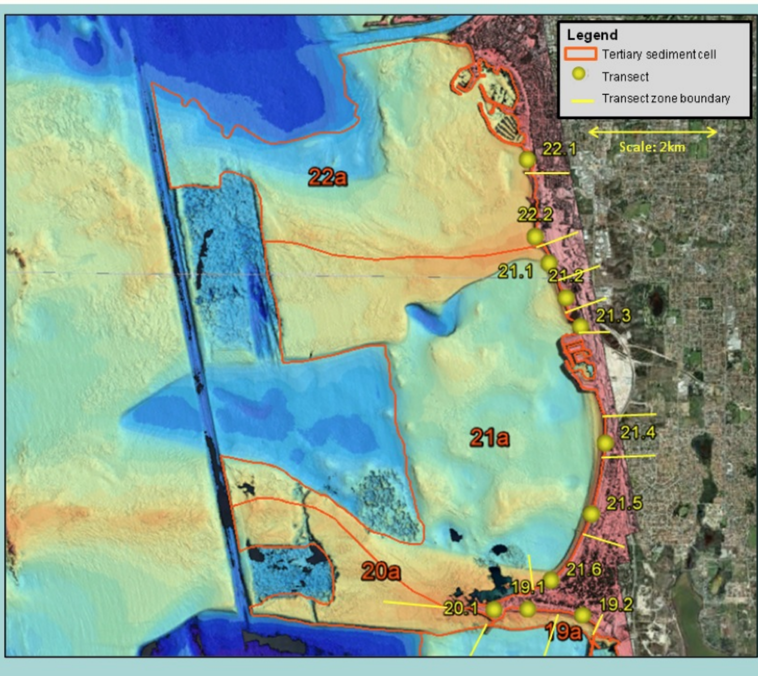
Cockburn Sound Coastal Alliance

Coastal Vulnerability Study

Erosion and inundation hazard assessment report

March 2013



coastal zone management pty ltd

THE UNIVERSITY OF WESTERN AUSTRALIA

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Executive Summary

This report summarises the outcomes of a coastal vulnerability assessment undertaken for Cockburn Sound, Owen Anchorage and the east coast of Garden Island (The OACS coast)[1], commissioned by the Cockburn Sound Coastal Alliance[2] and undertaken by a specially assembled consortium of Coastal Zone Management Pty Ltd, the UWA School of Environmental Systems Engineering, Damara WA Pty Ltd and Oceanica Consulting Pty Ltd.

This vulnerability assessment focuses on potential impacts on the OACS coast from climate change and associated sea level rise. The work undertaken has involved the stages of:

- Project Scoping
- Inundation Hazard Representation; and
- Erosion Hazard Representation

Outputs of this coastal vulnerability assessment will inform a subsequent values and risk assessment for coastal assets at threat from these coastal processes, followed by the development of adaptation strategies for informed coastal planning and management cognizant of these risks[3].

PROJECT SCOPING (REPORT SECTION 2)

Data Acquisition (Report Section 2.1)

The project scoping undertaken has built on the coastal data and information inventory previously prepared in 2009[4],[5] establishing the availability of any additional pertinent information. Key additional datasets have been identified and subsequently used, including Laser Airborne Depth Sounder (LADS) and Light Detection and Ranging (LIDAR) datasets collected by Department of Planning and the Department of Water. These datasets provided accurate ground levels and ocean floor depths in the vicinity of the coastline.

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[1] See Figure 1 and 2 in body of main report. The study area extends from the Garden Island causeway in the South to Fremantle Harbour in the North and includes the east coast of Garden Island

[2] City of Cockburn; City of Rockingham, Town of Kwinana, Department of Defence, City of Fremantle, Cockburn Sound Management Council.

[3] Phase 2 of the Cockburn Alliance Coastal Vulnerability Study

[4] Consultancy commissioned by the City of Cockburn, City of Fremantle, Town of Kwinana, City of Rockingham, Cockburn Sound Management Council and Department of Defence (Royal Australian Navy) to produce a Study Brief for a project to assess coastal vulnerability in Cockburn Sound and the Owen Anchorage.

[5] The stakeholder engagement process is summarised in Appendix 1 along with an exert of the updated inventory. Appendices 4 and 5 contain details of useful datasets.

Climate Change Projections (Report Section 2.2)

Climate change scenarios and projection time frames were reviewed and identified[6] with the timeframes selected being present day, 2070 and 2110, which are consistent with the West Australian State Planning Policy (SPP 2.6). Also selected were the associated sea level rises for these timeframes of 0m, 0.5m and 0.9m respectively. Additionally, a sea level rise of 1.5m at Year 2110 was also adopted to determine high-end (worst case) sensitivity.

EXISTING COASTAL DYNAMICS (REPORT SECTION 3)

The Physical Process Assessment[7] has been undertaken to determine and report on wind, wave, water level conditions, sediment dynamics and variability relevant to the study area, together with consideration of the impact of coastal structures on sediment dynamics along the coastline **(Section 3.1-3.6)**.

The OACS coast is a sheltered, relatively low energy and highly modified coastal system with distinct and variable beach morphology (both alongshore and offshore). It is partitioned by geological coastal structures as well as Fremantle Harbours, Catherine Point groyne, Woodman Point groyne and Garden Island causeway.

The coast is presently accreting (building up) slowly through a sand supply-distribution pattern that feeds marine sediment onshore at Success and Challenger banks, and which is then transported alongshore through waves and currents. This situation has enabled moderately effective use of coastal protection structures, which act to control the areas receiving sand supply. This control has been particularly effective in the areas closest to the source of sediment, albeit by reducing the supply of sediment to downdrift areas, which includes South Beach Fremantle, and Coogee Beach.

Evaluation of available beach profiles has indicated that some structures, particularly smaller ones, produce shoreline changes that whilst functional for amenity, have only cosmetic effect on overall coastal evolution.

To facilitate the modelling and spatial interpretation, the sediment cells framework mapped by Stul *et al.* (2012) was adopted to separate the coast into sections that exhibit similar processes and morphology, giving eight mainland and three Garden Island segments. The Physical Process Assessment assisted to inform the approach taken to evaluate coastal hazards.

[6] A discussion on climate change scenarios is provided in the ***Set the Context Report*** available in Appendix 2 and summarised in Section 2.1 of this report.
[7] A Physical Process Assessment Report was produced as an interim Project Deliverable (See accompanying DVD Appendix 3 for full report with a summary of key findings provided in Section 3)

HAZARD ASSESSMENT METHODOLOGY (REPORT SECTION 4)

The approach to the hazard assessment was to use physical observations, as much as possible, to validate the projected coastal change dynamics. This was because observed coastal morphology, including the extensive coastline modification, suggested that active coastal processes are at the edge of valid domains for analytic, empirical and numerical coastal modelling. The inundation and erosion hazards have been dealt with separately, each dealt with as follows:

Assessing Inundation Hazard

Inundation hazard was considered using a 'bathtub' approach due to the relatively small extent of flooding (geographically and vertically) that would arise on this coastline on account of wave setup and runup **(Section 4.1).** Work undertaken to complete the inundation hazard assessment involved the following steps:

1. Mapping and analysis of the existing coastal topography;
2. Analysis of existing water level datasets, including with the expected influence of storm events of 1 year, 10 year, 100 year and 500 year Annual Recurrence Interval (ARI) intensity;
3. Addition of projected sea levels for the specified climate change scenarios of 0.5m @ Year 2070, 0.9m @ Year 2110 and 1.5m @ Year 2110; and
4. Application of inundation levels to high resolution topography for presentation in a series of interactive maps

Assessing Erosion Hazard

Potential erosion hazard was determined through a combination of several different processes at multiple scales **(Section 4.2).**

Specifically this has included considering the anticipated change in sediment availability at varying spatial scales and considering local controls such as coastal structures. The approach to the analysis may be summarised as follows:

1. Assessment of potential short-term erosion associated with normal coastal processes and various intensity potential storm events;
2. Assessment of gradual changes in shoreline position arising from both sea level rise (SLR) and storm occurrences, including through evaluation of the amount of sediment removed from the shore arising from these events and processes; and
3. This has enabled a projection of the landward retreat of the shoreline (erosion) within each section of the coast.

This information was used as the basis for establishing erosion hazard lines for each scenario considered in the study (Discussed in Section 6).

