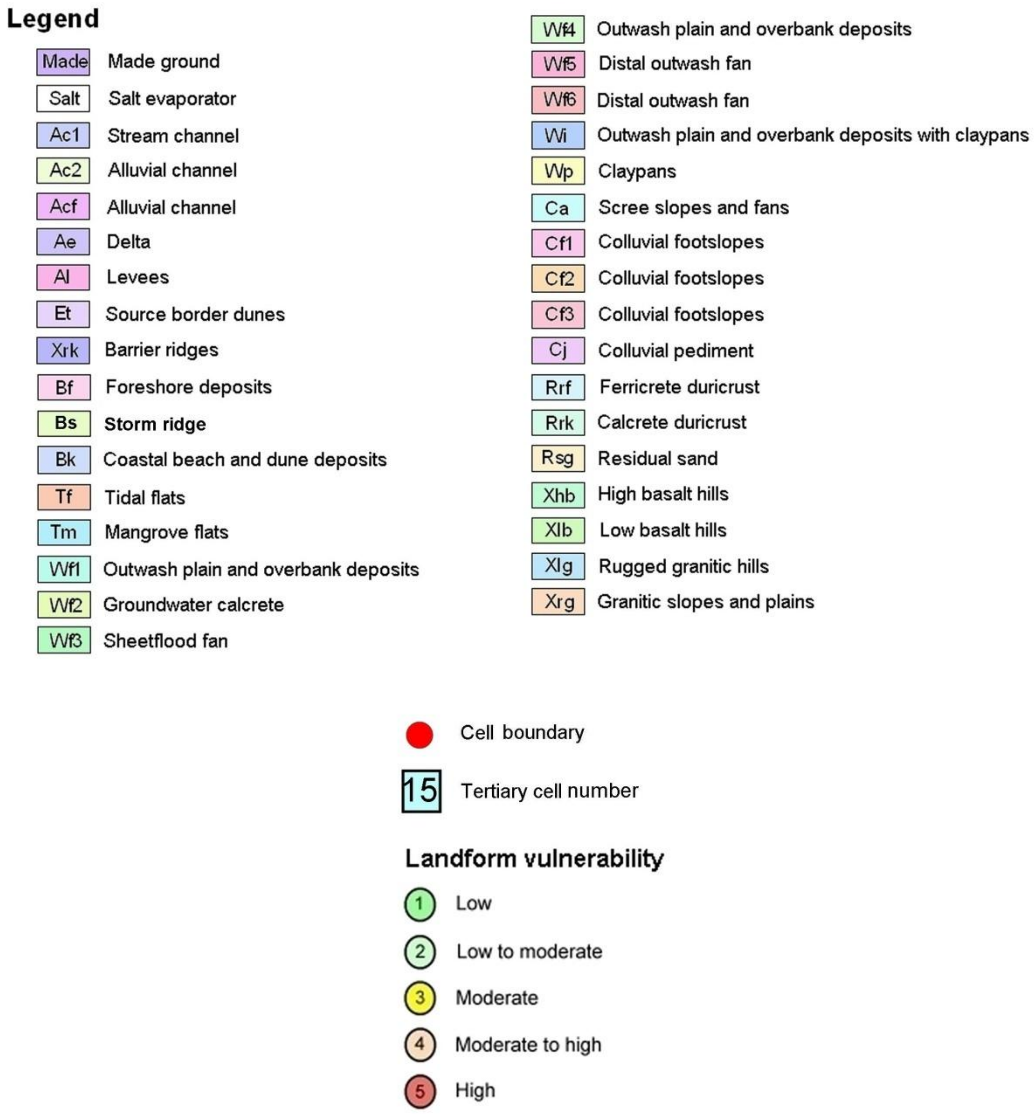


Figure 6-18: Karratha Landform and Vulnerability Map Legend

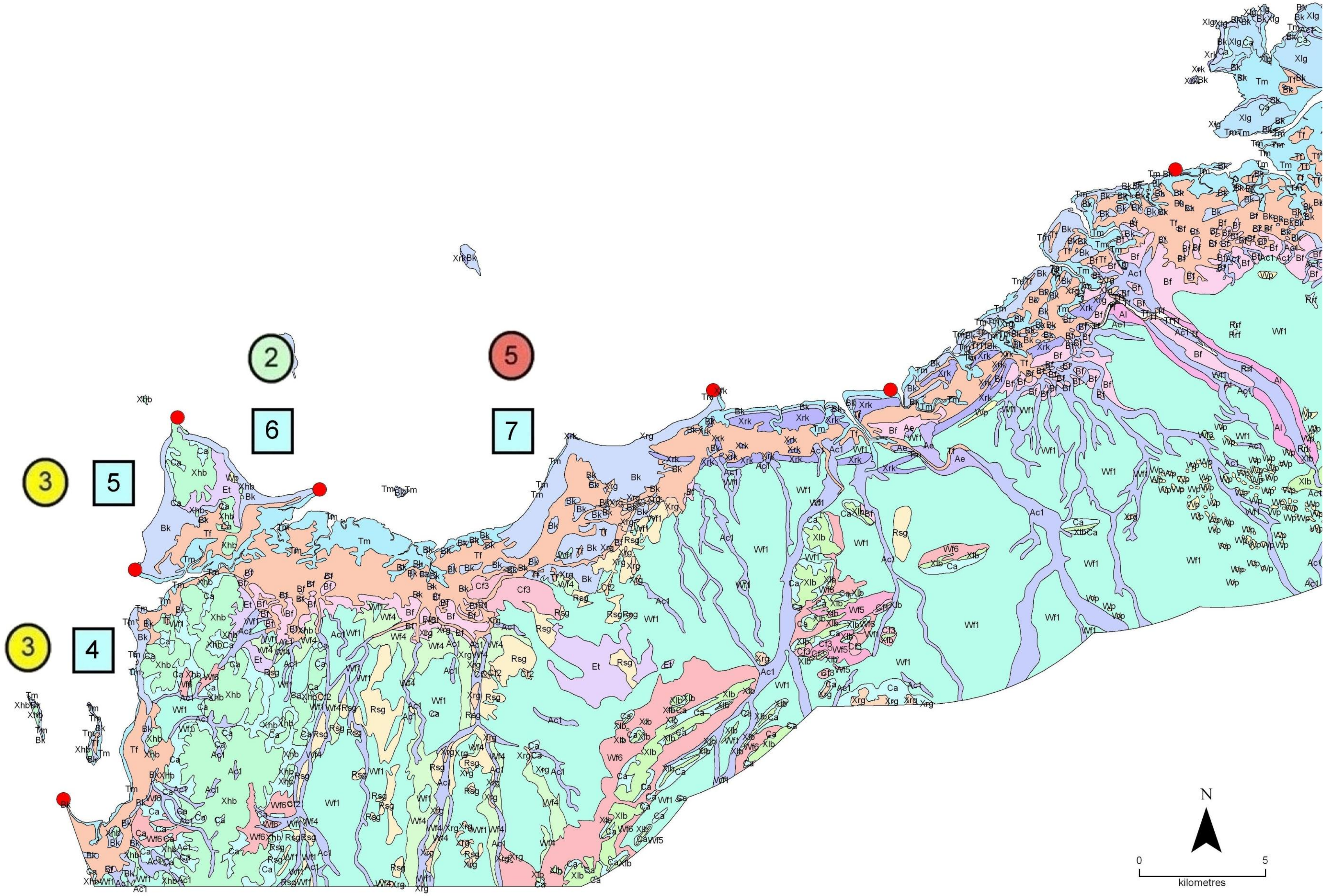


Figure 6-19: Karratha Area Vulnerability and Landforms (1 of 5)
Legend in Figure 6-18

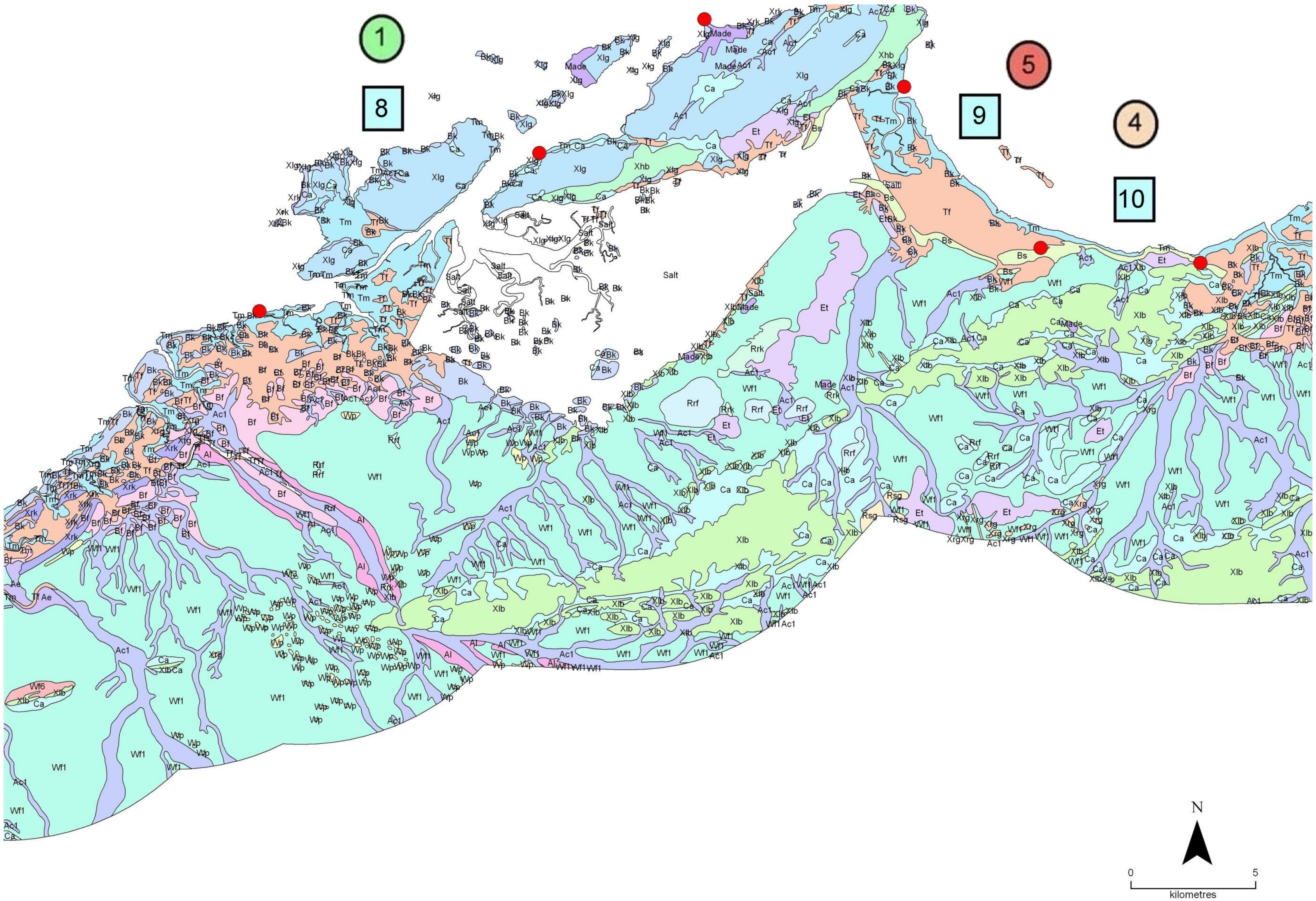


Figure 6-20: Karratha Area Vulnerability and Landforms (2 of 5)
Legend in Figure 6-18

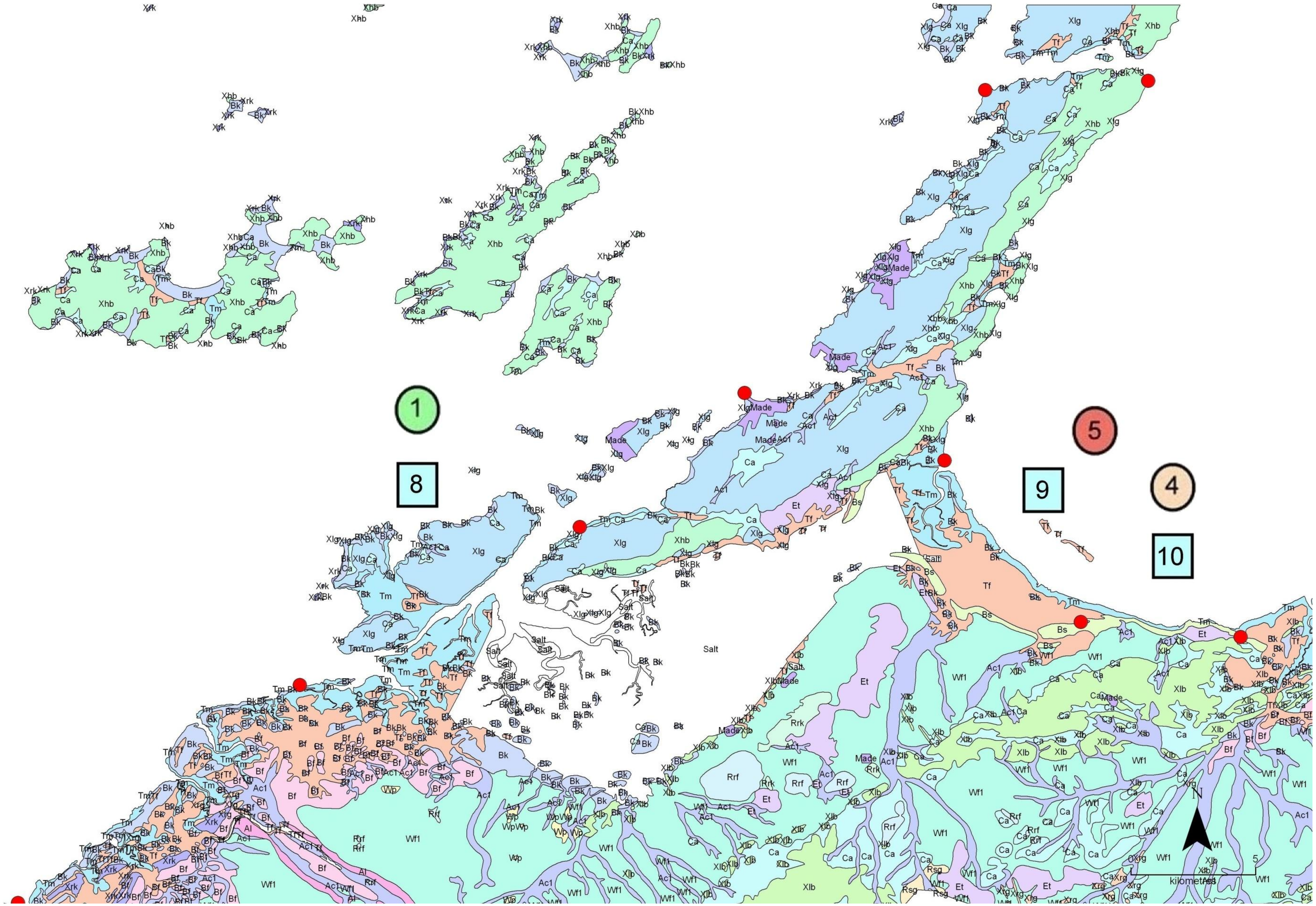


Figure 6-21: Karratha Area Vulnerability and Landforms (3 of 5)
Legend in Figure 6-18

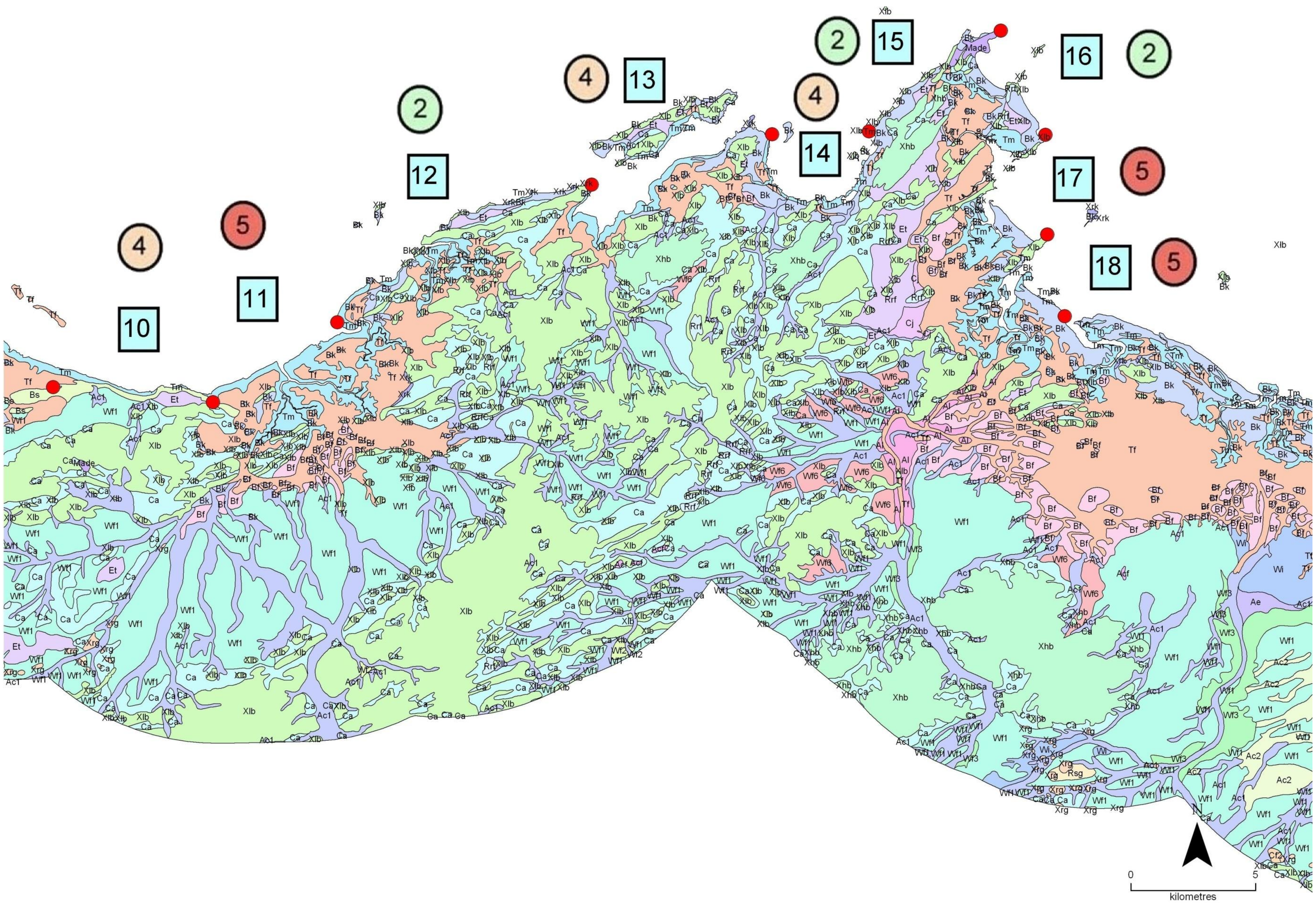


Figure 6-22: Karratha Area Vulnerability and Landforms (4 of 5)