INUNDATION HAZARD REPRESENTATION (SECTION 5)

The key output of the inundation hazard assessment is an interactive, layered electronic mapping product (Appendix 7). This mapping tool allows the user to view the areas of the coast likely to be impacted by inundation for 1 year, 10 year, 100 year and 500 year Annual Recurrence Interval (ARI) storm event scenarios coupled with various (present, 0.5m, 0.9m and 1.5m) Sea Level Rise (SLR) scenarios.

Inundation is not expected for much of the coast within the study area due to coastal dunes or topography higher than a 1.5 metre SLR 500 year ARI storm event scenario, even after allowing for erosion. The inundation areas will increase with sea level, but still comprise a smaller area than that identified as potentially affected by coastal erosion.

Under present day conditions, there are a number of areas along the coastline susceptible to coastal flooding due to the local topography, including where the dunes are naturally low or have been removed. These areas with a high present-day inundation risk are:

- Reclaimed land and the three harbours of Fremantle (Cell 22 in City of Fremantle);
- Woodman Point and small areas of Australian Maritime Complex (Cells 18-21 in City of Cockburn); and
- Southern Cockburn Sound including large areas of Rockingham (Cells 15-16 in Town of Rockingham.

Three further areas where inundation will become an issue in the future (in addition to those currently susceptible to inundation) are in Cells 17 and 18 within the City of Kwinana's boundaries, being:

- James Point (+0.5m SLR 100yr ARI);
- BP Australia (+1.5m SLR 100yr ARI); and
- Verve Energy (+1.5m SLR 100yr ARI).

EROSION HAZARD REPRESENTATION (SECTION 6)

Coastal erosion hazards are also presented graphically, in the form of a series of lines that represent a horizontal distance of expected shoreline recession for a range of sea level rise and storm event scenarios. These horizontal distances have been derived through a consideration of anticipated coastal response to present and future erosive pressures. They provide an indication of the relative sensitivity of the shoreline to erosion if no particular coastal management is employed in response to projected occurrences (SLR and storm events).

The seven erosion scenarios are presented in GIS format as lines buffered landward of a baseline of the +1m Australian Height Datum (AHD) contour, provided along with the erosion distance values at the points where they were calculated.

Areas where existing acute erosion hazard threatens infrastructure include:

- Garden Island north of Colpoys Point (Cell GI1b in the jurisdiction of the Department of Defence),
- Palm Beach (Cell 16 in City of Rockingham); and
- Kwinana Bulk Terminal (Transects 18.3 and 18.4 in Cell 18 in the City of Kwinana).

Areas presently experiencing gradual recession due to coastal processes are:

- North of Catherine Point (Cell 22 in the City of Fremantle and City of Cockburn);
- Woodman Point area (Cells 19-21 in the City of Cockburn); and the
- Kwinana Industrial Area to James Point (Cell18 in the City of Kwinana).

Changes to the areas experiencing recession are likely to occur through several different mechanisms, including sea level rise contributing to decrease or cessation of onshore sediment supply, geometric response of the coast (due to shifting the hydraulic zone), and increased exposure of rock.

The study has concluded that the onshore feed of sediment may be insufficient to keep up with these changes by the year 2070. Additional locations that the modelling indicates will experience recession, unless suitably managed, are:

- South of Catherine Point groyne (Cell 21 in the City of Cockburn);
- James Point and Kwinana Industrial Area (Cells 17 and 18 in the City of Kwinana);
- South end of Garden Island (Cell GI2a in the jurisdiction of the Department of Defence);
- South Beach, potentially enhanced by partitioning of the coast (Cell 22 in the City of Fremantle and City of Cockburn); and
- The cliff line of the Spearwood Ridge (which will extend south to Challenger Beach as the coast erodes) (Cell 18 in the City of Kwinana)

In addition, the coast is likely to experience a significant change in behaviour between 2070 and 2110 for the projected sea level rise. Within this timeframe, the loss due to profile adjustment arising from sea level rise coupled with normal storm events will begin to exceed the sediment supply onto the coast, resulting in net erosion. Structures that hold sediment will preferentially recover from storm erosion, at the expense of unprotected areas, which will be progressively eroded, with limited or no recovery after storms. In such a situation, protection of one section of coast will more clearly be at the expense of the adjacent unprotected coast.

CONCLUSIONS AND RECOMMENDATIONS (SECTION 7)

Modeling of beach profile change in response to sea level change has suggested that there is an average retreat of 5m per 0.1m of sea level rise. However, this response is highly variable, determined by the relative ease with which sand can be transferred between and within the resulting coastal segments.

The present sand supply-distribution pattern is likely to change through either decline of sediment feeds or heightened demand from the beach and coastal flats to adjust to higher sea levels. In general, this will result in increased erosion towards the downdrift end of coastal segments. However, where there is potential for higher alongshore sand transport, erosion may be enhanced on the updrift side, with the southern side of Catherine Point most likely to be affected. The capacity for such reversal, along with a relatively small sand supply to balance sea level rise, provides opportunity for significant changes in coastal behavior that will require a change in coastal management approach, projected to be required prior to 2070 using the study scenarios. A more holistic approach within coastal segments is likely to be required.

Evidence used to estimate projected future change is not compelling, and there is uncertainty associated with estimates of sand supply, alongshore transport and the pathways of coastal response to sea level rise. As a consequence, it is appropriate to apply an adaptive framework to coastal management within the OACS region. Key questions that may need to be evaluated through monitoring include: the effectiveness of alongshore sand transfers and post-storm recovery; the role of existing and artificially created sediment sinks; and the relative contributions of coastal terraces and dunes to change.

Seabed (profile) changes appear to provide a better indication of gradual evolution than shoreline or vegetation line, which are more responsive to short-term erosion and recovery. Consequently, it is recommended that management triggers for the OACS coast should be related to the historic and present profile monitoring program that has been applied to varying degrees along the OACS coast. For effective assessment, profiles should occasionally, say every five years, extend offshore past the seaward toe of the terrace. The existing Cockburn Cement and Port Coogee profiles would be sufficient for Owen Anchorage. Funding should be secured for a resurvey of the Cockburn Sound profiles last measured in September 2003.

The near shore terrace behaviour and response could be investigated using these profile datasets and comparison of historic bathymetric datasets. For example, the reasonably detailed 1944 bathymetry could be digitised and compared to more recent digital bathymetry from the 1980s and the 2009 LiDAR to determine longer-term trends in the terrace structures. The profile datasets would be used to detect shorter-term trends and fluctuations. A further recommendation of this study is the consideration of erosion projections to evaluate the likely ongoing presence of beaches around the OACS coast. While the present study evaluated erosion hazard as sediment demand landward of the +1m AHD contour only, a significant value at risk of erosion at the OACS coast is the presence of a beach for amenity and recreation. Further investigation of potential loss of beach width could be used as a proxy for this purpose.

Numerical wave models have limited capacity for calibration to capture the correct process-response relationships without measured wave data at multiple locations. This study identified that numerous wave measurements have been made, but these were not made available for the project. It is recommended that improved data sharing agreements be sought with private industry. In the future, the ability to interpret change and achieve greater consensus between coastal interest groups through a greater knowledge-base for the OACS coast would require long-term deployment of several wave instruments within Cockburn Sound.

Potential changes to sediment transport caused by sea-level change are further complicated by the unknown future modification of the coast by engineering works. Therefore, it is important that a holistic approach to coastal management be developed, with suitable triggers set to indicate a need to change management.

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1. Introduction

This document describes a climate change vulnerability assessment for the coastal zone of Cockburn Sound (including the Eastern coast of Garden Island) and Owen Anchorage (Figure 1 & 2). For the purposes of this Report this area will be referred to as the Owen Anchorage & Cockburn Sound Coast (OACS coast).

The hazard assessment is the first phase of the Cockburn Sound Coastal Vulnerability and Adaptation Pathways Program initiated by the Cockburn Sound Coastal Alliance (CSCA). The Alliance is comprised of the Cities of Cockburn, Fremantle and Rockingham, the City of Kwinana, the Department of Defence (Defence Support and Reform Group) and the Cockburn Sound Management Council (CSMC). The envisaged four-phase adaptation pathways project is programmed to be completed in the coming 2 to 3 years with the output of Phase 1, the present hazard assessment, to support Phase 2. The work scheduled for Phase 2 will include a valuation of coastal assets along the OACS coast, assessment of their relative risk to climate change impacts and formulation of a series of Coastal Hazard Risk Management and Adaptation Plan(s).

Phase 1 activities have been undertaken between June 2012 and January 2013 by Coastal Zone Management (CZM) Pty Ltd, the School of Environmental Systems Engineering University of Western Australia (SESE), Damara WA Pty Ltd and Oceanica Consulting Pty Ltd (the Project Team). This report largely deals with erosion and inundation assessment outcomes derived through Phase 1 works of the wider CSCA Project. It may be viewed, in conjunction with the range of interim deliverables and reports produced throughout the life of Phase 1 activities[8] (See Section 1.4 below).

1.1 MOTIVATION

The OACS coast has a long history as a sheltered anchorage and port. Population growth and industrial expansion within the area has increased dramatically in recent years resulting in increased potential impacts within the coastal zone. In particular, the future threat of greenhouse-gas induced climate change and associated sea level rise mean that the coastal zone is likely to be subject to a long-term progressive erosion trend, adding to the threat presented by historic episodes of erosion and inundation. In order for these impacts to be mitigated, it is vital to establish which areas are likely to be affected and what form likely impacts will take.

[8] This report provides summaries of interim deliverables and their key outcomes where appropriate throughout the text. This information is intended to provide a basis for understanding the overall project context and should be supplemented with more detailed information in the discrete accompanying reports themselves where required. All reports, data sets and supplementary information produced through the life of Phase 1 activities is provided in the DVD that accompanies this report – See Table 2 for list of supporting resources.

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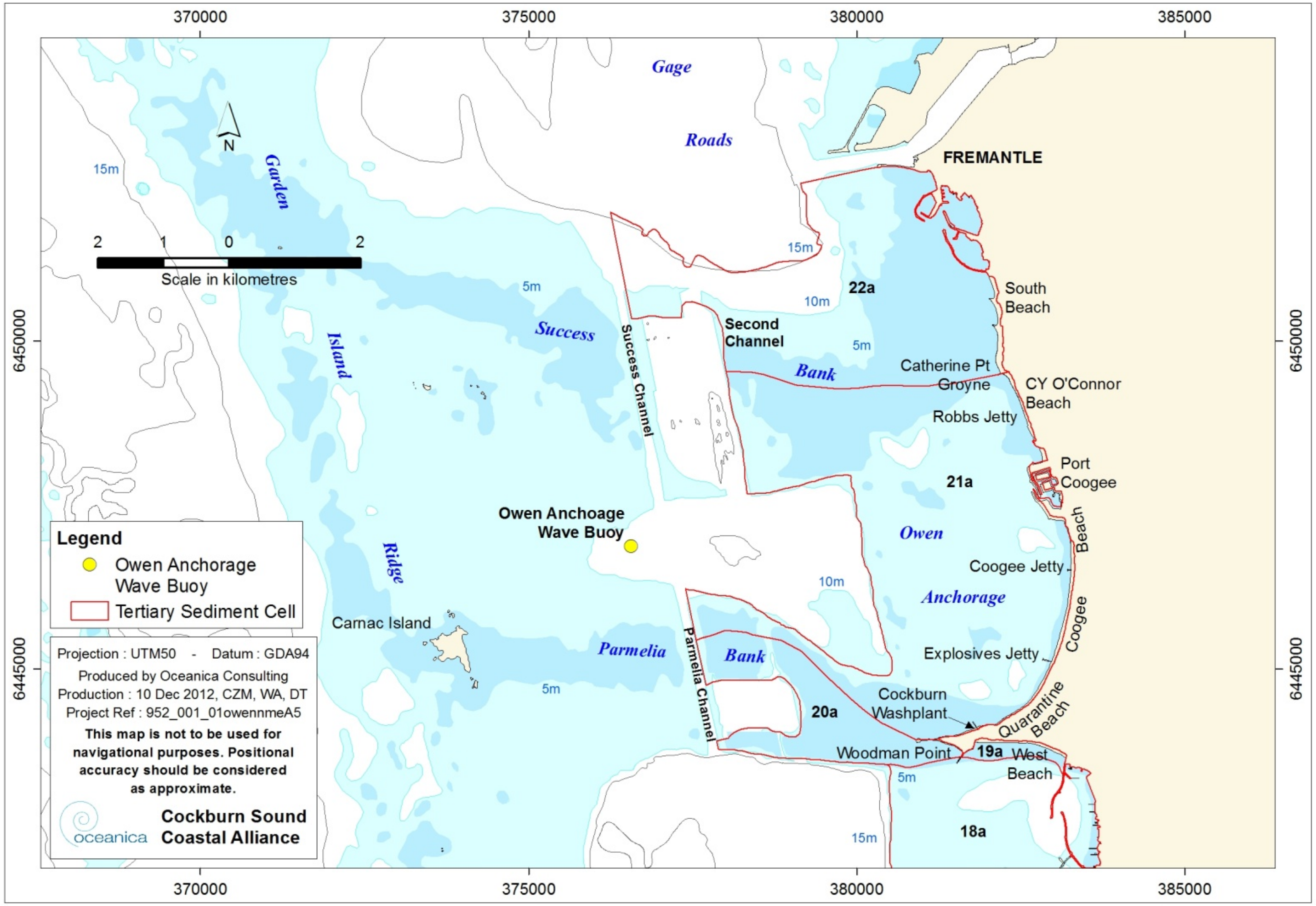

Figure 1: Northern Reaches of OACS coast, Owen Anchorage

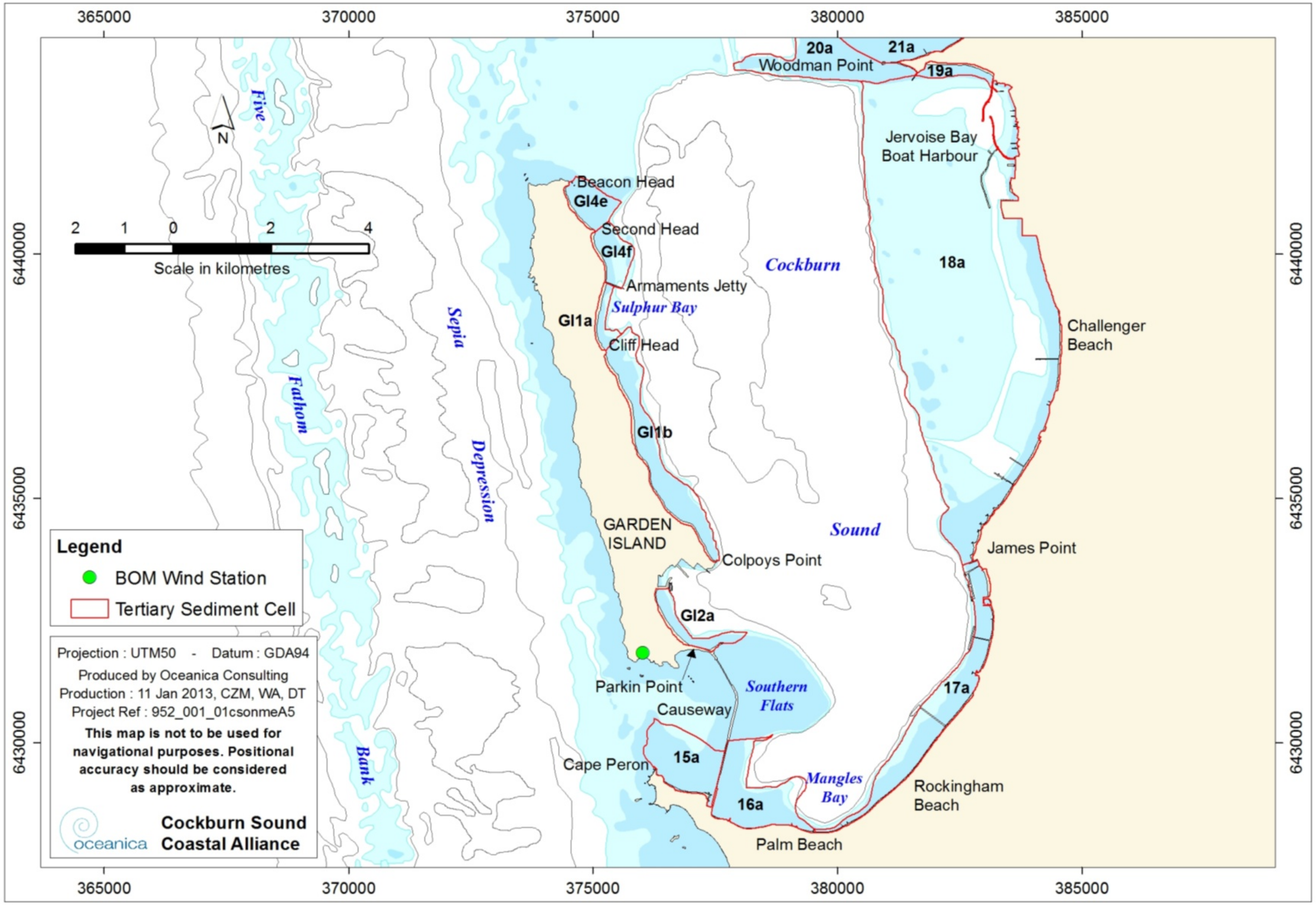

Figure 2: Southern Reaches of OACS coast, Cockburn Sound & East Coast Garden Island

Four local government areas have jurisdiction along the OACS coast (City of Cockburn, City of Fremantle, City of Rockingham & City of Kwinana) with the Garden Island Coastal area managed by Department of Defence (Royal Australian Navy). Key stakeholders from each of these organisations have formed an alliance along with the Cockburn Sound Management Council to facilitate cooperation and coordination with respect to their common interest in sustainable management and development across their shared OACS coast.