Legend in Figure 6-18

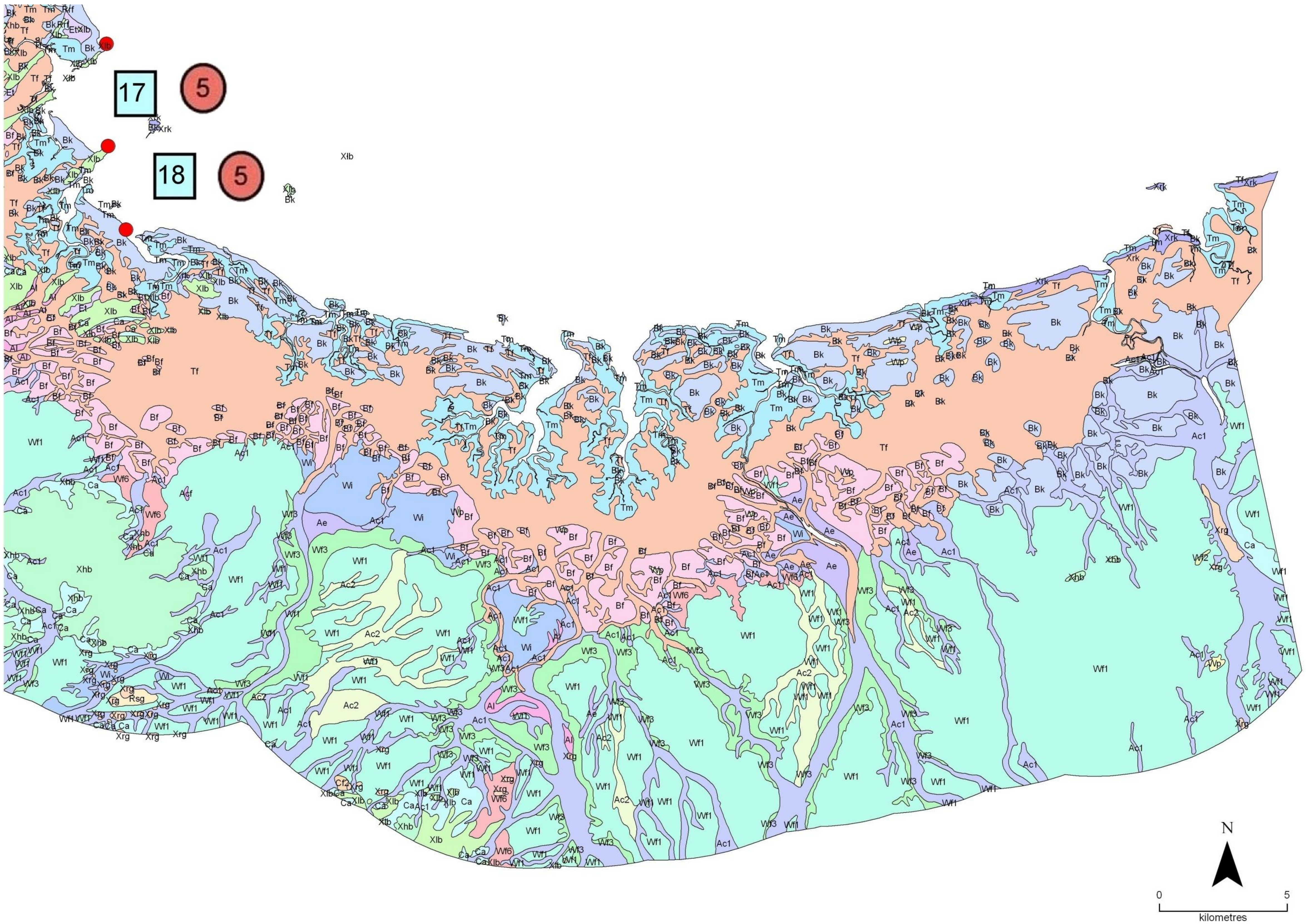


Figure 6-23: Karratha Area Vulnerability and Landforms (5 of 5)
Legend in Figure 6-18

Table 6-11: Landforms of the Karratha Area and their Relative Instability (After: Gozzard 2012a). See Table 2-7B for Explanation of Colour Codes

Landform	Description	Relative Instability
Made ground (Made)	Made ground	Low (Stable)
Salt evaporator (Salt)	Salt evaporator	High (Unstable)
Stream channel (Ac1)	Silt and silty sand in smaller watercourses and sands and gravels with subangular to subrounded pebbles of Precambrian rocks in the larger watercourses	High (Unstable)
Alluvial channel (Ac2)	Variably consolidated sand, silt and clay with a gilgai surface occupying abandoned alluvial channels on outwash plains, locally dissected by present-day drainage	High (Unstable)
Alluvial channel (Acf)	Ferruginous pisolitic ironstone gravel capping mesas dissected by present-day drainage system	High (Unstable)
Delta (Ae)	Dissected deposits of consolidated alluvial sand, silt and clay preserved in small deltas	High (Unstable)
Levees (Al)	Medium- to coarse-grained sand in levees and sandbanks along the lower sections of major drainages and associated with deltas	Moderate
Source border dunes (Et)	Reddish yellow, fine- to medium-grained sand derived from adjacent floodplain deposits; some local sand ridges, some of which are unstable; overlies colluvial and sheetwash deposits	Moderate
Barrier ridges (Xrk)	Lime cemented shelly sand, dune sand and beach conglomerate, commonly exposed in tidal zone and preserved inland as old coastal dunes and strandlines; locally called Bossut Formation	Low (Stable)
Foreshore deposits (Bf)	Sand deposits of mixed alluvial and eolian origin as irregular low dunes and sandbanks extensively developed where deltas enter lagoons and alluvial deposits have been eroded and redeposited along the coast	High (Unstable)
Storm ridge (Bs)	Large supra-tidal storm bar as linear mounded ridges up to 8 m in height comprising sand with some gravel	Low (Stable)
Coastal beach and dune deposits (Bk)	Shelly sand in coastal dunes and old beach deposits; contains *Anadara granosa*	High (Unstable)
Tidal flats (Tf)	Intertidal and supratidal halophyte mudflats; all heavily salt-impregnated	High (Unstable)
Mangrove flats (Tm)	Flat to gently inclined surface vegetated by dense thickets of *Avicennia marina* up to 4 m high on an organic-rich muddy substrate	High (Unstable)
Outwash plain and overbank deposits (Wf1)	Reddish brown to yellowish brown, very silty sands and sandy clays, locally with expansive clay or 'gilgai'	Moderate
Groundwater calcrete (Wf2)	Massive, nodular, cavernous groundwater calcrete found in drainages where the catchment is dominated by mafic and ultramafic rocks	Moderate
Sheetflood fan (Wf3)	High-level gravel deposits, unrelated to present-day drainages and mostly concealed by younger outwash deposits; gravel beds up to 5 m thick are known; used locally as a source of gravel for road construction	Moderate
Outwash plain and overbank deposits (Wf4)	Sand and silt dominated by quartzofeldspathic material	Moderate
Distal outwash fan (Wf5)	Gravel, sand and silt dominated by quartz-rich debris, granitoid rock, chert and vein-quartz debris	Moderate
Distal outwash fan (Wf6)	Silt, sand and pebbles	Moderate
Outwash plain and overbank deposits with claypans (Wi)	Reddish brown to yellowish brown, very silty sands and sandy clays	Moderate

Landform	Description	Relative Instability
Claypans (Wp)	Small claypans and playa systems formed by ponded floodwaters or local heavy rain on outwash plains	High (Unstable)
Scree slopes and fans (Ca)	Coarse-grained pebbly sand fringing bedrock hills; commonly has a well-defined radial drainage system of small gullies originating from adjacent hills	Moderate
Colluvial footslopes (Cf1)	Sand and silt with ultramafic rock debris	Moderate
Colluvial footslopes (Cf2)	Quartz rubble and debris adjacent to quartz veins	Moderate
Colluvial footslopes (Cf3)	Sand, silt and gravel dominated by ferruginous material	Moderate
Colluvial pediment (Cj)	Dissected consolidated clay, silt, sand and gravel derived from adjacent bedrock outcrop	Moderate
Ferricrete duricrust (Rrf)	Ferruginous duricrust and pisolitic ironstone capping mesas dissected by present-day drainage system	Low (Stable)
Calcrete duricrust (Rrk)	Massive, nodular, cavernous pedogenic calcrete developed by weathering of the underlying amphibolite bedrock; variably silicified	Low (Stable)
Residual sand (Rsg)	Quartzofeldspathic sand with quartz and rock fragments derived from weathering of the underlying granitoid bedrock or nearby outcrops	Moderate
High basalt hills (Xhb)	Rugged basalt hills, strike-controlled ridges and plateau remnants with up to 110 m relief; abundant basalt rock outcrop with extensive surface mantles of basalt pebbles, cobbles and boulders with pockets of skeletal red stony clays	Low (Stable)
Low basalt hills (Xlb)	Extensive low hills and strike-controlled ridges with 20-80 m relief, rounded and undulating crests and summits with abundant basaltic rock outcrop and mantles of pebbles and cobbles; soils are generally skeletal red stony clays	Low (Stable)
Rugged granitic hills (Xlg)	Moderately to steeply inclined hill crests and ridge summits with abundant granite outcrop and mantles of granitic pebbles and cobbles; soils are stony skeletal	Moderate)
Granitic slopes and plains (Xrg)	Undulating to gently inclined rocky slopes with mantles of granitic pebbles and cobbles on steeper slopes and quartzofeldspathic grit on lower slopes	Low (Stable)

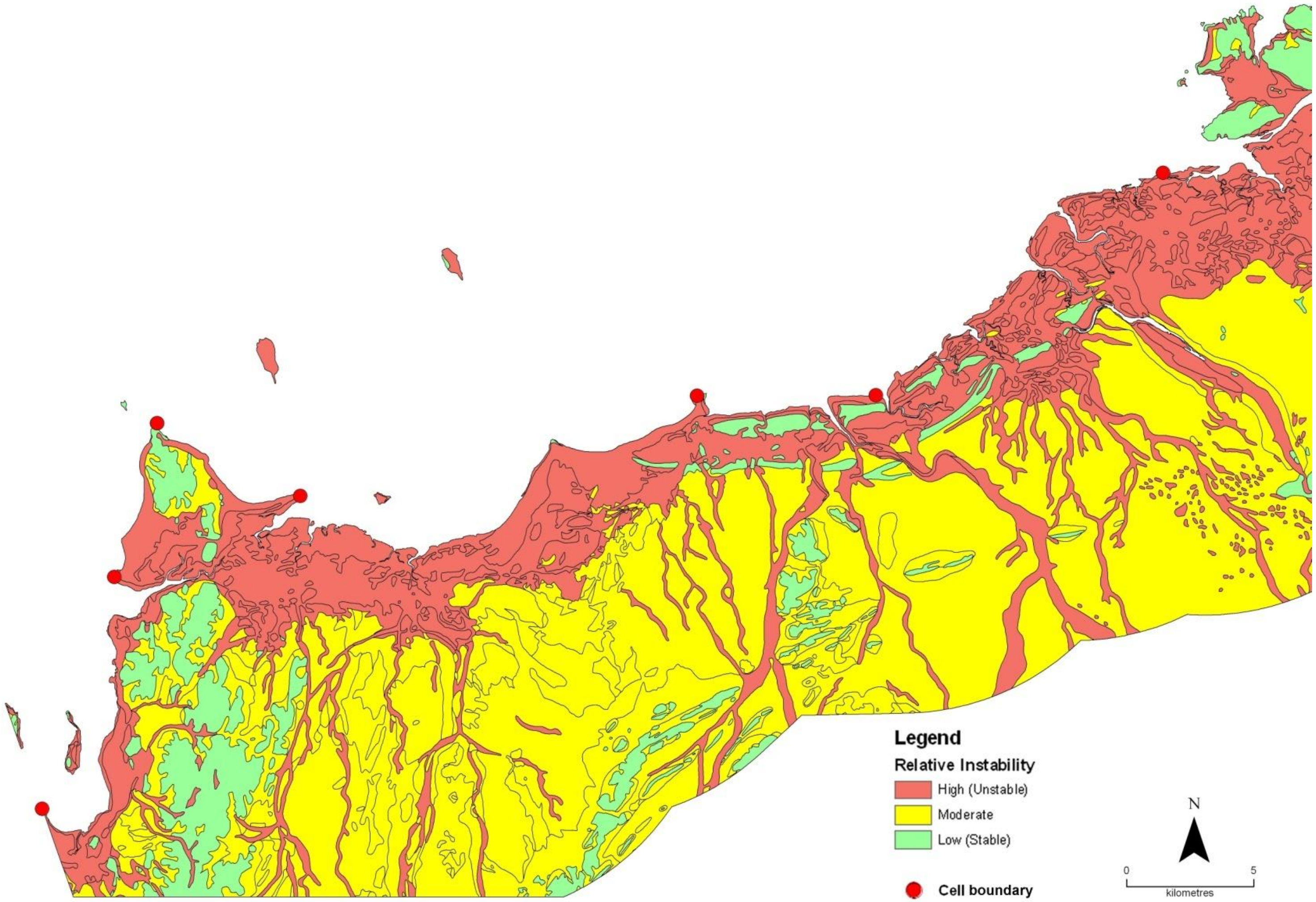


Figure 6-24: Karratha Area Landform Instability (1 of 5)

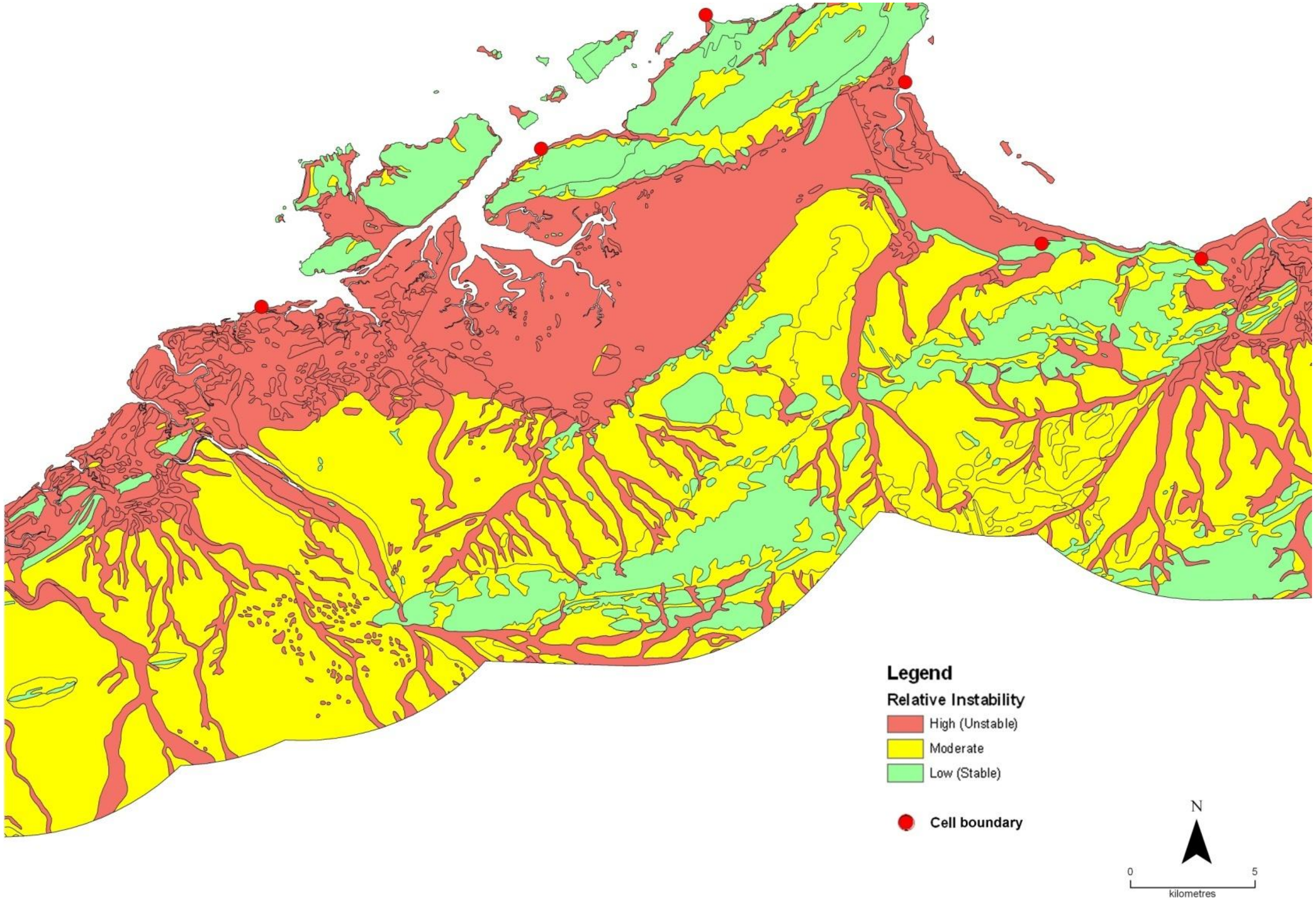


Figure 6-25: Karratha Area Landform Instability (2 of 5)