This Alliance (Cockburn Sound Coastal Alliance or CSCA) presently regulate development within their coastal zone considering associated risks from coastal erosion and inundation. This largely occurs as a component of Town Planning Schemes, which are required to conform to relevant State Planning Policies. The Royal Australian Navy also manage their assets with an awareness of shoreline change and water level fluctuations within their environmental sustainability programs and are presently involved in planning strategies that address environmental concerns.

Collectively, the CSCA are responsible for extensive coastal infrastructure such as coastal protection, buildings, recreational facilities, recreational areas and coastal roads. These infrastructure resources, and those of other government agencies and private interests fronting the coast, are at the front line in terms of coastal erosion and inundation risk (e.g. Figure 3). Their effective management, both now and in the future, requires an understanding of the exposure and sensitivity of the surrounding coastline to the potential impacts of natural variability and climate-induced change.

Figure 3: Rockingham Foreshore Storm Damage, May 2003

The stakeholders of the Cockburn Sound Coastal Alliance clearly recognise this issue and have commissioned this study with a strong desire to take strategic, proactive action in terms of assessing possible coastal risks, on behalf of themselves and other stakeholders with interests in the built and natural assets along the coast.

1.2 APPROACH

There were three key components undertaken during Phase 1 of the CSCA Coastal Vulnerability Project as per the accepted Proposal for Services:

- Project Scoping
- Inundation Hazard Representation; and
- Erosion Hazard Representation

The method adopted by the Project Team to deliver these three components was couched in an 'evidence based' approach to analysis. This involves the use of available data and information to determine an understanding of historic and contemporary coastal behaviour. This understanding then forms the basis of projections for likely change in coastal behaviour into the future under the effects of a changing climate. Importantly, due to the partitioned nature of the OACS coast (discussed further in Section 3 below), careful conceptual interpretation of available evidence with respect to coastal signals is required.

1.3 REPORT STRUCTURE

The Project was designed to provide iterative outputs to allow communication with the client and key stakeholders throughout the assessment process. The reports produced through this process are provided as appendices to this document and should be considered as an important supplementary resource. In this respect, this document is intended to provide a brief summary of the approach adopted by the Project team to deliver the requested work with a focus on presentation of the erosion and inundation assessment outcomes.

Table 1 provides an overview of the structure of this report and aligns each of the key work components to relevant supplementary documentation and Project deliverables where appropriate.

1.4 HOW TO USE THIS REPORT

The information in this report requires interpretation with acknowledgement of its limitations to inform effective decision making. Mapping that has been generated should be used as a tool to assist strategic decision making and specifically to inform assessment through Phase 2 of this study as opposed to a basis for development approvals.

Inundation mapping represents inundation hazard from sustained high water level events for the topography measured in 2008. It excludes local wave setup and runup which would generate higher short-term water levels. The maps and inundation values should not be used in design of coastal structures, determination of finished floor levels or consideration of overtopping or overwash hazard. Use of the inundation assessment outputs in this fashion would require the addition of further water level components to the reported inundation values if they are to be used for such purposes.

Erosion mapping represents an indication of the relative sensitivity to erosion, noting that coastal management structures alter the mapped coastal response. The erosion hazard lines are comprised of acute and progressive components. Acute erosion allowance has been estimated by considering scenarios for cross-shore and alongshore sediment transport. The progressive erosion allowance is representative of the sediment demand caused by sea level rise (varying alongshore) converted to a representative horizontal distance. Any management of the coast within the cell should be accounted for by altering adjacent erosion line distances. Erosion lines may be adjusted for existing or potential future coastal structures, with consideration of the rock and structural controls applicable at the relevant scale. Erosion maps and values should not be used as a decision-making tool (e.g. for setback definition) without consideration of active management, to avoid a cascade of adverse impacts that may be brought about by actions of independently managed sites.

Table 1: Components of this Report

Report Section	Title	Key Elements	Associated Deliverables
2	Project Scoping	Data inventory and information gathering (**Section 2.1**) Set baselines, define key terms and attributes for use in ongoing assessment (**Section 2.2**)	**Project Initiation Document** – Outlines stakeholder engagement process, data inventory and information gathering tasks undertaken and **Set the Context Report** – Provides and overview of climate change scenarios used in the present study as well as the consideration of pertinent model assumptions
3	Existing Coastal Dynamics	1: Geology (**Section 3.1**) 2: Geomorphology (**Section 3.2**) 3: Engineered Controls (**Section 3.3**) 4: Water Levels (**Section 3.4)** 5: Wind & Waves (**Section 3.5**) 6: Coastal Change (**Section 3.6**) 7: Definition of coastal segments for use in analysis (**Section 3.7**)	**Physical Process Assessment Report –** Summarises the present behaviour of the coastal system to inform interpretation of future change under rising sea levels
4	Methodology	Outlines approach and methodology adopted to hazard analysis and specifies the methods employed in	**N/A**

		assessment of inundation **(Section 4.2)** and erosion hazard **(Section 4.3)**	
5	Inundation Hazard	Application of inundation levels to the high resolution DEM LIDAR to determine areas that will be inundated with a direct connection to the coast (**Section 5**)	**Series of inundation hazard maps provided as interactive PDFs accompanying this report -** 1 map for each of the 1 year, 10 year, 100 year and 500 year ARI events. Each map has 4 layers representing sea level rise scenarios for present day, +0.5, +0.9, and +1.5m. The future scenarios correspond to timeframes of 2070, 2110 and a high end sensitivity for 2110.
6	Erosion Hazard	Evaluation of combined volumetric contributions to shoreline retreat to calculate horizontal distance of erosion per sediment cell (**Section 6)**	**Series of erosion hazard maps provided as interactive PDFs accompanying this report** 1 map incorporating lines buffered landward of a 1mAHD contour to represent a sediment demand. The map has four main layers with scenarios of present day acute erosion, and long-term response for 2070, 2110 and a high end sensitivity for 2110 (2110+). Three additional layers represent the 2070, 2110 and 2110+ long term response with added buffer for acute storm response.
7	Conclusions and & Recommend-ations	Recommends further actions for the Cockburn Alliance in terms of monitoring and evaluation as well as activities to supplement the use of the present outputs in subsequent work phases of the proposed Cockburn Alliance Coastal Climate Change Risk Assessment.	

2. Project Scoping

The main focus of the Project Scoping Phase was production of an updated coastal data and information inventory for the OACS coast. This involved engagement with key stakeholders to establish what additional information was available to supplement a previous inventory produced as part of a study undertaken in 2009[9]. The stakeholder engagement process is summarised in Appendix 1 along with an exert of the updated inventory. This should be updated as and when new information is available or additional feedback is gained from stakeholders. A summary of key datasets and their application in this study is provided in Section 2.1 and Appendix 4.

2.1 DATA AND INFORMATION

The history of human occupancy, industry and development within Cockburn Sound and Owen Anchorage, particularly the construction of the Garden Island Causeway in the early 1970's, has resulted in the existence of a wealth of coastal process information relating to the area (relevant exert provided in Table 2)

This is particularly advantageous when attempting to understand the behaviour of a complex environmental system through time in order to accurately predict likely behaviour into the future as a result of projected changes to coastal climate.