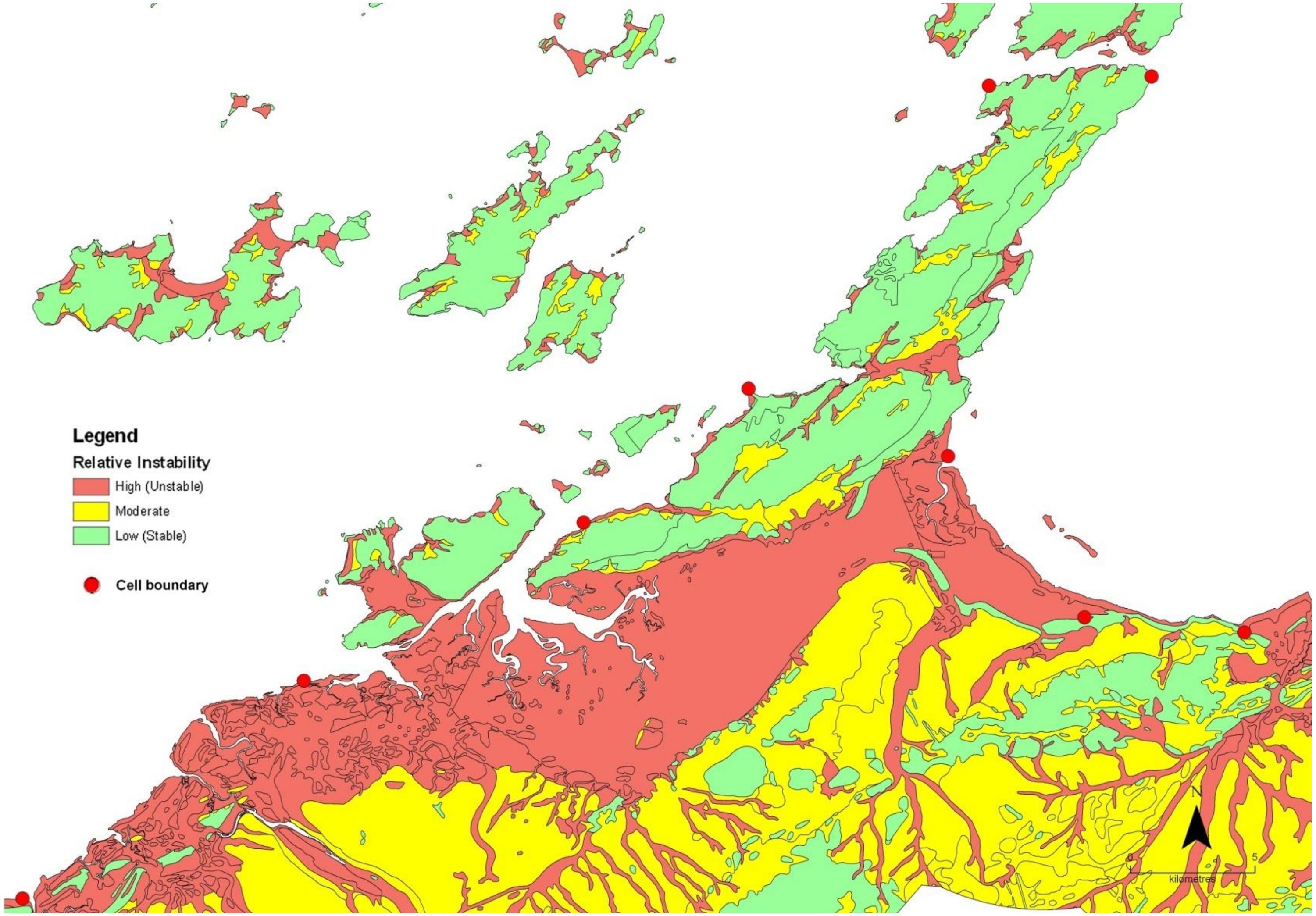


Figure 6-26: Karratha Area Landform Instability (3 of 5)

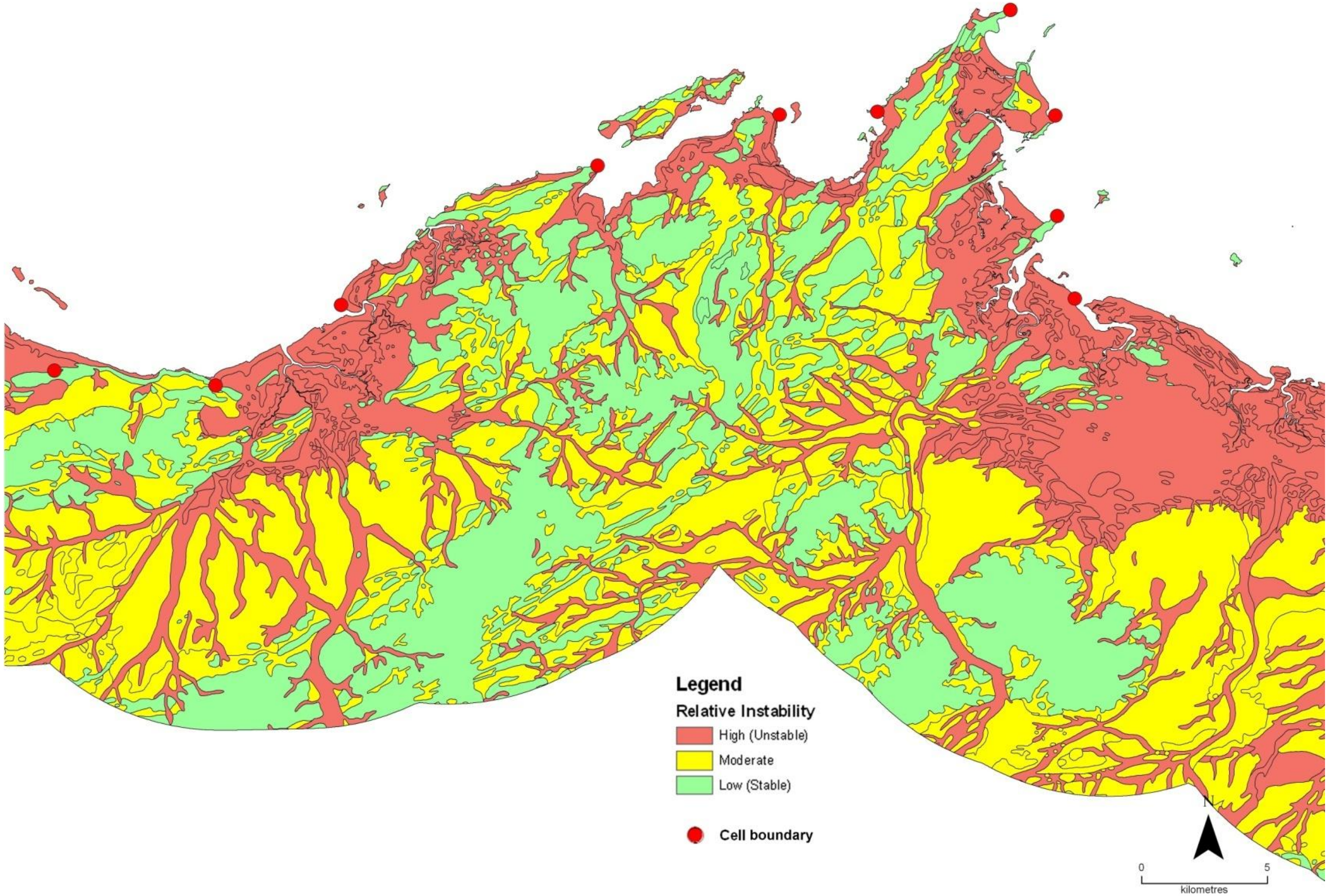


Figure 6-27: Karratha Area Landform Instability (4 of 5)

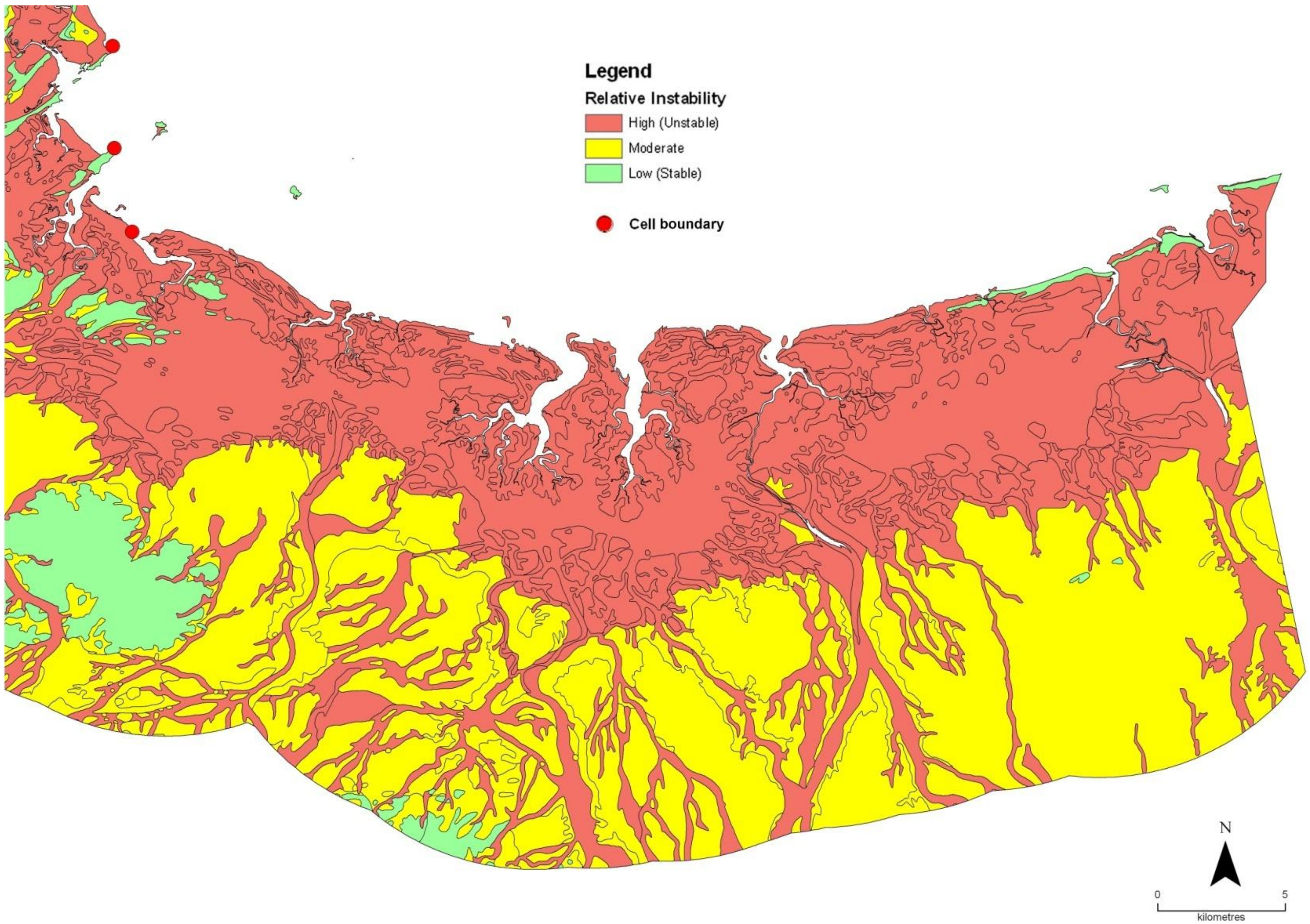


Figure 6-28: Karratha Area Landform Instability (5 of 5)

Table 6-12: Karratha Area Tertiary Sediment Cell Description

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
Point Samson	18. Reader Head to Butcher Inlet (E)	The sediment cell is located in the Cape Lambert to Sherlock Compartment. The inner-shelf is moderately wide. Water depth is <10m approximately 20km from shore in the centre of the embayed compartment and 20m approximately 35km from shore.	The cell spans a second, structurally controlled ENE facing embayment, 3km wide and 1.5km deep. It has broad sandy terraces with nearshore shoals and numerous tidal channels. The deepest channel is a distributary of the Harding River. Water depth is <5m for up to 8.5km from shore. There is <25% exposed reef or pavement in the inshore waters.	The two parts of the shore are at right angles and separated by a tidal creek directly connected to a distributary of the Harding River. The northern shore is rocky with perched beaches and fringing mangroves in small shallow embayments. The southern sandy shore abuts a lithified chenier with overlying perched dunes and located between the mouths of two large tidal creeks.	The shore is backed by extensive deltaic plains and inherited basins of the Harding River, which was dammed in 1984. The mudflats are split by a rocky ridge and a low-lying causeway linking Cossack to its hinterland. The ridge is an elongate feature extending discontinuously over 3km from southwest to northeast. On the southern shore, mudflats landward of the lithified chenier are connected to the Harding River delta. The chenier is a composite feature comprising old and modern shorelines.
	17. Point Samson to Reader Head	The sediment cell is located in the Cape Lambert to Sherlock Compartment. The inner-shelf is moderately wide. Water depth is <10m approximately 20km from shore in the centre of the embayed compartment and 20m approximately 35km from shore.	The cell spans a structurally controlled E facing embayment, 4km wide and 3km deep. It has broad sandy terraces with numerous tidal channels. Water depth is <5m for 6 to 8.5km from shore. Jarman Island is 2km offshore of Reader Head, the southern boundary of the cell. There is <25% exposed reef or pavement in the inshore waters.	The two parts of the shore are at right angles, with the northern part facing SE and the southern part facing NE. The northern shore opens through gaps in a narrow rocky ridge into the funnel-shaped mouth of a tidal creek complex. The southern shore is comprised of spits, cheniers and a tidal creek complex; between rocky headlands.	The shore is backed by extensive deltaic plains and inherited basins of the Harding River, which was dammed in 1984. The northern shore is mainly rocky and impounds a largely inactive branch of the Harding River, whereas the southern shore is more directly related to the river. Landward of the cheniers are broad tidal flats with numerous tidal channels. There are 7 tidal creeks along the 6km of coast.

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
	16. Cape Lambert to Point Samson	The sediment cell is the west part of the Cape Lambert to Sherlock Compartment. The inner-shelf is moderately wide. Water depth is <10m approximately 20km from shore in the centre of the embayed compartment and 20m approximately 35km from shore.	Water depth is <5m for 6 to 8.5km from shore. The nearshore waters are separated into two parts by elongate rock outcrops extending 1-2km perpendicular to shore. In the northern part tidal flats extend up to 1km offshore and are perched on extensive rock platform. The southern part has a narrower tidal flat perched on an extensive rock pavement and platform. The inshore waters include 50-75% rock pavement.	In the northern part of the cell the perched sandy beach is at the head of a shallow NE facing embayment. It is backed by coastal dunes. The beach on the southern part is on a straighter coast with a near continuous intertidal pavement and rock outcrops.	Cape Lambert supports a port facility. In the northern part sandy beach backs onto a low wide foredune plain with Sam's Creek, a tidal creek, and mudflats to landward. The mudflats occupy a basin that extends into the northern part of the adjoining cell to the south. The mudflat is separated from the coast by rocky terrain and perched dunes in the southern part, near Point Samson.
Cleaverville-Anketell	15. Rocky Ridge to Cape Lambert	The sediment cell is the east part of the Cleaverville Creek to Cape Lambert Compartment. The inner-shelf is narrow. Water depth is irregular. It is <10m approximately 6.5km from shore; and 20m approximately 23km from shore. Delambre Island is surrounded by shoals and well offshore.	Water depth is irregular and is <5m for approximately 2.5km from shore. The inshore waters include >75% reef or pavement.	A near continuous pavement, intermittent intertidal platform and perched beaches are common features of the NW facing shore. Planar beaches drop steeply into the inshore waters. The beaches occur in shallow embayments along the coast and are separated by rock outcrops.	Sandy beaches abut episodic transgressive dunes, comprised of a mainland barrier perched on rocky terrain. Cape Lambert supports a port facility.
	14. Anketell to Rocky Ridge	The sediment cell is located in the Cleaverville Creek to Cape Lambert Compartment. The inner-shelf is narrow. Water depth is irregular. It is <10m approximately 6.5km from shore; and 20m approximately 23km from shore. Delambre Island is surrounded by shoals and well offshore.	The cell encompasses a deeply NNE facing embayment 4km wide at its mouth and 2.5km deep. The cell contains several small islands close to shore. Water depth is irregular and is <5m for approximately 2.5km from shore. The inshore waters include 25-50% reef or pavement. The embayment appears to be a sediment sink. Its inshore waters have broad tidal flats with numerous tidal channels.	Spits line the eastern and western shores of the NNE facing embayment close to its mouth. Further into the embayment the shore is arcuate, broken by a rock outcrop in the southeast. It is also cut by six tidal creeks. A sandy beach occurs along a chenier landward of a wide band of fringing mangroves.	Sandy shore abutting or perched on bedrock occurs intermittently as spits, cheniers and perched barriers around the eastern shore of Anketell and western shore of Cape Lambert. Broad low foredune plains, which may be lithified, are located at the head of the embayment. Streams draining off the rocky terrain flow onto mudflats landward of the foredune plains. The mudflats are connected to several small tidal creeks (>5 per 10km).

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
	13. Jockeys Hill to Anketell	The sediment cell is located in the Cleaverville Creek to Cape Lambert Compartment. The inner-shelf is narrow. Water depth is irregular. It is <10m approximately 6.5km from shore off Dixon Island; and 20m approximately 23km from shore and 2km north of Delambre Island. Three Islands are located in State Waters. The largest islands are Dixon Island, close to shore, and Delambre Island, which is surrounded by shoals and well offshore. Dixon Island is less than 1km from shore.	Dixon Island is less than 1km from shore and is separated from the mainland by a broad channel which opens to the northwest near Jockeys Hill and to the northeast near Anketell Point. Port Robinson, a broad embayment with an irregular shore, is located immediately south of Jockeys Hill. Its inshore waters and those of the channel include 25-50% reef or pavement. In the lee of Dixon Island tidal flats are dissected by numerous tidal channels.	The irregular shoreline includes two components. In the west, tidal flats up to 2km wide are lined by mangroves and mudflats up to 1km to landward. Further east, sandy shore abuts and overlies rocky coast around Anketell Point. In places the sandy shore abuts chenier spits. Elsewhere rock outcrops impound narrow mudflats. High level wrack lines are common in the Anketell area and are indicative of extreme water level events.	In the west, the backshore includes extensive mudflats and floodplain drained by Rocky Creek. Rocky terrain occurs close to the shore in the centre of the cell. Further east, sandy shore abuts or is perched on bedrock. The sandy shore occurs intermittently as spits, cheniers and perched barriers around the eastern shore of Anketell. The Anketell peninsula may be separated from the mainland by mudflats inundated during extreme water level events.
	12. Fields Creek to Jockeys Hill	The sediment cell includes part of two compartments: Karratha Back Beach to Cleaverville Creek and Cleaverville Creek to Cape Lambert. The coast faces NW and is the eastern shore of Nickol Bay, a deep embayment open to the N to NE. The inner-shelf is wide. Water depth is <10m approximately 15km from shore and 20m approximately 30km from shore. There are two small islets in the inshore waters, Walcott Island and Pemberton Island.	Water depth is <5m approximately 2km from shore. Unconsolidated sediments overlie rock pavement and reef along the subtidal shoreface, with 50-75% rock exposed. Tidal flats extend over 3km seaward of the beachrock and are cut by the Cleaverville Creek drainage system.	An irregular, seawardly-convex shoreline constitutes a mainly rocky coast. It has been cut by Cleaverville Creek. Small sandy beaches and cobble beaches are located in shallow embayments. These are perched on beachrock and banded iron platforms. Much of the shore is lined by mangroves.	Two large basins are contained by the high rocky ridge along the coast and high rock outcrops to landward. The basins, in the west and central part of the cell are partially infilled with mudflats and support mangrove vegetation along the creeks. Elsewhere high bedrock topography is drained by ephemeral streams. Closer to the coast low dune ridges overlie tempestites and bedrock in the shallow embayments.
Karratha	11. Nickol Bay Mine to Fields Creek	The sediment cell is the central part of the Karratha Back Beach to Cleaverville Creek Compartment. The coast faces NW and is the eastern shore of Nickol Bay, a deep embayment open to the N to NE. The inner-shelf is wide. Water depth is <10m approximately 15km from shore and 20m approximately 30km from shore.	Water depth is <5m approximately 3km from shore. The inshore waters cover mainly unconsolidated sediments particularly sands deposited in the vicinity of the Nickol River mouth. The tidal flats extend over 3km seaward of the beachrock and have been cut by several tidal channels.	An irregular shoreline is located between two rock headlands. The 6km of shore is broken by five tidal creeks, two of which have channels extending over 3km seaward across the tidal flats. The shore is lined by mangroves and overlies beachrock.	The backshore includes an area of mudflats where marine sediments have filled an irregular depression in the bedrock topography. The mudflats follow stream channels and extend over 5km landwards at their widest. They are cut by tidal channels lined by mangroves for up to 4km landwards. The Nickol River discharges onto the mudflats but is not directly connected to the tidal creeks unless the river is in flood.

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
	10. Karratha to Nickol Bay Mine	The sediment cell includes part of two compartments: Cinders Road to Karratha Back Beach and Karratha Back Beach to Cleaverville Creek. The coast is set at the head of a deep NE facing embayment, Nickol Bay. The inner-shelf is wide. Water depth is <10m approximately 15km from shore.	Water depth is <5m for approximately 4km from the seaward margin of mudflats at the head of the bay. There is 50-75% rocky substrate, with a linear reef apparent. Tidal flats are over 3km wide.	The NE facing shore is at the head of Nickol Bay, a deeply indented embayment approximately 32km long and 45km wide at its mouth. A narrow perched beach is fronted by mangroves and backed by a 7-15m high storm ridge with a veneer of eolian sediments. The ridge has been intersected by several intermittently flowing creeks.	The storm bar along the coast is separated from bedrock topography to landward by a low wide swale. The bedrock topography is drained by numerous ephemeral streams, draining onto the swale. There is potential for floodwaters to interact with marine inundation by storm surge during extreme meteorological events.
	9. Nickol Bay (W) to Karratha	The sediment cell covers most of the Cinders Road to Karratha Back Beach Compartment. The coast is set at the head of a deep NE facing embayment, Nickol Bay. The inner-shelf is wide. Water depth is <10m approximately 15km from shore.	Water depth is <5m for approximately 4km from the seaward margin of mudflats at the head of the bay. There is 25-50% rocky substrate, with a linear reef apparent in the eastern part of the cell. Tidal flats are over 3km wide.	The NE facing shore is at the head of Nickol Bay, a deeply indented embayment approximately 32km long and 45km wide at its mouth. Along the low coast a chenier ridge approximately 100m wide is fringed with mangrove vegetation and intergrades with a tidal flat over 3km wide. The chenier has been breached by three tidal creeks along approximately 10km of coast; one creek is the drain from Dampier Salt ponds. Overwash fans occur along the landward side of the chenier ridge.	Tidal creeks and mudflats extend up to 2km to landward where they abut a retaining wall for the Dampier Salt ponds or the old land surface. The headwaters of some tidal creeks spilling from the salt pond drain have depositional fans. However, most of the tidal creeks have headwater gullies and are actively eroding the mudflat. A stream discharges on to the mudflats but is not directly connected to the tidal creeks unless it is in flood.
Dampier	8. Sharp Peak to Dampier	The sediment cell is the southwest part of the West Intercourse Island to Dolphin Point Compartment. The inner-shelf is moderately wide. Thirty three named islands comprising the Dampier Archipelago are located in State Waters. The islands are in waters <10m deep. Water depth is 20m approximately 28km from shore, and 50m approximately 80km from shore. A chain of five islands is located less than 2km offshore of the cell.	A chain of five islands is located less than 2km offshore of the cell and is separated from the shore by Hamersley Channel. The inshore substrate includes hard rock and >75% reef or pavement. It also includes limesand and other unconsolidated sediments. The small sandy beaches are perched on rock platforms.	The nearly continuous rocky shore has small sandy beaches either perched on rock platforms or located at the heads of small shallow embayments. This is an industrial area with causeways, reclaimed land and harbours.	With localised exceptions, the coastal hinterland largely comprises the rugged bedrock terrain of the Burrup Peninsula. A small tidal creek discharges into the southern part of the cell, blocked by freight rail structures. Other small streams drain the rocky terrain and discharge into the intertidal environments of the small embayments.

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
Cape Preston	7. Little Hill to Pelican Point	The sediment cell is the eastern part of the Cape Preston to Pelican Point Compartment. The inner-shelf is narrow. Water depth is <10m approximately 12km from shore to the seaward side of the reef; 20m approximately 22km from shore; and 50m approximately 75km from shore. The shallow water isobaths are closer to shore in the eastern part of the cell. Two islands, South East and North East Regnard Island, are located in State Waters.	Water depth is <5m for approximately 10km from shore in the west of the cell, where it abuts an offshore reef. The seabed has 50-75% reef or pavement. Nearly all subtidal features overlie rock pavement, commonly coral reef. The western shoreface has tidal flats and numerous, some large, tidal channels.	The complex shore has two components. In the western component of the cell broad rock platforms, identifying old shoreline features, have been dissected by numerous tidal channels. The tidal flats of the western shore support mangrove vegetation and overlie the nearshore reef. Further east, a sandy beach is apparent along a spit segmented by tidal creeks. This merges with the NW facing flank of a cuspate foreland at Gnoorea Point and continues around the shore of a shallow embayment facing NNW between Gnoorea and Pelican Points. Nearly all intertidal shore features are perched on rock, commonly a 500m wide old coral reef.	In a seaward direction, outwash plain merges with mudflats approximately 4km wide. Two streams, McKay and Eramurra Creeks, discharge onto the mudflats, but neither is directly connected to the ocean. In the eastern part of the cell the backshore comprises a series of low dune ridges overlying rock. The ridge impounding the mudflats to landward comprises a segmented spit which points towards the western part of the embayed cell. There are 10 tidal creeks in the exposed western part of the cell, the longest extending approximately 3km landward. The tidal creeks drain inherited basins between discontinuous relic shorelines.
	6. Cape Preston to Little Hill	The sediment cell is the western part of the Cape Preston to Pelican Point Compartment. The inner-shelf is narrow. Water depth is <10m approximately 12km from shore to the seaward side of the reef; 20m approximately 22km from shore; and 50m approximately 75km from shore. Two islands, South East and North East Regnard Island, are located in State Waters.	An extensive subtidal pavement flanks the NE facing shore. It forms part of an old rhythmic shoreline and fringing coral reef.	A sandy shore facing N to NNE shore abuts an older dune surface and overlies rock platforms merging with an extensive inshore pavement. The shore has two planform components: a straight reach of coast between rock outcrops in the northern part of the cell; and a shallow embayment in the southern part. The NE facing arm of the embayment abuts the bedrock headland. Further east the N facing arm is an extensive spit perched on what appears to be an eroded lithified spit.	A high and moderately wide dune barrier occurs along the straight reach of coast in the western part of the cell. The barrier has receded and is perched on rock pavement and platform. It overlies the bedrock topography to landward. Further south the NE facing arm of the embayment is backed by a high and narrow dune barrier overlying rock pavement and impounding lagoonal flats. The sand spit along the southeast part of the cell overlies a high rock platform and is backed by mudflats.

Area	Tertiary Cell	Compartment Inner-Shelf Morphology	Subtidal Shoreface	Intertidal Shore	Backshore Landforms
	5. Preston Spit to Cape Preston	The sediment cell is the northern part of the James Point to Cape Preston Compartment. The inner-shelf is moderately wide. Water depth is <10m approximately 20km from shore in the centre of the compartment; 20m approximately 26km from shore; and 50m approximately 75km from shore. Preston Island is within 1.5km NW of Cape Preston	Water depth is highly variable but generally <5m for approximately 8km from shore. There is >50% reef or pavement in the inshore waters together with a broad sandy shoal in the southern part of the cell.	The coast is comprised of two shallow W facing embayments in unconsolidated sediments and a rocky headland, the last forming Cape Preston. Much of the sandy coast is perched on rock pavement or platform. The coastal plan includes two forelands, the southern is tidally controlled and the northern is associated with rock outcrops. The sandy shore is nearly continuous.	The sandy shore backed to landward by a low foredune plain. In the south the foredune plain is over 1km wide landward of the cuspate foreland at Preston Spit and adjoins an extensive mudflat. Further north the foredune plain abuts rocky terrain. Runoff from the bedrock headlands is discharged on to the foredune plain.
	4. James Point to Preston Spit	The sediment cell is the southern part of the James Point to Cape Preston Compartment. The inner-shelf is moderately wide. Water depth is <10m approximately 20km from shore in the centre of the compartment; 20m approximately 26km from shore; and 50m approximately 75km from shore. Several islands, including Potter Island and Carey Island, as well as shoals and reefs are located in State Waters.	Water depth is highly variable but generally <5m for approximately 8km from shore. There is extensive, >50%, rock platform or pavement in the inshore waters. Broad tidal flats extend along the southern part of the cell, whereas the northern part has narrower tidal flats. There are several large tidal channels on the shallow subtidal shoreface.	Apart from a N facing embayment in its southern part the remainder of the coast faces W to WNW. Much of the coast is perched on rock pavement or platform. In the south eastern part of the embayment a narrow chenier ridge has formed landward of the mangroves. Tidal flats over 1km wide are fringed by mangrove vegetation and merge with broad tidal flats, particularly in the south eastern part of the embayment. The central part of the embayment, where rocks are close to the shore, has narrow tidal flats and a sandy shore backed to landward by a low foredune plain.	The compartment incorporating this sediment cell is an area of geologic change from dominantly unconsolidated sediments of the western compartments to igneous rocks comprising the spine of Cape Preston. The mudflats of the cell occupy embayments in the rocky terrain. There are 10 tidal creeks per 10km in the cell with streams draining the rocky hinterland and discharging onto mudflats.

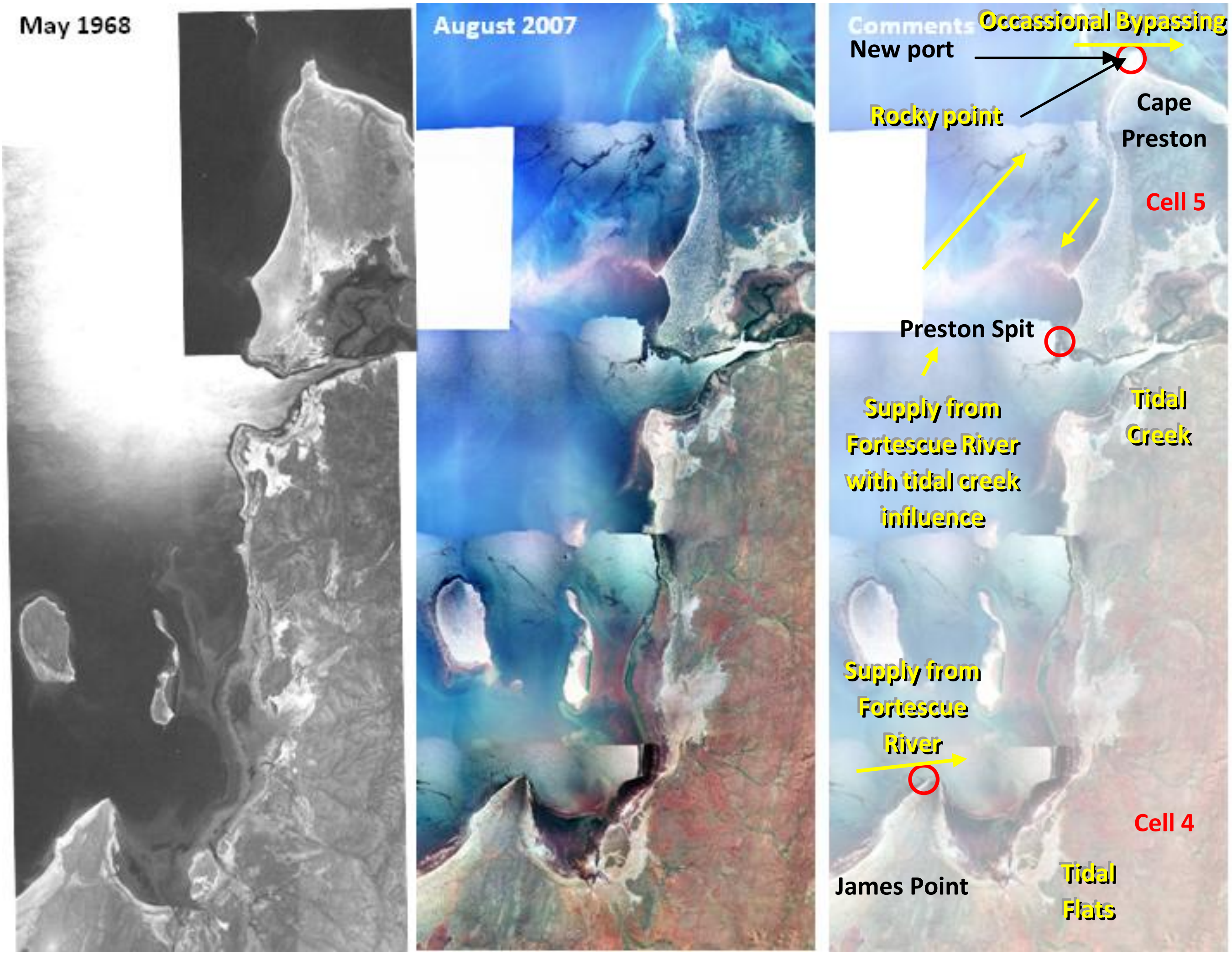


Figure 6-29 : Aerial Photography Cells 4 & 5: James Point to Cape Preston (1968-2007)