The coastal data set for Cockburn Sound and the Owen Anchorage is a rich resource unavailable for many other locations in the state and even continent of Australia. However, several gaps and limitations do exist. An overview of information gaps associated with key coastal attributes was summarized in the previous data inventory exercise commissioned by the Cockburn Alliance in 2009[10] (see Table 3 and Table 4)

The work undertaken by the Project Team through the present study addressed these information gaps wherever possible and added extra material to the data inventory. A review of all available information was undertaken to identify key resources (Table 2) and other supplementary information (Table 4) to deliver the key aims and objectives of the work reported on here.

[9] Consultancy commissioned by the City of Cockburn, City of Fremantle, City of Kwinana, City of Rockingham and Department of Defence (Royal Australian Navy) to produce a Study Brief for a project to assess coastal vulnerability in Cockburn Sound and the Owen Anchorage

[10] See the Cockburn Coastal Climate Change Study Brief, 2009 for further details

Table 2: Key Data & Information for OACS coast Erosion and Inundation Hazard Assessment

Bathymetry				
LADS	To 20m depth only.	5m x 5m grid	2009	Department of Planning
Map of soundings	Public Works Department OACS coast soundings	PWD 33486-11-03 Drawing	1944	Department of Transport
Topography (DEM)				
LiDAR	Excludes Garden Island	1m x 1m grid	2007-2008	Department of Water
Beach profiles				
Owen Anchorage	Six monthly in spring and autumn. March 2003 profiles do not extend offshore	8 of 18 profiles co-located with transects. 500-600m since 2006 (see Appendix)	1988-Present. (3/2003 & 9/2003)	Cockburn Cement Limited/ Oceanica (2010a)
Cockburn Sound and Garden Island	60 profiles include historic information with 11 profiles added for 2003 including marine surveys	14 of 71 profiles co-located with transects – depth of 4m or 300m[11]	1974-1990. 3/2003 & 9/2003	Department of Defence/Department of Transport/ Travers (2007)/DALSE (2003)
Extracted profiles	Profiles extracted from LADS/LiDAR at the 35 transects and merged visually.	LADS at 5m intervals, LiDAR at 1m intervals – 4000-5000m from BM (150m landward of 0 AHD where possible)	2007-2009	Department of Planning/Department of Water
Sediment for beach response modelling				
Median grain size (D50)	Sediment size analyses conducted for prior analyses.	18 of 35 transects co-located with sediments	2005	Department of Planning/ MP Rogers & Associates (2005a), Stul (2005)
Coastal change and sediment transport rates				
Vegetation line mapping	Mapped changes in vegetation lines, presentation of results, determination of rates of change.		1942-2008	Department of Transport/Cockburn Cement Limited. Oceanica (2010a, b), MP Rogers & Associates (2005a, b), Oceanica et al. (2007), Department of Transport (2004, 2009)
Sediment transport rates	Sediment transport rates inferred from numerical modelling and vegetation line interpretation			Oceanica (2010a, b), MP Rogers & Associates (2005a, b), Oceanica et al. (2007), DoT (2004, 2009), Damara, Smith (2009), Hamilton (2011)

[11] Whichever came first was adopted – however, this should be adjusted to at least below of the terrace in future – see recommendations in Section 7.

Waves				
Offshore Regional	Rottnest (47) Station	32° 05' 39" S 115° 24' 28" E	1994-Present	Department of Transport
Local (non-directional)	Owen Anchorage (53) Station	32° 06' 28" S 115° 41' 30" E	26/02/08-Present	Department of Transport
Hindcast/Modelling	WW3			NOAA
Water levels				
Local	Fremantle tide gauge station	32° 03.9' S 115° 44.9' E	1959 - Present (Jun 2011)	Department of Transport. Eliot (2012)
Hindcast/Modelling	ACE-CRC			
Winds				
Local	Garden Island (HSF) (9256) station		2001-2010	Bureau of Meteorology
Coastal Regional	Swanbourne (9256) station		1993-2010	Bureau of Meteorology
Coastal Regional	Rottnest Is. (9193) station		1987-2010	Bureau of Meteorology
Modelling	NOAA NCEP			NOAA

An important lesson learnt throughout the subsequent project phases was that the approach used was not an efficient means to discover information. It is unclear whether this was caused by the information request being too broad in scope, whether contacted staff were inappropriate, or whether information storage and retrieval systems are inadequate. This failing was clearly demonstrated when a focused search for digital wind and wave data within Cockburn Sound was undertaken. Queries directed towards metocean and coastal engineering consultants revealed a large number of additional, albeit often short-term, data sets that have been collected to support proposals or developments in Cockburn Sound (Appendix 4). This approach effectively captures many of the privately held datasets, which are not otherwise recorded on regulatory or data custodian databases. Due to project brevity, analogue data sets were not sought, but it is considered likely that there is significant additional information available.

Table 3: Gaps in Existing Studies Identified in 2009 Data Inventory (CZM & Damara, 2009)

Attribute	Details	Gaps	Relevance to Present Study
Wave Climate	Previous studies include hindcasting; wave modeling using 2GWAVE and more recently SWAN	In general modeling has not adequately accounted for the local sea breeze and the importance of fetch restricted wind waves within the OACS coast. Need to balance modeling of swell wave components with more accurate understanding of wind wave climate	This remains an outstanding gap It was not possible to satisfactorily validate a local wind wave model using data available during this study. At the conclusion of this work, it has come to light that a number of important additional datasets that are privately held. It is recommended that CSCA directly access these datasets for use in future undertakings (See Appendix 5 for details)
Wind Climate	Original synoptic analyses by Steedman & Craig (1979) with storm assessment by Steedman & Associates (1982). Locally relevant work by MJE, assessing geographic variation	Previous studies are not directly relevant due to fact that much of data sets used were old, short lived and from inappropriate location to apply to OACS coast. Need to accurately analyse Garden Island wind record and recognize how sea breezes in the area may change with climate or apply a factor of uncertainty	Alongshore transport modeling was not successfully completed as a part of the present study. This was due to the fact that ambient climate modeling was not developed to a sufficiently accurate state to warrant manipulation /evaluation of sea breeze changes through the study area. It is recommended that future wind/wave modeling be revisited as per the comment above and the advice in Appendix 5[12]
Water Level	Useful studies for BP carried out by Eliot & Pattiaratchi (2007)	Need to modify existing studies to more adequately account for the seiche and local basin set up	This was undertaken in the current study by factoring of historic extreme distributions - Mangles Bay data was evaluated and did not demonstrate significant local variation.
Topography	Topography of land has been accurately surveyed & bathymetry has been established but two datasets are not seamlessly integrated	Recent LIDAR information should remove many of the previously encountered barriers in gaining accurate topographical information for a vulnerability assessment	LIDAR was used in the analysis to gain accurate topographical information. However, there remain some issues with the integration of the LIDAR and LADS datasets largely owing to the fact one a DEM and one a DTM. It is recommended that stitching of the datasets be further checked to maximize use of this information for future studies.
Geomophology	Recent work on Sediment Cells by DoP and coastal typology by WAGS	Need to use locally relevant compartments (as outlined in present study brief) as basis for high resolution hazard assessment presently under discussion	This was the fundamental basis of the work conducted through this study. That is, local physical characteristics formed the basis of locally relevant projected coastal change.
Geology	Broad geologic framework well described e.g Searle & Semeniuk 1985. Cockburn 1986 DAL 1998, Oceanica et al., 2008 – with additional	While broad geology is well described, local geologic control not well established or its influence on local coastal processes well understood.	The use of LIDAR and LADS in this study confirmed scale and size and nature of controls more clearly than was previously possible. Additionally, the work undertaken by Gozzard (2011) was useful. A combination of

[12] A comprehensive discussion on future requirements for modeling is provided in the Project Close Out Document submitted as an additional deliverable to this report. This document summarises the lessons learned by the Project Team through the conduct of the analysis undertaken and provides recommendations for future studies/works.

	information available through the Sediment Cell study by DoP		this information meant it was possible to determine more clearly where underlying geology would act as a long term control point. It is recommended that geotechnical investigations be undertaken for specific areas through the OACS coast where the extent of rock is particularly important. For example, the perched beach area at Coogee Beach; the cliff area near Challenger Beach; the platform at James Point.