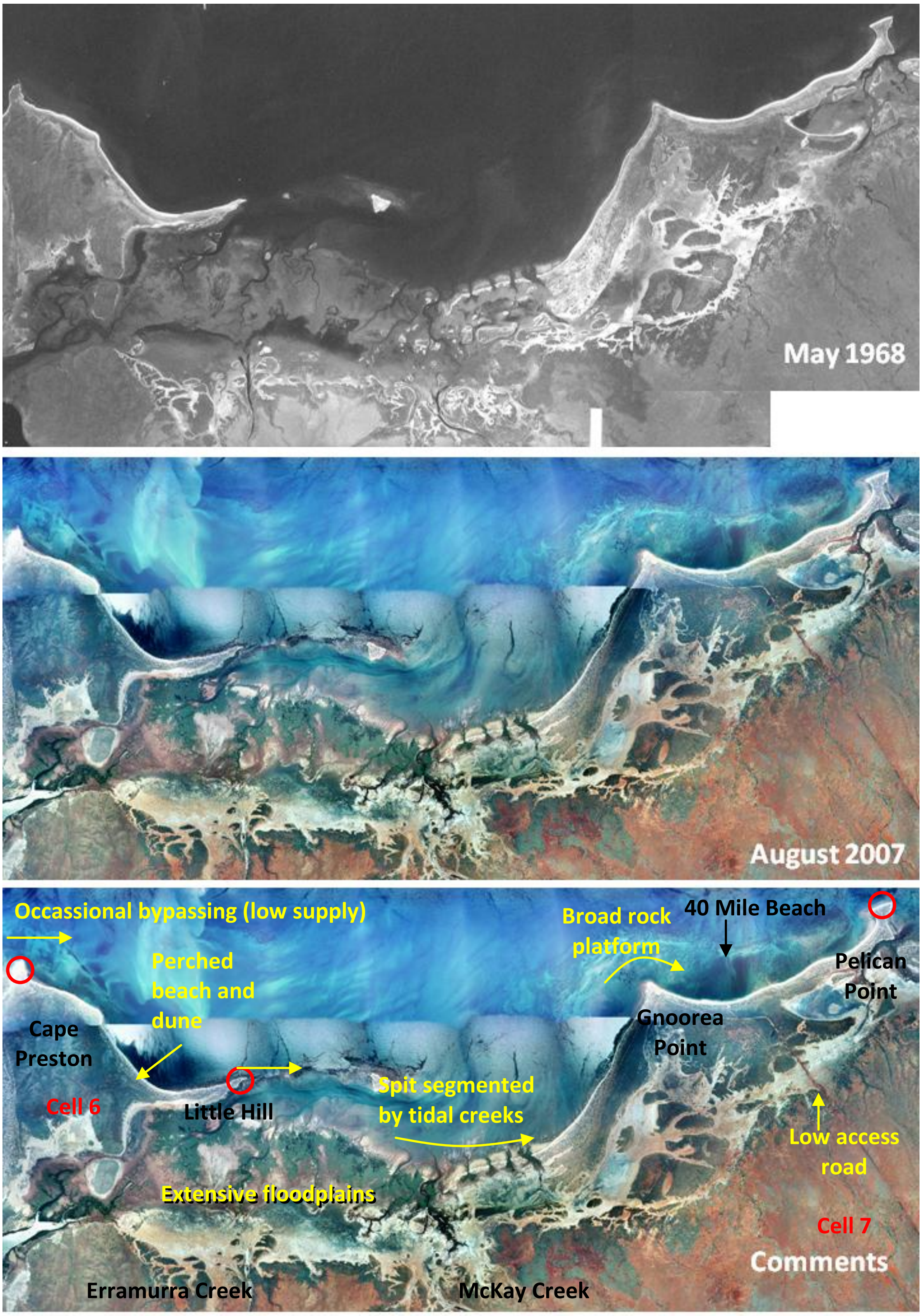


**Figure 6-30 : Aerial Photography Cells 6 & 7: Cape Preston to Pelican Point (1968-2007)
Gas pipeline shore crossing immediately east of Gnoorea Point**

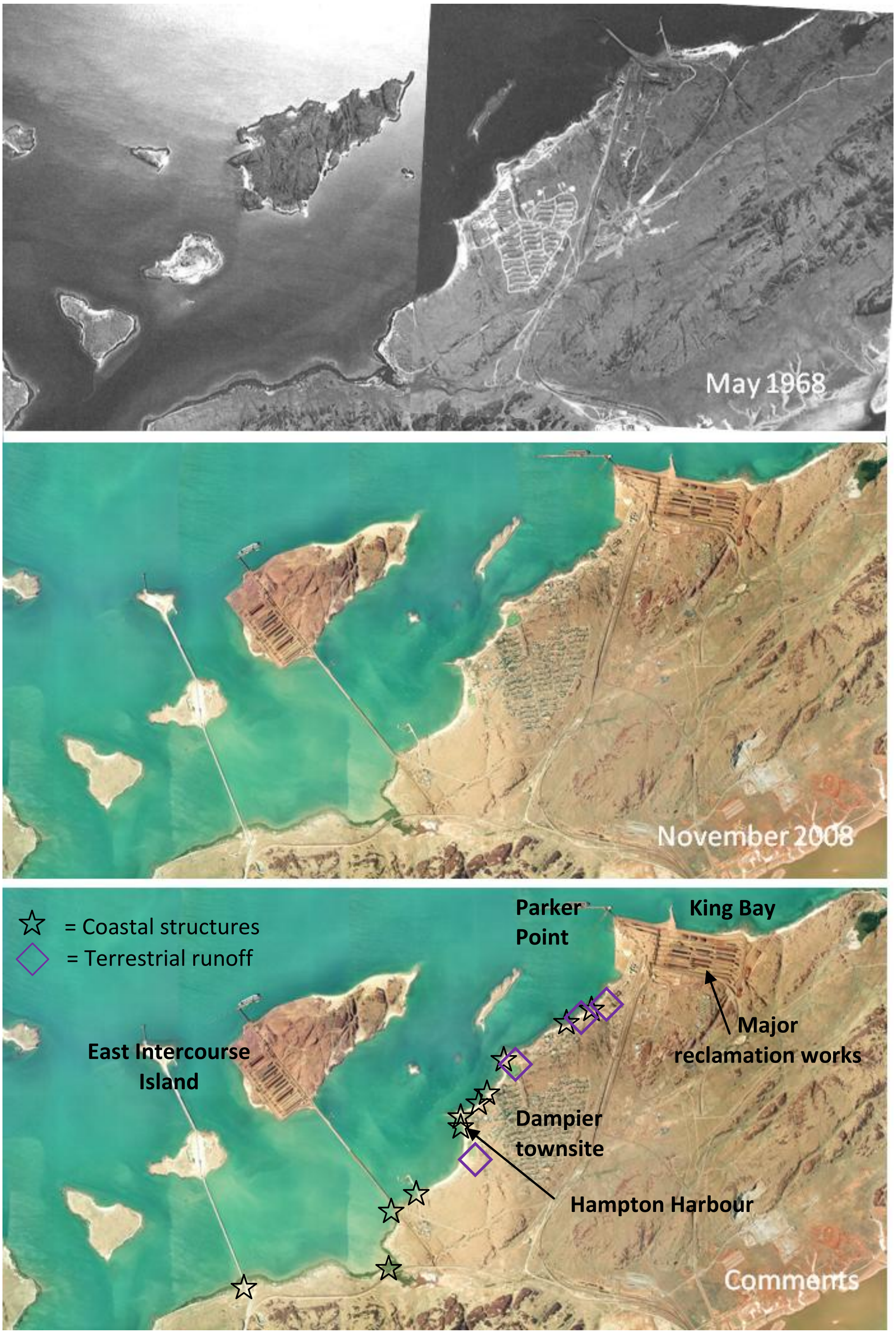


Figure 6-31 : Aerial Photography Cell 8: Dampier (1968-2008)

Figure 6-32 : Aerial Photography Dampier Finer Spatial Scale (1943, 1968, 2008)

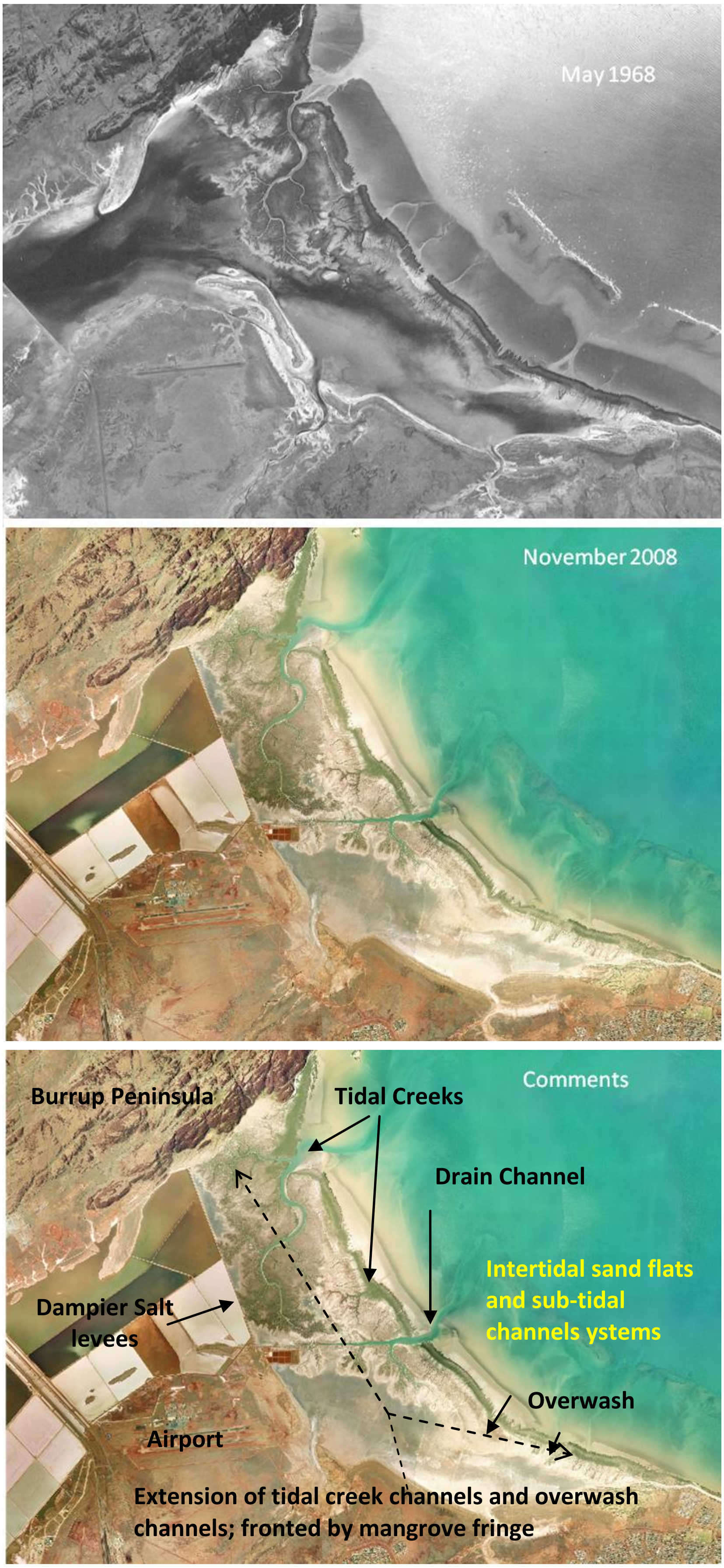


Figure 6-33 : Aerial Photography Karratha Cell 9 (1968-2008)

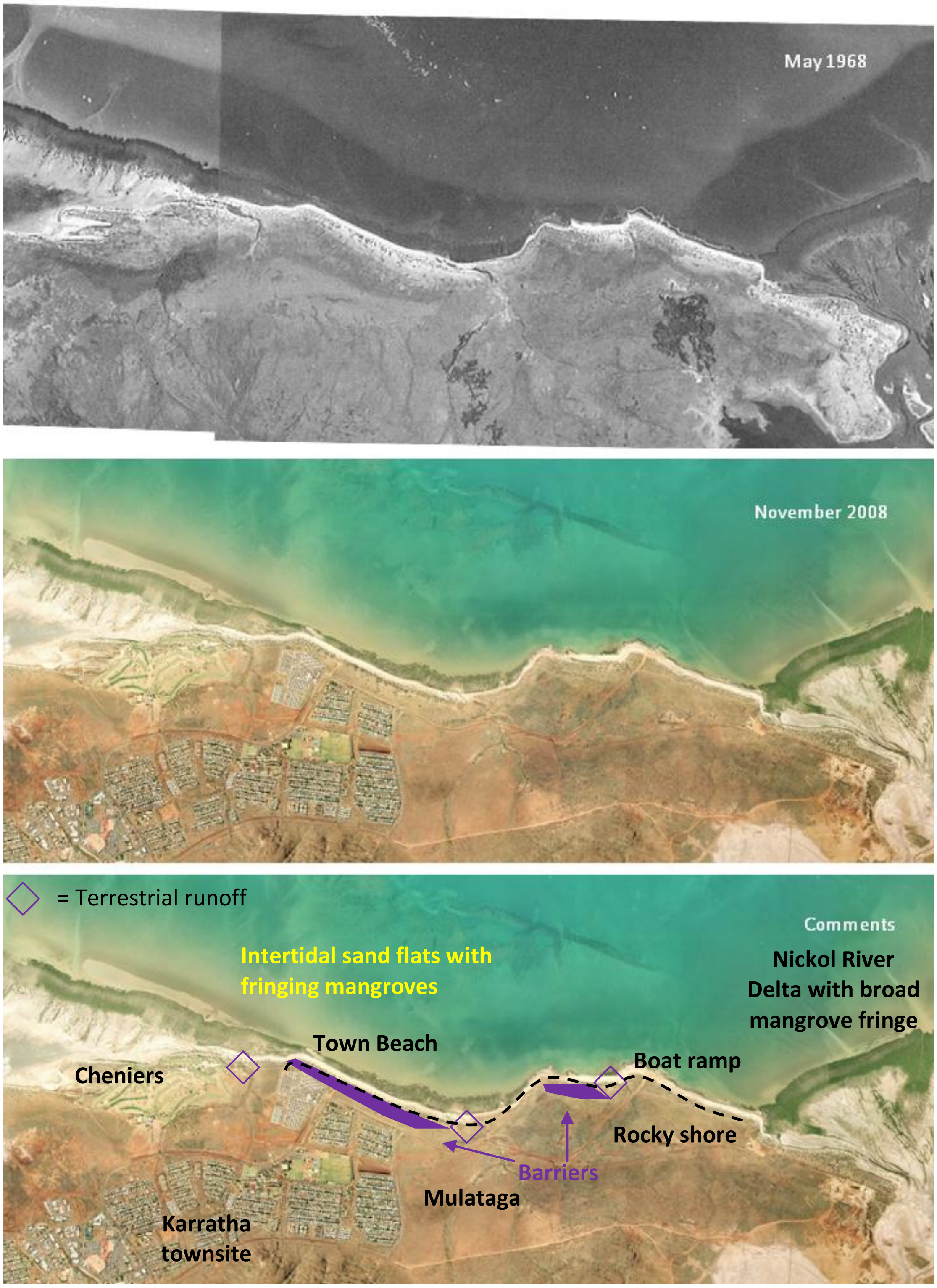


Figure 6-34 : Aerial Photography Karratha Cell 10 (1968-2008)

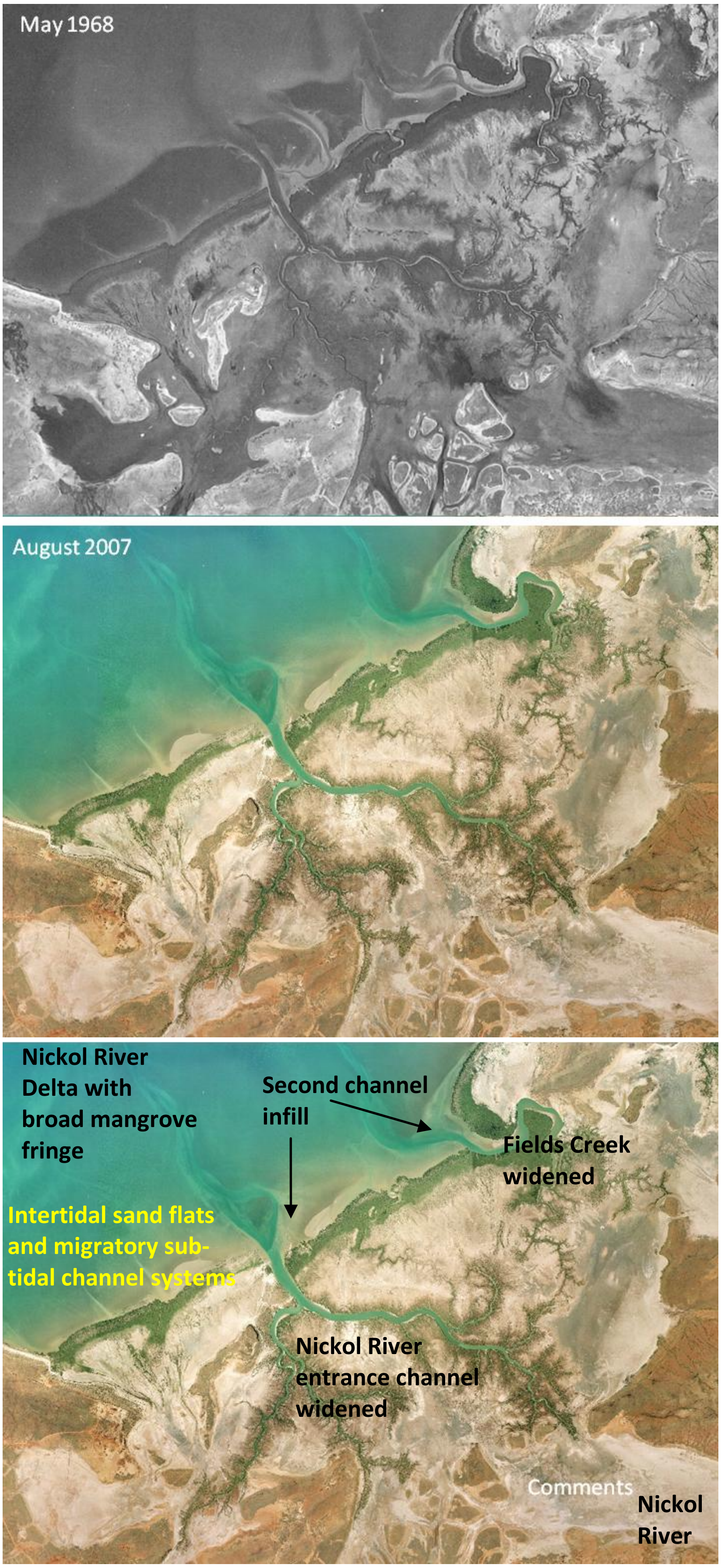


Figure 6-35 : Aerial Photography Karratha Cell 11 (1968-2008)

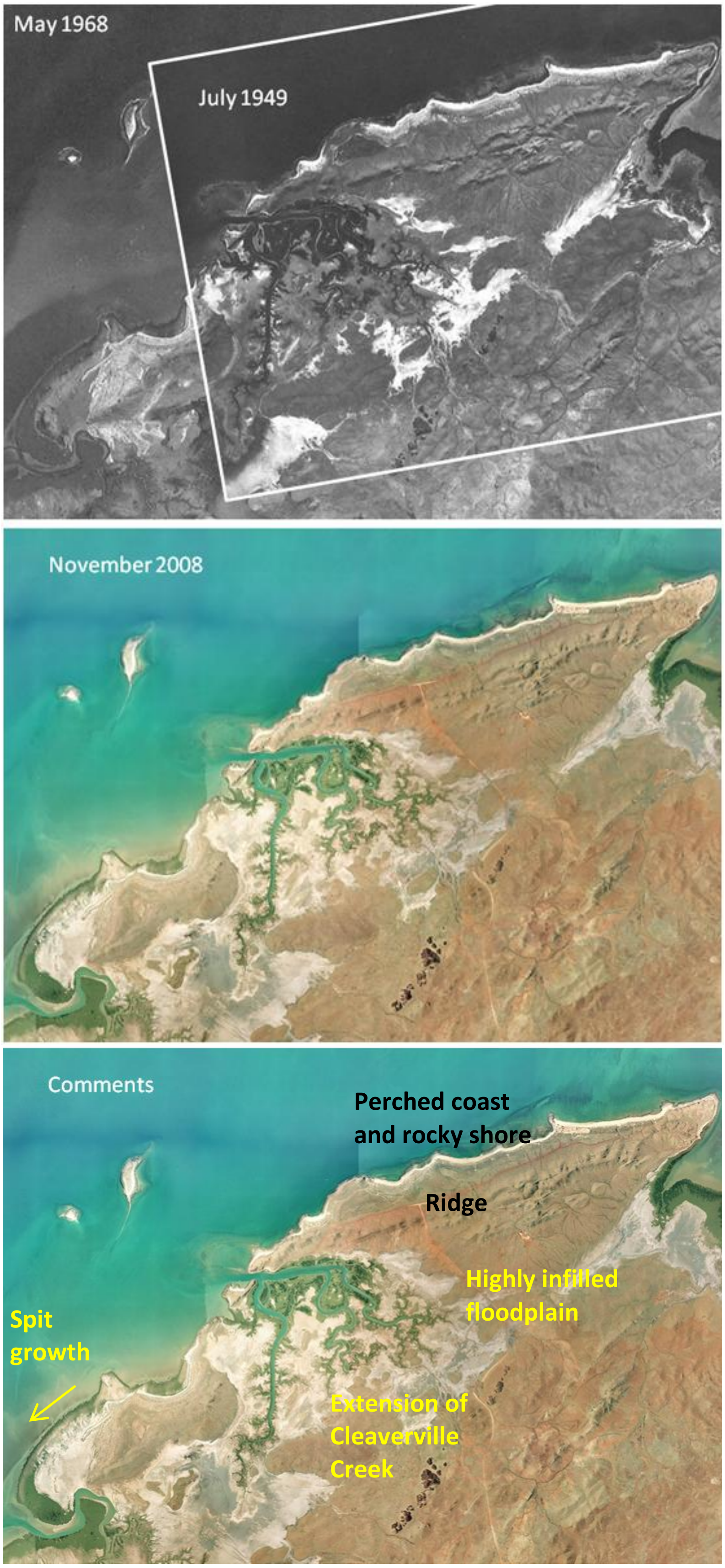


Figure 6-36 : Aerial Photography Cleaverville-Anketell Cell 12 (1949/1968 - 2008)

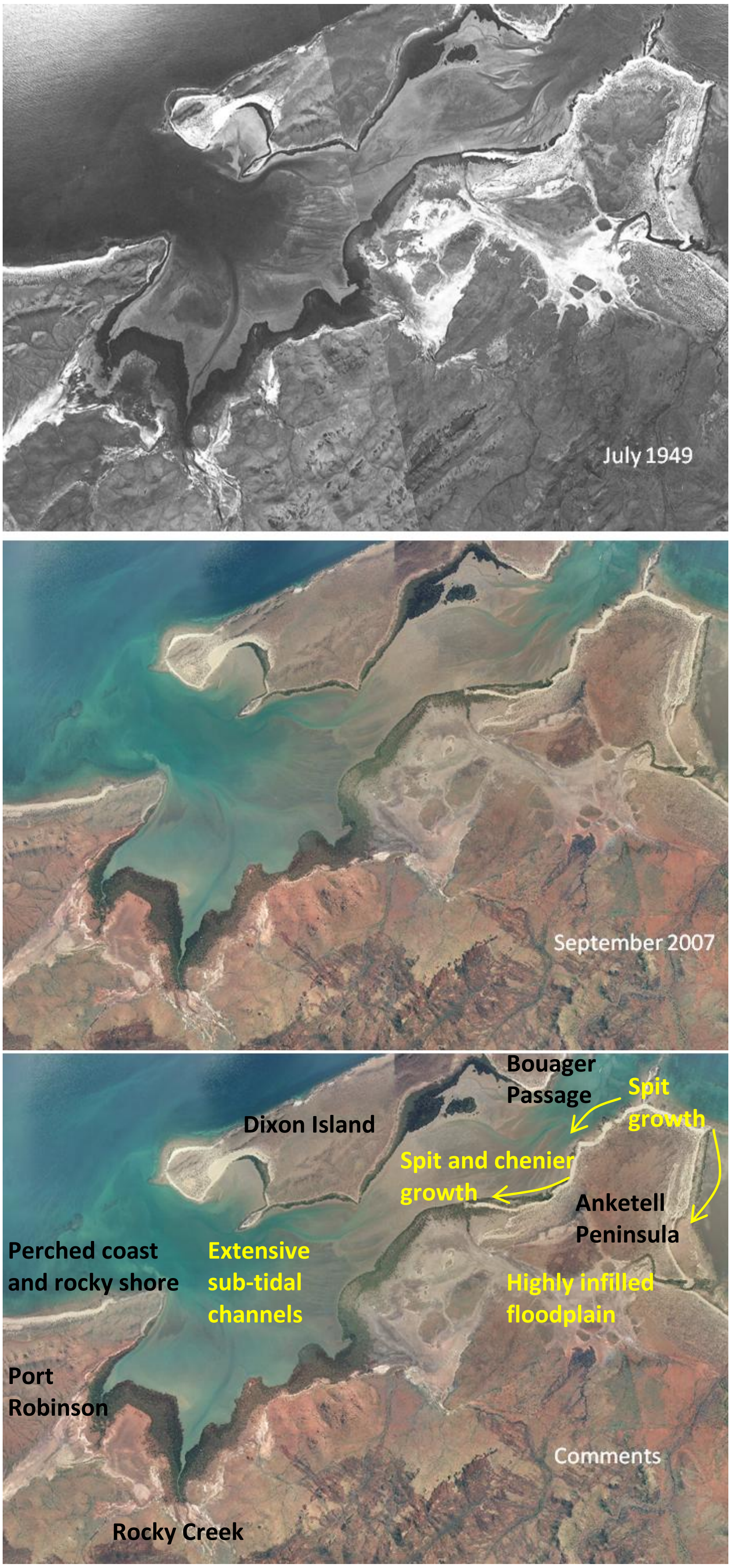


Figure 6-37 : Aerial Photography Cleaverville-Anketell Cell 13 (1949 - 2007)

Figure 6-38 : Aerial Photography Cleaverville-Anketell Cell 14 (1949 - 2007)

Figure 6-39: Aerial Photography Cleaverville-Anketell Cell 15 (1949 - 2007)

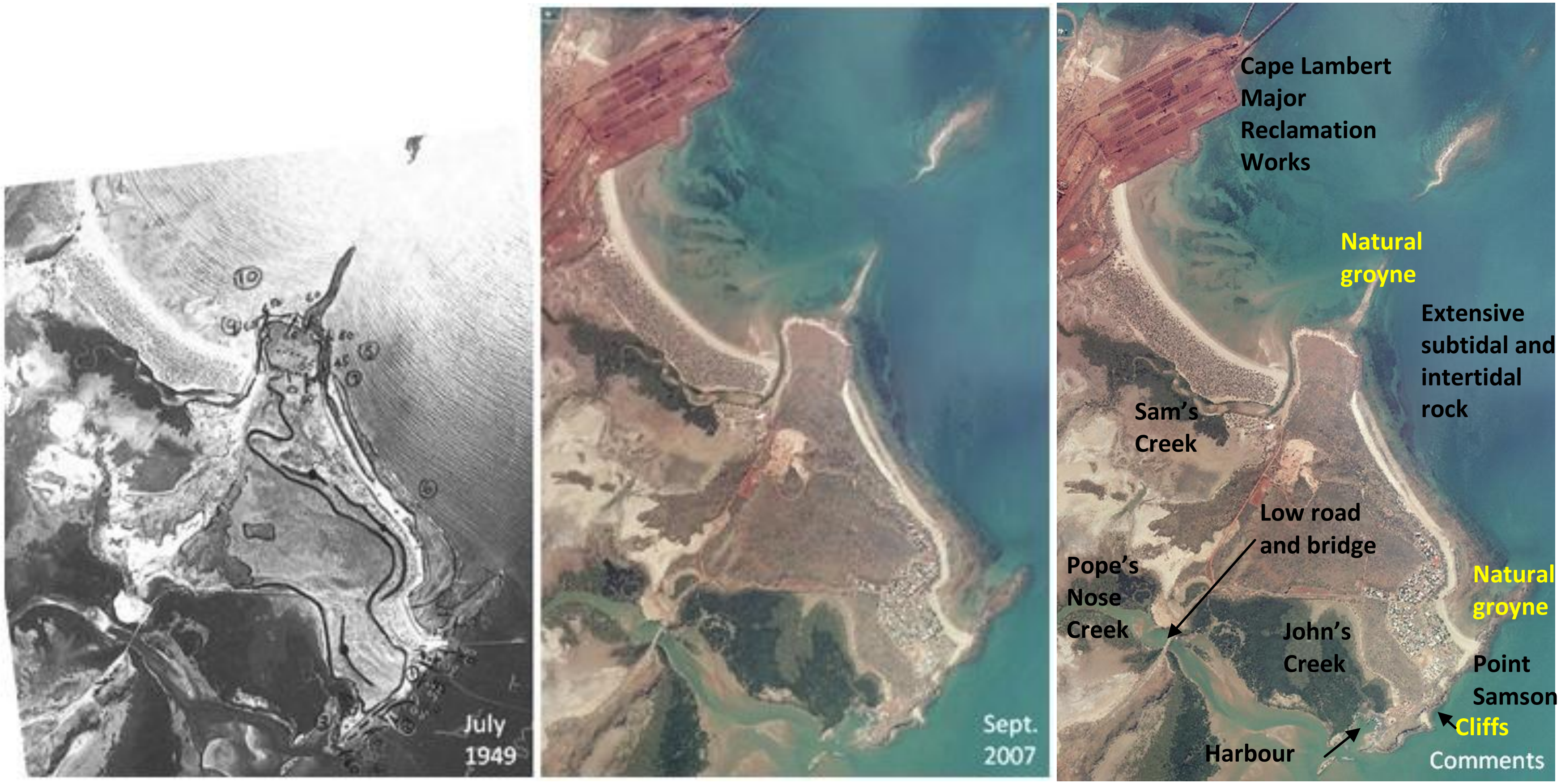


Figure 6-40 : Aerial Photography Point Samson Cell 16 (1949-2007)
Finer scale view of Point Samson in Figure 6-43

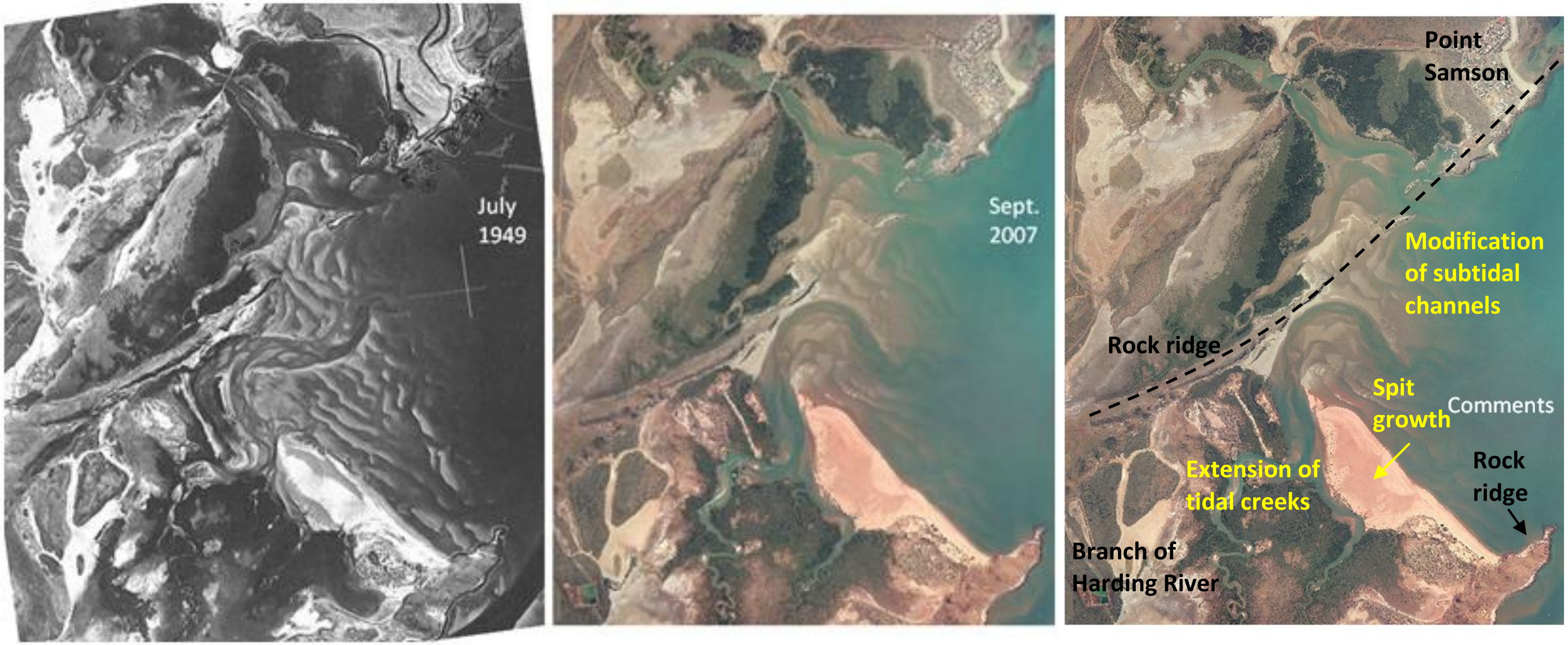


Figure 6-41 : Aerial Photography Point Samson Cell 17 (1949-2007)