Table 4: Additional Contextual Datasets/Information

Data	Details	Reference
Aerial photography	Landgate 2011, Historic landgate, Nearmap, GoogleEarth, WACoast (obliques)	Landgate, Nearmap, Google Earth, GSWA Gozzard (2011)
Landforms	Landform maps 3km from the shoreline	GSWA/Gozzard (2011)
Site photos	Photos from beaches in 2008. 2003 storm photos	GSWA/Gozzard (2011). Travers (2007)
Sediment Cells		Department of Transport/ Stul et al. (2012)
Rock locations	From site photos, aerial photography, navigation maps, geologic maps and LADS	Landgate, Searle & Semeniuk (1985), Chart, Gozzard (2011), LADS, Skene et al. (2005), Oceanica (2010a, b)
Engineering works	Details of structures, dredging and renourishment	Oceanica (2010a, b), MP Rogers & Associates (2005a), Oceanica et al. (2007), Damara & Shore Coastal (2009)
Prior storm response modelling	Storm response modelling along OACS coast (MP Rogers & Associates 2005) and in the Cockburn Coast (Oceanica et al. 2007)	MP Rogers & Associates (2005a), Oceanica et al. (2007)
Long-term change in seagrass	Mapping of seagrass change	Cambridge (1997), Cambridge & McComb (1984)

2.2 SCENARIOS AND TIMEFRAMES

During the scoping phase the most appropriate scenarios for climate change to be used in the study and timeframes for assessment were also considered. A discussion on climate change scenarios is provided in the ***Set the Context Report*** available in Appendix 2.

The selection of climate change scenarios has implications for both the timing and type of potential required management actions. Consequently, it is important that the selection of climate change scenarios is neither too mild nor severe. A simple example is suggested by response to sea level rise at Fremantle, where a rise less than 0.5m requires limited action, but a rise greater than 2.5m suggests extreme response, such as abandonment of sections of Fremantle or massive coastal defences. The influence of scenario selection is illustrated schematically by Figure 4, which suggests that increased severity will cause earlier and more extreme responses. Consequently, there is a role for the evaluation of mild scenarios, to provide the subtlety required for intermediate responses, or to identify sites likely to be affected earlier than others.

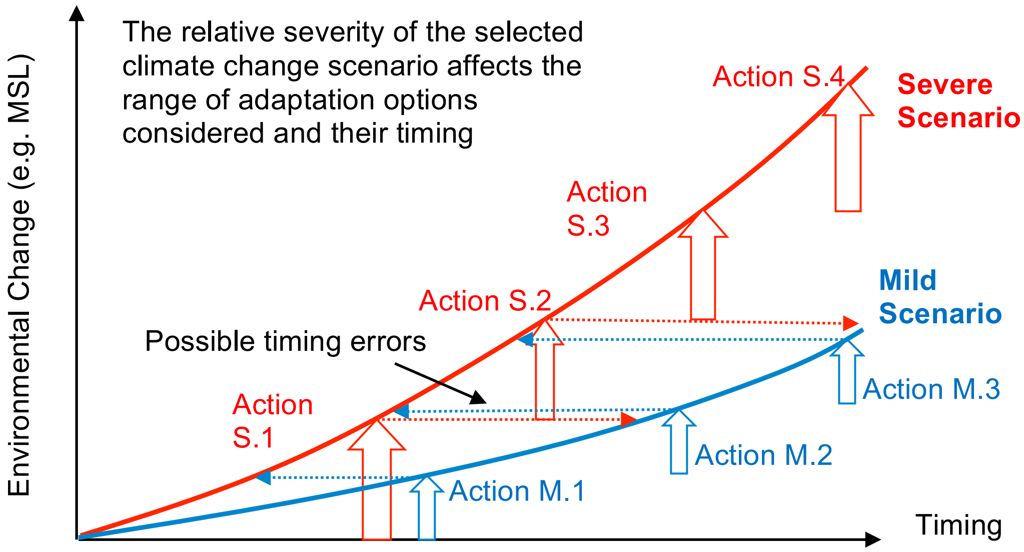

Figure 4: Effect of Scenario Selection upon identified Adaptation Sequence

Basic guidance for criteria selection is given by State Government natural hazard and coastal planning policies (WAPC 2003, 2006). These suggest consideration of extreme conditions (100 year average recurrence interval, ARI) over a 100 year planning time frame. However, different coastal hazards present different impacts when criteria are exceeded. Therefore application of uniform likelihood criteria presents the possibility of an unbalanced risk profile. For the present study, the implications of erosion threat are far more severe than those of inundation. This is simply illustrated through the marginal impact of both hazards on a house – erosion reaching the house will likely cause failure, whereas inundation causes damage, but generally more than 0.3m inundation is required to cause structural failure (Figure 5).

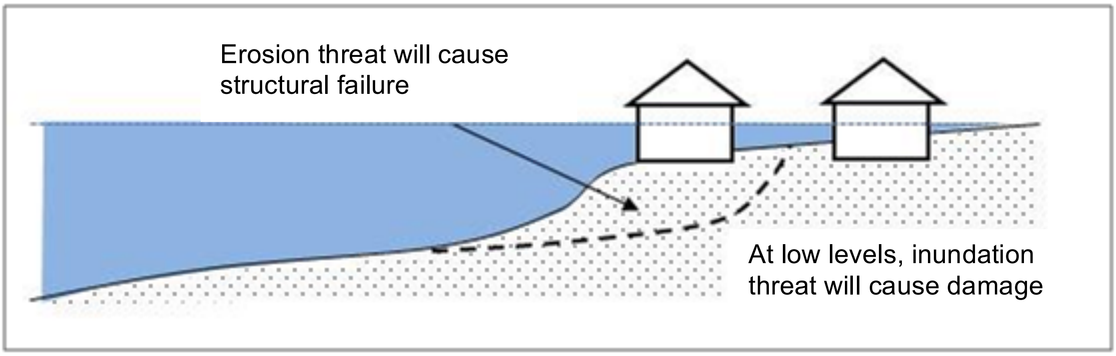

Figure 5: Schematic Illustration of Erosion and Inundation Threats

On consultation with the client liaison[13] it was confirmed that timeframes for consideration should be present day, 2070 and 2110 to be consistent with available projections and Western Australian State Coastal Planning Policy SPP 2.6. The associated sea level rise figures to be used for each of these timeframes were 0m, 0.5m and 0.9m respectively (Department of Transport 2010). It was also agreed that analysis would be carried out using a sea level rise of 1.5m to account for a high end sensitivity for 2110. Justification for this high end scenario came from considering the present status of climate science and a reflection on recent published work advocating use of a high end scenario when conducting vulnerability assessments:

The First Pass National Coastal Vulnerability Assessment (DCCEE, 2009) used a 'high end' scenario of 1.1m by 2100 that 'considers the possible high end risk identified in the IPCC AR4 and includes some new evidence on icesheet dynamics published since 2006 and after the AR4'. Further the report states (p. 27) that 'very recent research also suggests that a 1.1m scenario by the end of the century may not reflect the upper end of potential risk, and that risk assessments could be informed by a higher level". This conclusion was more recently echoed in the report entitled "America's Climate Choices: Panel on Advancing the Science of Climate Change, Board on Atmospheric Sciences and Climate, Division on Earth and Life Studies, NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES (2010) (Chapter 7: 7 Sea Level Rise and the Coastal Environment)". This report concluded: *"The 2007 IPCC projections are conservative and may underestimate future sea level rise because they do not include one of the two major processes contributing to sea level rise discussed in this chapter: significant changes in ice sheet dynamics (Rahmstorf, 2010).(p. 243-244)*

Indeed, the sea-level rise could be up to 1.6 m by 2100, as shown in the NAS report (Figure 6). As such, a significantly higher sea-level rise in the range of 1.4-1.6m by 2100 may be justified as a 'high end sensitivity assessment'.

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[13] Mr Doug Vickery from City of Cockburn acted as the liaison for the Cockburn Alliance throughout the Project.