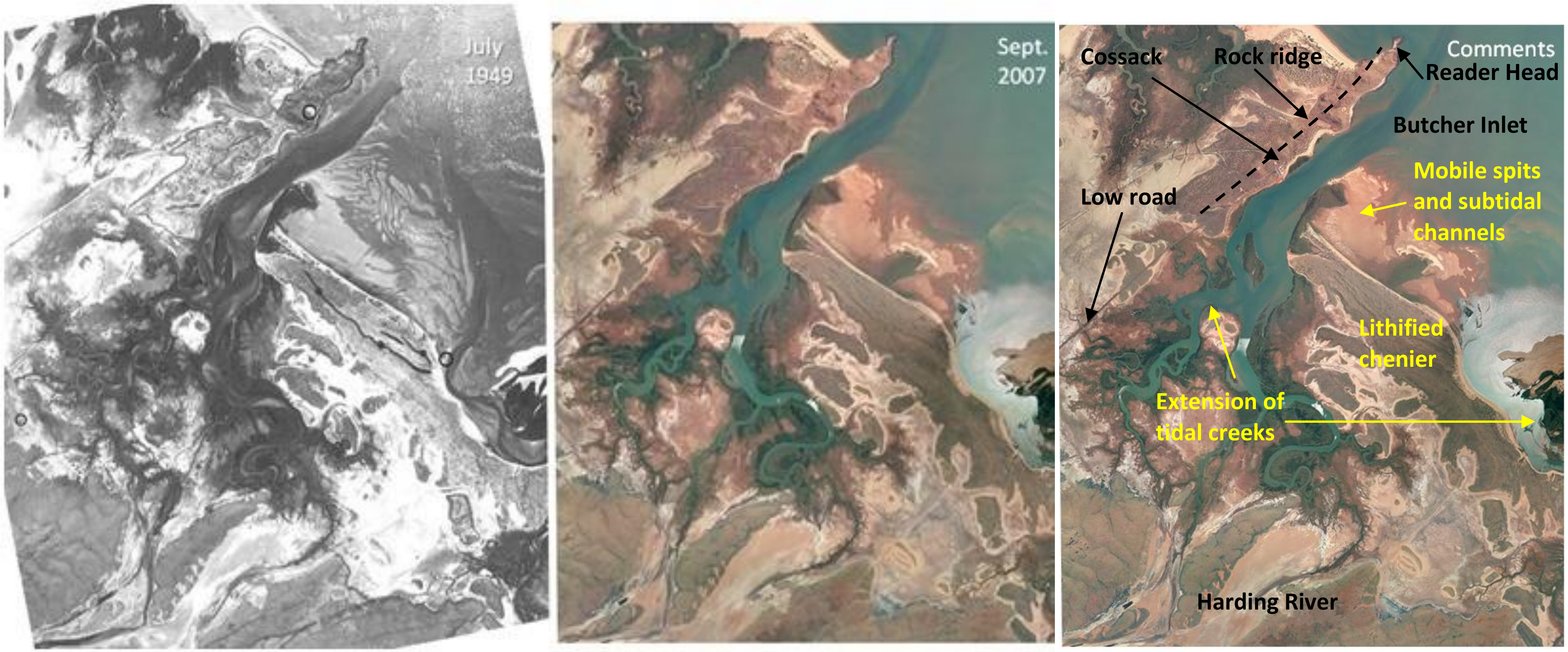


Figure 6-42 : Aerial Photography Point Samson Cell 18 (1949-2007)
Finer scale view of Cossack in Figure 6-44

Figure 6-43 : Aerial Photography Point Samson Town (1949-2007)

Figure 6-44 : Aerial Photography Cossack Town (1949-2007)

6.3.4. Coastal Susceptibility, Instability and Vulnerability

Coastal landform vulnerability has been assessed at a sediment cell scale for the wider Karratha area using the combination of instability and vulnerability described in Section 2 (see classifications in Table 2-7, Table 2-11, Table 2-12 and Figure 2-20). Cell susceptibility, instability and vulnerability varies from low to high dependent on the level of rock control, sediment availability, exposure to extreme events and interaction between tidal and fluvial dynamics on the low-relief coastal floodplain landforms (Table 6-13 and Table 6-14; Figure 6-19 to Figure 6-23). Cells with high vulnerability have extensive low-lying coast with floodplains and tidal creeks, within broader embayments; with low to low-to-moderate vulnerability for cells with extensive rock control.

The high ranking of coastal landform vulnerability across the low-lying cells indicates that any coastal development is subject to significant management constraints that should be addressed with caution. In particular, treatment of storm surge and runoff flooding hazards requires careful consideration, as management of one threat may exacerbate the other hazard. This is particularly significant for areas adjacent to tidal channel networks, which are highly dynamic and may episodically switch between expansionary or contracting behaviour.

The highly controlled nature of the **Cape Preston Coast** (cells 4 to 6) determines that the shoreline is relatively insensitive to mild variations of sediment supply (seasonal or inter-annual), with the exception of the foredune plain landward of Preston Spit. The erosive effect of extreme events, particularly tropical cyclones, is potentially enhanced because wave direction and the vertical level of hydraulic forcing may often be outside the range associated with prevailing conditions. As a consequence, sediment eroded from the upper profile has a low capacity for recovery, with storm-cut scarps prevalent along the perched coast persisting for years to decades. Recovery following erosion of the lower profile is expected to be relatively rapid under prevailing conditions due to the rock controls, but will produce a downdrift lag, with shoreline features recovering increasingly slowly toward the east. The solid causeway recently constructed at Cape Preston is expected to reduce the rate of erosion recovery for beaches east of the port (GEMS 2008c). The potential influence of sea level rise upon this section of coast is significant, as it represents a large change relative to the shallow depths across rock platforms, and may drastically reduce the capacity for low-lying rock features to provide structural control. The higher topography present across much of the Cape Preston headland determines that inundation issues are predominantly restricted to lower-lying tidal wetlands south and east of Cape Preston (LeProvost Environmental 2008). Tidal flows through these wetlands enable them to be highly dynamic in response to climate variations or man-made interventions.

In contrast to Cape Preston, the Regnard Bay coast (cell 7) has a very limited supply of sediment and coast-defining rock features are lower level, including the underlying rock platform. This causes high sensitivity to all forms of climate variation, and particular susceptibility to sea level rise if control provided by the headlands at Gnoorea and Pelican Point is reduced. The Gnoorea recreation area may be cut off by flooding of the access road.

Dampier coast is relatively insensitive to weather systems and environmental change, due to the presence of high mainly rocky topography. Exceptions largely occur at artificial or highly modified sections of coast, including sites where coastal dunes were flattened to provide the town’s sporting ovals; and reclaimed port areas (Damara WA 2011b). Vulnerable areas include road embankments, the club houses south of Hampton Harbour and the two sports ovals. Runoff drainage provides an additional potential source of change at these sites, as the most highly modified areas are all located along drainage paths.

Karratha Coast has a mixture of low-lying mangrove fringed coast, and rocky land with higher topography. Significant coastal dunes are present along the landward side of the western coastal lagoon and adjacent to Karratha townsite, composed of sand and gravel, which suggests storm-built origins. To the west of Karratha, low-lying floodplain is located landward of the dunes, including the area on which Karratha airport has been constructed.

The sheltered and structurally controlled nature of Nickol Bay limits the susceptibility of the low-lying shore to variation of weather conditions. However, its low topography, and the potentially enormous difference between prevailing and extreme conditions determine that this part of the coast is highly susceptible to extreme events and sea level rise. Coastal hazard assessment for the Karratha Coast (JDA *et al.* 2011b Attachment 3) has incorporated assessment of potential pathways for coastal change due to sea level rise. Analysis of historical aerial photographs indicates that change has largely occurred landward of the fringing mangroves, with progressive expansion of tidal creek networks (Figure 6-33 and Figure 6-35). This suggests that the Karratha coastal lagoon is undergoing a 'drowning' phase, following the terminology of Semeniuk (1994), which further implies potential for dramatic rapid coastal retreat and landward extension of tidal creek networks. Landward extension of tidal creeks may stress the eastern levees of Dampier Salt ponds.

The coastal dunes and the higher rocky topography are expected to provide a fair level of protection over a planning horizon of 100 years, although extreme events may cause dune breaching, or cause flooding through existing gaps in the dunes. The most vulnerable area of dunes is immediately adjacent to the airport, where the landward slope of the dune has been excavated; with more minor excavation at Mulataga for gravel mining.

Runoff drainage within Karratha townsite (Cell 10) is a potential source of change to the dune barrier as three local streams intersect the existing barriers.

Cleaverville and Anketell Coast is highly controlled by rock structures and therefore is relatively intolerant to variation of weather conditions, as indicated by the limited change evident in historical aerial photographs. However, the extensive low-lying sections of coast are subject to tidal flows and therefore have the capacity for significant coastal change in response to sea level adjustments; including floodplain infill and extension of tidal creeks. Higher topography features illustrate a range of geomorphic markers characteristic of extreme storm events, including boulder deposits, overwash channels and erosion scarps.

Installation of facilities across the tidal flats is likely to alter tidal flows, changing the sub-tidal channel and sill structures. Modification to tidal flows may alter sediment transport pathways, sand spit behaviour and cause accumulation on the adjacent coast, requiring management of sand drift.

Point Samson Coast is partly controlled by rock structures, which act as training systems for channels, including the tidal creeks adjacent to Point Samson and Cossack. The latter creek system has also historically acted as a floodway for the Harding River, but was dammed in 1984 (WRC 1999). The area has a relatively low rate of alongshore sediment transport, further constrained by the relict barrier system, with mobile sediment largely present in an almost horizontal (and therefore low mobility) subtidal terrace. The width and shallow gradient reduces gross mobility of the terrace in response to changing conditions. Instead, change is reflected in the ephemeral and migratory behaviour of spits and sandbars on the terrace surface.

The low-lying nature of much of the coast determines that inundation during extreme events is a significant issue, although the barrier systems provide a large degree of protection against direct wave attack. Townsites may be isolated in extreme events as the roads to Point Samson and Cossack may be inundated or breached during extreme events or through migration of tidal creeks. The incidence of isolation is likely to increase with sea level rise.

Considerable dynamics of both the tidal creek networks and subtidal terrace have been observed historically, suggesting that the floodplain will be susceptible to sea level rise. The structure of the supratidal lagoon, tidal creeks and relict barrier suggest that the Point Samson Coast and further east have a relatively low rate of sediment supply, which implies the 'drowning' wetland response to sea level rise (Semeniuk 1994) is likely to occur. Change associated with this conceptual model includes dramatic rapid coastal retreat and landward extension of tidal creek networks.

6.3.5. Advice

Hazard assessment and risk mitigation for the Karratha area should follow the risk framework in Section 6.1, including separate considerations for erosion and inundation. Detailed information on erosion risk management has not been included in Section 6.1.

Coastal dynamics within the region are recognised to be a complex interplay between rock features, fluvial systems and coastal floodplains, requiring assessment to be undertaken at a range of scales, with active and adaptive coastal management. For both coastal and runoff flooding, a key requirement is to consider a full range of possible events, such that risk may be minimised within an available development envelope. The high degree of uncertainty associated with flood hazard assessments should be recognised, with allowance made for potential flood mitigation works.

Various parts of the Karratha area are subject to coastal flooding, runoff flooding or a combination of the two. Any approach used for hazard mitigation should be cognisant of the potential transfer of risk to adjacent sites or other processes. This may include drainage focusing or deflection of floodwaters. An example of transfer between processes is where raising ground levels to reduce the risk of coastal flooding acts to constrain a runoff floodway and cause increased flood levels upstream of the restriction. A parallel may occur on coastal floodplains where levee construction prevents landward propagation of surge waters, allowing more rapid development of coastal surge components that may enable higher total water levels. Any planning or potential mitigation works for areas prone to flooding should incorporate the requirements within the Better Water Management Plan (WAPC 2008b) at the relevant scale. This includes the planning of any new roads, such as a road eastward from Mulataga (WAPC 1998a). Flood hazard mitigation advice should be sought from the Department of Water with additional advice from the Department of Transport coastal engineers for works with a coastal component.

Construction should be avoided within any floodways or the active coastal margin. Any development within the broader Area of Planning Interest should incorporate drainage management.

Table 6-13: Karratha Area Tertiary Sediment Cell Vulnerability Rankings

Area	Tertiary Sediment Cell	Cell Boundaries	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 (Shoreline)	Hinterland Topography or Supratidal Mudflats	Instability Score	Instability Ranking	MATRIX SCORE	Vulnerability
Point Samson	18	Reader Head to Butcher Inlet (E)	3	4	4	4	15	H	4	4	4	4	16	H	5	H
	17	Point Samson to Reader Head	3	4	5	4	16	H	4	5	5	4	18	H	5	H
	16	Cape Lambert to Point Samson	3	4	3	2	12	M	2	2	3	2	9	L	2	L-M
Cleaverville - Anketell	15	Rocky Ridge to Cape Lambert	4	2	3	3	12	M	1	1	2	1	5	L	2	L-M
	14	Anketell to Rocky Ridge	4	5	5	4	18	H	4	4	3	3	14	M	4	M-H
	13	Jockeys Hill to Anketell	4	4	4	4	16	H	3	4	3	2	12	M	4	M-H
	12	Fields Creek to Jockeys Hill	3	2	3	1	9	L	2	3	3	2	10	M	2	L-M
Karratha	11	Nickol Bay Mine to Fields Creek	3	4	5	5	17	H	4	5	5	5	19	H	5	H
	10	Karratha to Nickol Bay Mine	5	5	5	5	20	H	2	2	4	5	13	M	4	M-H
	9	Nickol Bay (W) to Karratha	5	5	4	5	19	H	3	4	4	4	15	H	5	H
Dampier	8	Sharp Peak to Dampier	2	1	3	1	7	L	1	1	1	1	4	L	1	L
Cape Preston	7	Little Hill to Pelican Point	4	2	4	5	15	H	2	4	4	5	15	H	5	H
	6	Cape Preston to Little Hill	4	1	3	3	11	M	1	1	2	2	6	L	2	L-M
	5	Preston Spit to Cape Preston	3	2	3	2	10	M	2	2	4	3	11	M	3	M
	4	James Point to Preston Spit	3	2	3	3	11	M	2	5	3	2	12	M	3	M

Table 6-14: Karratha Area Tertiary Sediment Cell Vulnerability Implications
Susceptibility and Instability Rankings should not be used independently.

Area	No.	Cell	From Lat.	From Long.	To Lat.	To Long.	Susceptibility		Instability		Vulnerability		
							Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Point Samson	18	Reader Head to Butcher Inlet (E)	117.20139	-20.666031	117.20767	-20.695515	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
Point Samson	17	Point Samson to Reader Head	117.20076	-20.630101	117.20139	-20.666031	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
Point Samson	16	Cape Lambert to Point Samson	117.1846	-20.592429	117.20076	-20.630101	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
	15	Rocky Ridge to Cape Lambert	117.13717	-20.628796	117.1846	-20.592429	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.

Area	No.	Cell	From Lat.	From Long.	To Lat.	To Long.	Susceptibility		Instability		Vulnerability		
							Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Cleaverville-Anketell	14	Anketell to Rocky Ridge	117.1022	-20.629879	117.13717	-20.628796	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
Cleaverville-Anketell	13	Jockeys Hill to Anketell	117.03722	-20.648019	117.1022	-20.629879	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
Cleaverville-Anketell	12	Fields Creek to Jockey Creek	116.94553	-20.697758	117.03722	-20.648019	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.
	11	Nickol Bay Mine to Fields Creek	116.90071	-20.726589	116.94553	-20.697758	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

Area	No.	Cell	From Lat.	From Long.	To Lat.	To Long.	Susceptibility		Instability		Vulnerability		
							Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Karratha	10	Karratha to Nickol Bay Mine	116.84315	-20.721176	116.90071	-20.726589	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M-H	Coastal risk is likely to be a significant constraint for coastal management.	The site has significant constraints due to a combination of low integrity of natural structures, poor natural resilience and/or moderate-high ongoing management requirements.
	9	Nickol Bay (W) to Karratha	116.79397	-20.662949	116.84315	-20.721176	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.
Dampier	8	Sharp Peak to Dampier	116.66254	-20.686895	116.72198	-20.638624	L	A mainly structurally sound geologic or geomorphic feature likely to require limited investigation and environmental planning advice prior to management.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L	Coastal risk is unlikely to be considered a constraint for coastal management.	The site has a good combination of integrity of natural structures, natural resilience and low management requirements.
	7	Little Hill to Pelican Point	116.25659	-20.858154	116.39692	-20.822805	H	Natural structural features are extensively unsound. Major engineering works are likely to be required.	H	Management responses require repeated installation or repair of major stabilisation works (eg. Port Geographe, Mandurah & Geraldton).	H	Coastal risk is a major constraint for coastal management.	The site has major constraints due to low integrity of natural structures, little natural resilience and high ongoing management requirements.

Area	No.	Cell	From Lat.	From Long.	To Lat.	To Long.	Susceptibility		Instability		Vulnerability		
							Rank	Implications	Rank	Implications	Rank	Risk	Rationale
Cape Preston	6	Cape Preston to Little Hill	116.20603	-20.832459	116.25659	-20.858154	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	L	Resilient natural system occasionally requiring minimal maintenance (eg. Alfred Cove, Milyu Reserve & Scarborough).	L-M	Coastal risk may present a low constraint for coastal management.	The site contains elements of low-to-moderate integrity of natural structures, elements of limited natural resilience or elements requiring management.
	5	Preston Spit to Cape Preston	116.19082	-20.886809	116.20603	-20.832459	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.
	4	James Point to Preston Spit	116.16537	-20.968834	116.19082	-20.886809	M	Some natural structural features are unsound hence the area may require further investigation and environmental planning advice prior to management. Detailed assessment of coastal hazards and risks is advised.	M	Management responses are required to accommodate occasional major events, regular moderate events or frequent minor events. Responses may involve stabilisation work (eg. Cottesloe, Floreat & Broun Bay).	M	Coastal risk may present a moderate constraint for coastal management.	The site has constraints due to a combination of low-to-moderate integrity of natural structures, limited natural resilience and/or ongoing management requirements.

Application of emergency management principles should apply to flood hazard mitigation, considering isolation of residential properties, ensuring key facilities are located in areas of low risk and providing a suitable evacuation plan. Emergency management principles are necessary for any planning for Cossack townsite. Access roads to Gnoorea and Forty Mile Beach recreation area (Cell 7; Figure 6-30), Cleaverville recreation area (Cell 12; Figure 6-36), Point Samson townsite (Cell 16; Figure 6-40) and Cossack townsite (Cell 18; Figure 6-42) may all be subject to flooding or erosion at relatively moderate levels, potentially providing a major constraint for emergency management. Maintenance and adaptation funding should be secured for the roads to Point Samson and Cossack townsites which are vulnerable to washout due to migration of tidal creeks.

Natural barriers and artificial structures should be maintained or fortified to ensure they have sufficient structural capacity to minimise erosion and inundation hazards. It is advisable not to excavate or mine natural barriers to inundation or wave action. Improved stabilisation of existing near-coast infrastructure in Dampier, particularly road embankments, is likely to be required with projected sea level rise.

Sediment transport on the inner continental shelf is highly dynamic, and may dramatically switch from prevailing tide-dominant conditions to transitory extreme responses to tropical cyclones. These changes may allow large changes in landform structure, which in turn modifies the nature of transport. Sediment transport under a broad range of environmental conditions may require consideration for coastal developments, particularly where the reliability of sediment supply may affect sedimentation or post-erosion recovery rates. This is particularly evident along the perched dune systems, such as occur on Cleaverville and Mulataga, where both erosion and recovery mechanisms are outside ambient conditions. Factors to consider for sediment supply for rock controlled shores of the Pilbara include the:

- floodplain response;
- sub-tidal terrace response;
- influence of the rock framework, including reduced capture capacity of control features with varied mean sea level;
- variation in proximity to sediment supply within a sediment cell;
- feature capture and rebuild behaviour; and
- variation in sediment supply from rivers, tidal creeks and offshore with associated landform response.

The relative supply of sediment to the floodplains and the sub-tidal terraces of the Karratha area and likely evolutionary pathways have not been established. The rate of sediment supply to coastal lagoons ultimately determines whether the lagoon infills or drowns under sea level rise.

The dynamics of sediment transport is of particular relevance in assessment of coastal development impacts on post-event recovery processes and pathways, including:

- Any **structure on beaches**, perched beaches or **spits** should be designed to minimise downdrift impacts, potential sediment accumulation and sand-drift issues. In this context, sand drift management may be required at Anketell, Point Samson and Cossack;

- Plans to dispose of large amounts of **dredged material** (e.g. proposed works at Anketell) should consider mechanisms for return of material to the dredged channel or onshore transfer. The impacts of dredged material disposal on long-term sediment transport pathways should be carefully evaluated, to avoid outcomes such as occurred at Port Hedland;
- Any **structure extending onto tidal flats** should be designed or managed to minimise impacts on tidal flows and sediment movement under cyclonic conditions; and
- Any works incorporating **excavation of inter-tidal rock and terraces** should be designed to minimise offshore loss of material through the excavated area;

There is potential significant environmental risk for collapse or breach of any the eastern levees of the Dampier Salt ponds to the west of the Karratha townsite. However, these facilities are third-party owned and managed, which provides a constraint upon risk management for the Shire, who are not responsible for levee upkeep and adaptation.

New or expanded wastewater treatment facilities will be required as the population in the area expands. Source-Receptor-Pathway investigations are required for siting of sewage outfalls for managing environmental and health risk given the broad shallow terraces and flats.

6.3.6. Further Studies

The following projects have been identified as being useful to the management of the Karratha regional coast:

- *Flood Hazard Building Criteria*. One-off identification of building design requirements in flood affected areas, with ongoing education and auditing programs to assist land owners.
- *Post-event surveys*. Ongoing program of post-flood surveys to assess influence of local processes. This information should be used for post-validation of inundation assessments.
- *Tidal Creek Baseline Assessment*. Identification of sites with values at risk, monitoring, triggers and possible management actions.
- *Evaluation of Runoff-Surge Coincidence*. Assessment of the potential for flood runoff and cyclonic storm surge to be coincidental, to facilitate floodplain hazard modelling and mitigation.
- *Aggregation of Resource Company Data*. Formation of database identifying available information collected by resource companies that is directly relevant to coastal planning and management.
- *Inundation Review*. One-off evaluation of the need to update runoff flooding hazards due to revision of *Australian Rainfall & Runoff – A Guide to Flood Estimation* (Pilgrim *ed.* 1987; due for 2012 completion). Confirmation of previously modelled synoptic climate and comparison of model performance against flood records every 5-10 years. Revision of models may be required if there is significant discrepancy.

In addition to these regional projects, information that is likely to be of particular value for Karratha town site includes:

- *Coastal Inundation Data Collection*. Installation of a tide gauge in Nickol Bay.
- *Flood Hazard Adaptation Study*. Identify possible forms of adaptation, particularly exclusion zones that may allow cost-effective flood mitigation.
- *Coastal Barrier Stability Assessment*. Geophysical and geotechnical assessment of the existing barriers that provide primary protection to Karratha. Identification of monitoring, triggers and opportunities for strengthening.

These studies are outlined in more detail below.

The Karratha region has a complex topography, comprising extensive floodplains and drainage channels, with a remote (more than 100 year ARI) possibility of flooding for a large number of residential and commercial properties. Within flood hazard areas, the potential for economic loss associated with flooding may be dramatically reduced through consideration of suitable design principles (ABCB 2012) and flood preparedness (EMA 2009a). Substantial additional guidance regarding building design and retrofitting is available from US Flood and Emergency Management Agency (FEMA 2005, 2009, 2011). This information should be made available to landowners, requiring an appropriate communication and education strategy. Following from the findings of wind-related damage after TC Yasi, a program of auditing is required to maximise the effectiveness of building design principles as a risk mitigation tool. It is recognised that this will require capacity building for the auditing agency.

Existing inundation models are largely unvalidated, with only a few well-recorded historic examples of tropical cyclone extreme impacts and limited representation of local processes within the models. Hence, future events may provide an opportunity for both further model verification and identification of sub-scale variability of flood hazard. At the coast, local processes include wave setup and overtopping, with similar factors along streams for bend-effects, hydraulic jumps and changes to channel morphology. Post-flood surveys enable the relative importance of these local processes to be assessed on-ground, which facilitates more refined scaling of setbacks and design of any adaptation works. Whilst the survey extent will vary according to the spatial signature of each event, the program should evaluate flooding in close proximity to development areas, and capture the variations with different landform types. Landform maps described in Section 6.3.3 (Figure 6-19 to Figure 6-23), along with the hillshade DEM within *WACoast* (Gozzard 2012a), may assist selection of survey coverage.

Historic observations suggest that coastal change in the Karratha region occurs focally, with potential for significant advance and expansion of tidal creek networks, particularly under projected sea level rise scenarios. Creek movement is likely to require active management given the proximity of creeks to coastal development, including pressure for reclamation at the margins of coastal lagoons. Aerial imagery analysis provides a preliminary means of historic assessment (JDA *et al.* 2011b Attachment 3), but provides only limited guidance for future behaviour. It is recommended that a tidal creek baseline assessment be undertaken within an adaptive management framework. The assessment should identify sites with values at risk, along with defining a monitoring program, triggers and possible management actions. Monitoring and management may be tied to the environmental approvals process, in limited situations, for large scale and industrial developments.

Considerable development in the Karratha region occurs within the coastal floodplain, where there is potential for coincidence of flood runoff with cyclonic storm surge. Preliminary evaluation cautiously suggested a link between the two (JDA *et al*. 2011a), but instead used an empirical relationship based upon review of Australia-wide policies. Notably, this approach does not acknowledge the relationship of runoff-surge coincidence to catchment and coastal lagoon scales, with smaller areas more likely to have joint occurrence. For non-cyclonic regions this is discussed in *Interaction of Coastal Processes and Severe Weather Events* (Westra 2012). Evaluating the flood hazard more accurately in the Karratha region may require assessment of high frequency pluviograph and radar datasets, combined with tide gauge and flood measurements. A major advantage of refining the flood hazard assessment is to more accurately assess potential benefits of hazard mitigation.

Extensive coastal data and model output is collected by resource companies in the Karratha region. Although access to this information is potentially commercially restricted, an information-base identifying what exists may provide an invaluable resource for coastal planning and management. Ideally the information-base should be accessible through a portal system similar to the *Australian Ocean Data Network*, developed for publically accessible data and model outputs from Western Australian Integrated Marine Observation Systems (WAIMOS), Bluelink and Western Australian Marine Science Institute (WAMSI) coastal node projects.

Runoff and coastal flooding hazards are evaluated on the basis of limited available historical flood and rainfall records, requiring periodic review to confirm the modelled synoptic climate and compare model performance against observed floods. The scheduled revision of *Australian Rainfall & Runoff – A Guide to Flood Estimation* (Pilgram *ed.* 1987), due for completion in 2012, should be evaluated to determine if previous flood hazard assessments require reconsideration. The most recent studies of coastal flooding for the region (GEMS 2009) and for Karratha townsite (JDA *et al*. 2011a, b) use relatively up-to-date data, and therefore may be adequate for the immediate future.

Hazard assessments of coastal flooding affecting Karratha townsite is presently limited by a poor record of water level phenomena, limited to a historic short-term tide gauge deployment in Nickol Bay and a long-term tide gauge record for King Bay, Dampier. More accurate estimation of tidal processes and surge characteristics requires permanent installation of a water level monitoring system, such as a tide gauge, within Nickol Bay. From a practical basis, the tide gauge and its management should be integrated into the Department of Transport tide gauge network.

The pressure for industrial and residential growth in Karratha is such that development is pushing the limit of the planning envelope, which for much of the town is defined by runoff flooding zones. This situation creates reduced capacity for adjustment to changes in flood hazard, which may occur due to channel dynamics, climate variability or occupation of the flood fringe. Consequently, following the principles of the *Better Urban Water Management*

Plan (WAPC 2008b) it is recommended that development planning within Karratha is supported by a flood hazard adaptation study (Section 6.1.6). The study rationale should consider economic value, identifying where carefully selected development exclusion zones may allow cost-effective flood hazard mitigation rather than intensive engineering solutions.

The coastal dune barrier at Karratha provides primary protection to the town site against coastal flooding, particularly by limiting wave action. Evaluation of sea level rise and extreme tropical cyclone impacts suggested that the barriers may be eroded or breached in the future (JDA *et al*. 2011b Attachment 3), although it was recognised that the presence of rock within the barrier may significantly ameliorate the threat. A detailed stability assessment for the coastal barrier is recommended, incorporating geophysical and geotechnical measurement of the dunes. Due to the high level of uncertainty associated with projected change, the stability assessment should identify a monitoring program, triggers for management and opportunities for strengthening the barrier system.

6.4. PORT HEDLAND

The Area of Planning Interest is focussed on the Port Hedland townsite, port and industrial areas, in the east Pilbara. The area was originally established due to its value as a port and for this same reason it has continued to act as a focal hub for regional development. Access to port waters has necessitated infrastructure transit across and construction upon the surrounding low-lying floodplain. Extensive modification of the local morphology has been undertaken through dredging, reclamation and barrier construction. This highly manipulated situation provides a development legacy that demonstrates varying approaches to risk avoidance or acceptance.

Port Hedland is nestled within a small catchment area between the much larger cathments of the Turner and de Grey Rivers. Its coast is rocky, comprised of discontinuous lithified coastal barriers, which variously act to capture and direct coastal sediment movements. The combined effect of catchment size and coastal barriers has constrained sediment availability locally at Port Hedland, allowing evolution of the extensive natural harbour. The harbour formation and maintenance of a deep entrance channel is supported by the high, 9m astronomical, tidal range.

Port Hedland Harbour is the largest of a series of tidal creeks and tidal estuaries between the Yule and de Grey Rivers that have formed along the coastal floodplain. The plain is confined at its seaward limit by a lithified former shoreline, with several further previous shorelines present offshore, defining ridges across the shelf. Breaks in the coastal ridge provide both opportunity for tidal creek systems and pathways for fluvial runoff, and often switch in such roles. The resulting constrained release for floodwaters and associated sediments has produced capacity for extensive channel avulsion, with breakout flows to adjacent catchments typical for many of the river systems. The resulting floodplain mobility to the west (Yule and Turner Rivers) and the east (de Grey River) has provided terrestrial constraints to the development of Port Hedland and its access.

The landform analysis completed for the Pilbara identified the Port Hedland area as one tertiary compartment (Figure 1-1) with four tertiary sediment cells based on distinct variations in the geomorphic character (Figure 6-45):

1. Islands - Tertiary Cell 19 from Downes Island to Finucane;
2. Hedland Harbour – Tertiary Cell 20 from Finucane to Spoil Bank W, including Wedgefield and South Hedland;
3. Old Hedland –Tertiary Cell 21 from Spoil Bank W to Cooke Point; and
4. Beebingarra – Tertiary Cell 22 from Cooke Point to Petermarer Creek.

Rock controls, tidal creeks and the spoil bank define the boundaries of the sediment cells. These boundaries are permeable to sediment transport (i.e. the cells are not closed), with significant variation of cross-shore and alongshore sediment exchange between ambient and tropical-cylone affected conditions. However, the boundaries are indicative of constriction points of focal sediment transport pathways. These pathways are indicated by the presence of sand ribbons, splays and bars, interacting with the underlying rock framework.

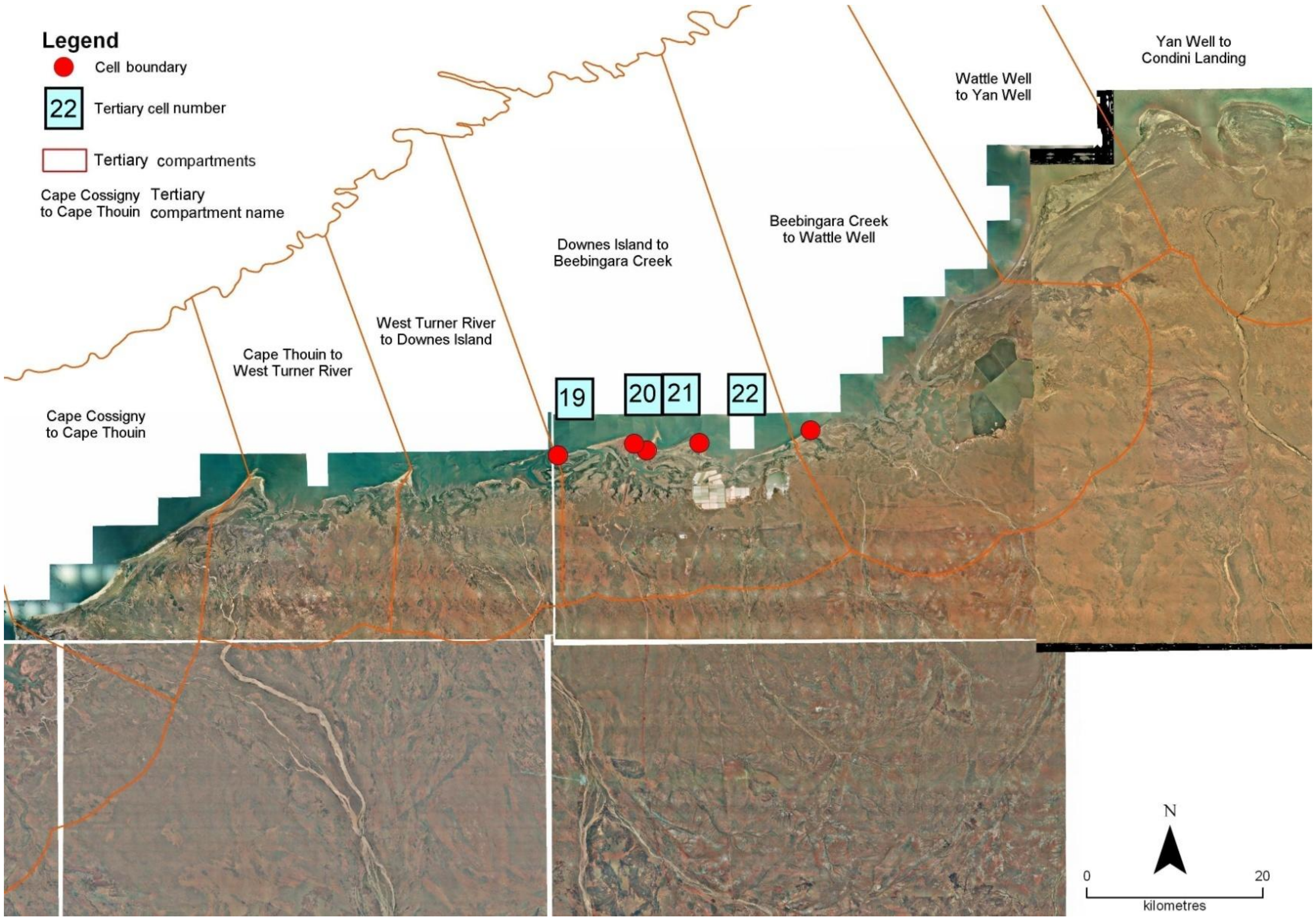


Figure 6-45: Port Hedland Tertiary Sediment Cells (Cells 19-22)