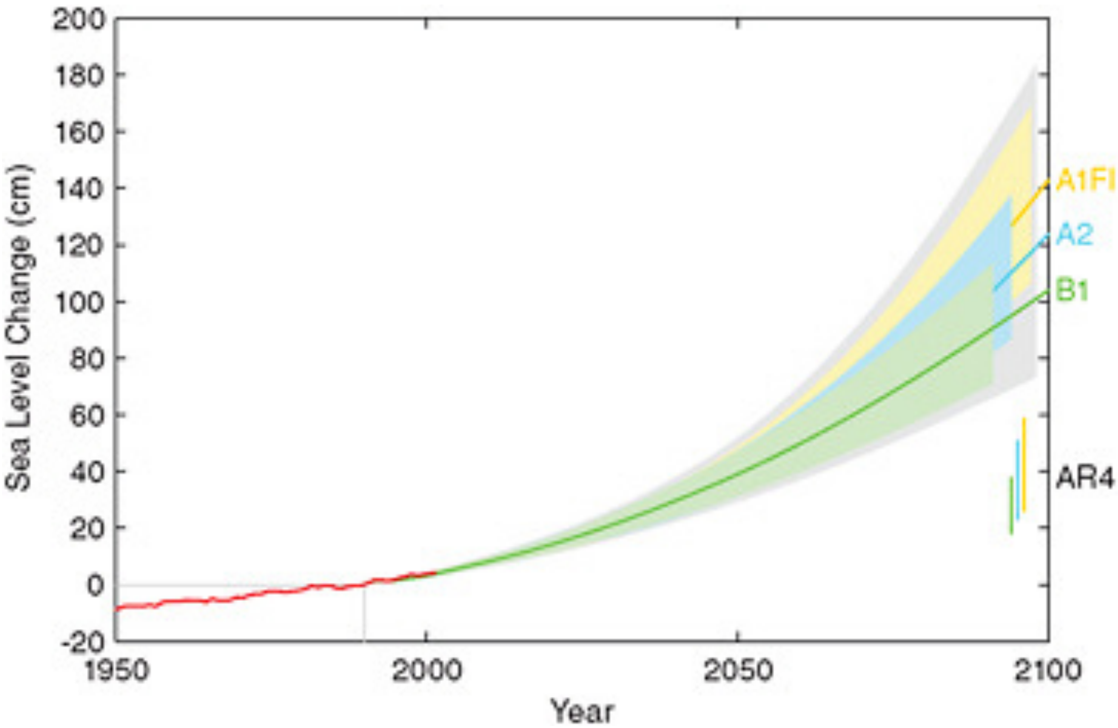

Figure 6*:* Projection of sea level rise from 1990 to 2100 (adapted from NAS, (2010)

Based on IPCC temperature projections for three different GHG emissions scenarios (pastel areas, labeled on right). The gray area represents additional uncertainty in the projections due to uncertainty in the fit between temperature rise and sea level rise. All of these projections are considerably larger than the sea level rise estimates for 2100 provided in IPCC AR4 (pastel vertical bars), which did not account for potential changes in ice sheet dynamics and are considered conservative. Also shown are the observations of annual global sea level rise over the past half century (red line), relative to 1990. SOURCE: Vermeer and Rahmstorf (2009)

3. Existing Coastal Dynamics in Cockburn Sound & Owen Anchorage

A Physical Process Assessment was undertaken to provide an understanding of the existing coastal system. This assessment addressed a number of key elements (listed below) with a view to elucidating an appropriate context for undertaking a coastal change assessment for the OACS coast:

- Geology & geomorphology
- Engineered controls
- Water levels
- Waves
- Coastal Change
- Compartments and cells for assessment

The assessment was largely based on a review of available literature and supplemented by recently available LIDAR and LADS data. It involved three main steps:

- Collate existing information on process and response elements of coastal system
- Evaluate pertinent information to describe present behaviour of the system
- Consider important attributes of the present functions to inform key considerations for erosion and inundation hazard assessment

A discussion pertaining to each of these elements may be found in the ***Physical Process Assessment Summary*** (Appendix 3). An overview of key physical characteristics of the OACS coast is provided in the sections that follow. Information has been drawn from the extensive existing information base for the OACS coast. The purpose of this summary is to provide a contextual backdrop for the inundation and erosion hazard assessment discussed in subsequent sections of this report rather than an exhaustive discussion on coastal process/response relationships which are discussed in more detail in subsequent report Sections .

3.1 GEOLOGIC FRAMEWORK

The geologic framework of the OACS coast has been described in detail by previous studies undertaken in Cockburn Sound and Owen Anchorage (Fairbridge 1950; France 1977; Playford et al. 1976; Searle & Semeniuk 1985; Cockburn 1986; Semeniuk & Searle 1987;

Searle et al. 1988; DAL 1998; Skene et al. 2005; Oceanica et al. 2008). A highly variable veneer of sedimentary features, including sand banks, sand sheets, perched beaches and terraces are draped over and interact with the geological framework. Broad geologic controls are illustrated in Figure 7a.

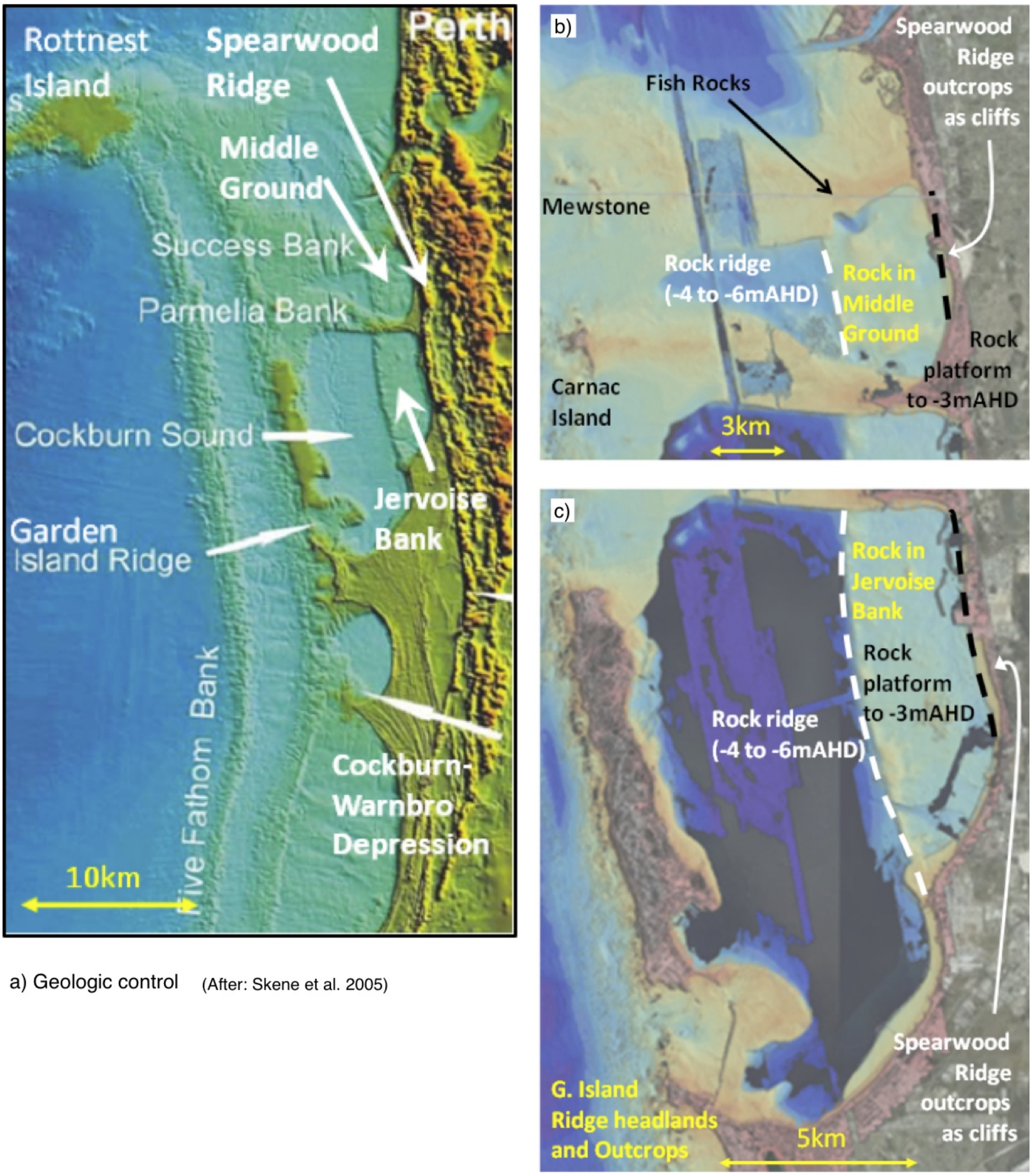

Figure 7: Overview of Key Geological Attributes of the OACS coast

From Figure 7a it is clear that the coastal system is characterised by a complex suite of submarine features which contribute to the partitioning of the coast. Figure 7b and 7c illustrate the widespread presence of rock and important bank controls within the OACS coast showing rock at multiple extents and elevations. The figure highlight outcropping of the Spearwood Ridge along the coastal plain, submerged ridges forming banks or island-reef chains, as well as the active sand feeds off Success and Parmelia Banks. The four significant rock ridges apparent along the OACS coast have each played different roles in affecting the supply and distribution of marine sediments to the OACS coast. The two outer ridges (Five Fathom Bank and Garden Island Ridge) define Sepia Depression, which largely isolates the OACS coast from the offshore shelf sediments (the Fremantle blanket: Collins 1988) and the onshore sand shunt that occurred due to the late Holocene sea level rise. Gaps in the Garden Island Ridge have provided focal zones for onshore movement of sediment, with influx south of Garden Island, Success and Parmelia Banks. The Jervoise Bank Ridge has enabled retention of a wide flat bank in Cockburn Sound and anchored the Kwinana coast south of James Point. The Spearwood Ridge has provided control for much of the modern OACS coast, with cliffs and perched beaches present at Spearwood and Henderson. These features effectively transfer fluctuations in sediment supply to beach extension or contraction along the line of the ridge

Importantly, the geologic framework has constrained the availability of sediment and focused its distribution, such that modern sedimentary features are still responding to the sea level changes experienced in the Holocene between 5,000-6,000 years before present. This has resulted in a number of inherited or relict landforms, including the low energy beach terraces, which limit offshore transfer and can dissociate nearshore and terrace-edge sediment transport. Because the system is not in equilibrium (that is, observed features were developed under a previous set of environmental conditions) past behaviour in terms of sediment dynamics requires careful interpretation to provide a proxy for future change.

KEY GEOLOGICAL ATTRIBUTES OF THE OACS COAST

Attributes:

- Rock at multiple extents and elevations
- Basin and banks continuing to respond to Holocene
- Complex system of submarine features

Implications:

- Broad geologic framework contributes to partitioning of the coast
- Rock controls may change in the future
- System is not in equilibrium resulting in difficulties with the use of past behaviour as a proxy for future change

Key References:

Searle and Seminuk, 1985; DAL, 1998; Skene et al. 2005; Oceanica et al., 2010a; Gozzard, 2011.

Figure 8: Summary of key geological attributes for the OACS coast and associated implications for the present study

3.2 COASTAL GEOMORPHOLOGY

Figure 9 illustrates the range of surface landforms that occur within 3 km of the coast (Gozzard 2011). Much of the coastal plain close to the shoreline is composed of relatively modern sedimentary landforms, mainly foredune plain (represented by the light yellow colour adjacent to shoreline in Figure 9). This newer material will likely be more susceptible to reworking and modification than older material found at the northern extent of Cockburn Sound and in the vicinity of Fremantle (represented by the darker colours in Figure 9).

A variety of coastal morphologies can be observed around OACS coast. These diverse coastal types occur in response to varying aspects and exposures to locally relevant processes (winds, waves and water levels) the nature of sand supply (onshore or alongshore) and the interaction with rock features. In some cases, the morphology has been affected by the long history of active coastal management along the coast (discussed further in Section 3.3). The discrete morphologies may be distinct over short distances – for example, the very low energy areas of Mangles Bay are characterised by long low profiles with extensive sub-tidal terraces extending for up to a kilometre offshore while immediately north of Rockingham profiles are characterised by a more convex-curvilinear shape (Travers 2007) and drop off into deep water at the terrace margin approximately 100m offshore.

The wide range of profiles is illustrated in Appendix 6. An indication of how variable the profiles may be over a relatively short distance is given by Figure 10, which shows Coogee Beach (Central and South) and either side of Catherine Point. The significant foreshore management efforts long Coogee Beach are demonstrated by the stability or growth of the foredune area. For central Coogee, a rock platform emergent around -5mAHD (visible on LADS imagery) provides partial control for the lower part of the profile, whereas for South Coogee, the lower part of the profile has been subject to steepening. The profiles north and south of Catherine Point both show a general pattern of erosion above the near horizontal offshore 'bed', although the trend north of the Point is complicated by slumping and partial (low-elevation) recovery.

The terraced beaches of Cockburn Sound have been evaluated in detail, displaying coastal morphotypes that are characteristic of low energy beaches (Travers 2007). A key aspect of their formation is the capacity for hysteretic behaviour between erosion and recovery (Travers *et al*. 2010), which results in gradual landward cutting of the shoreline, with the terrace a relict from the original configuration that is reworked on its outer margin by alongshore transport.

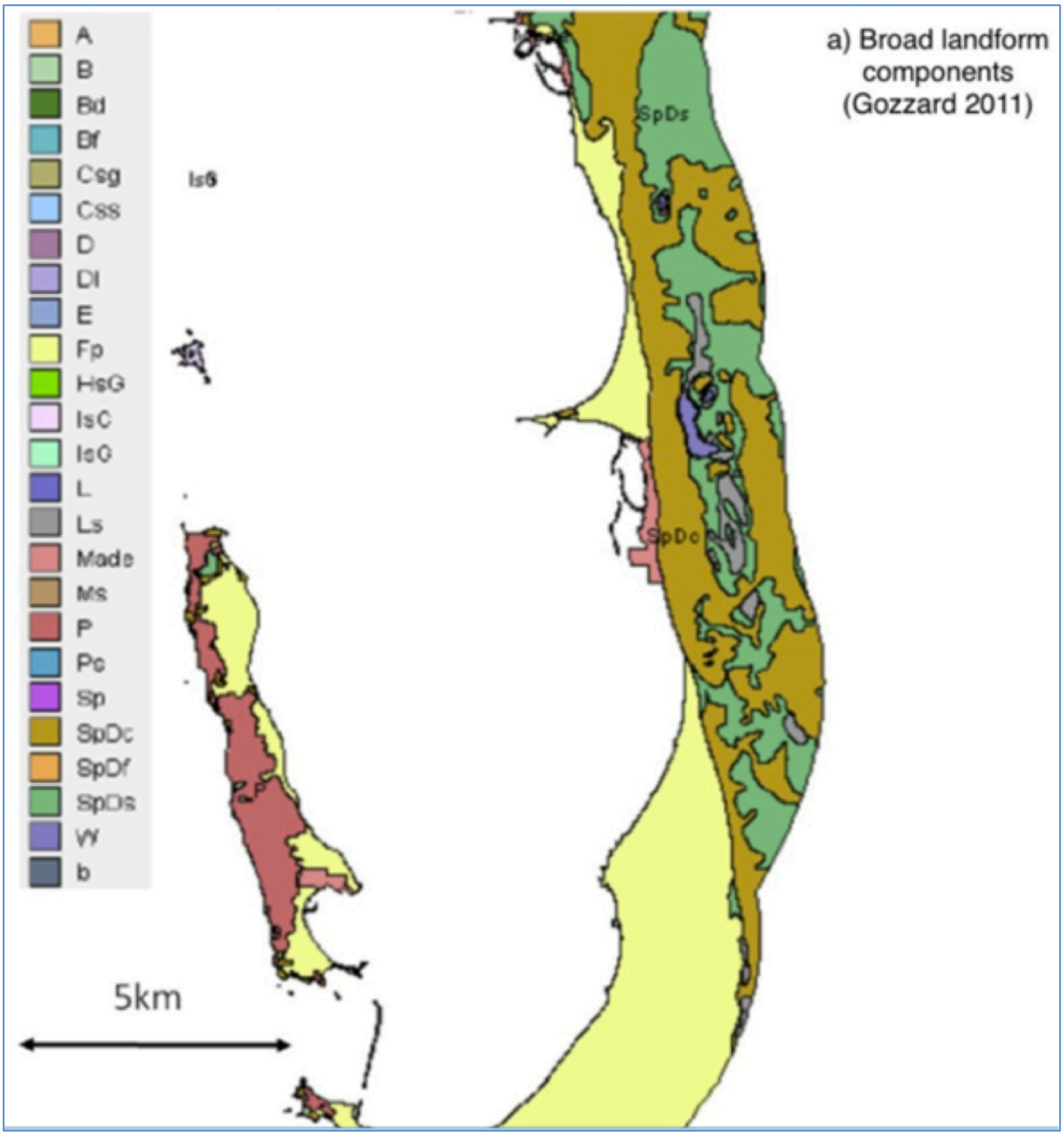

Figure 9: Coastal Landforms, OACS coast (Source: Gozzard, 2011)

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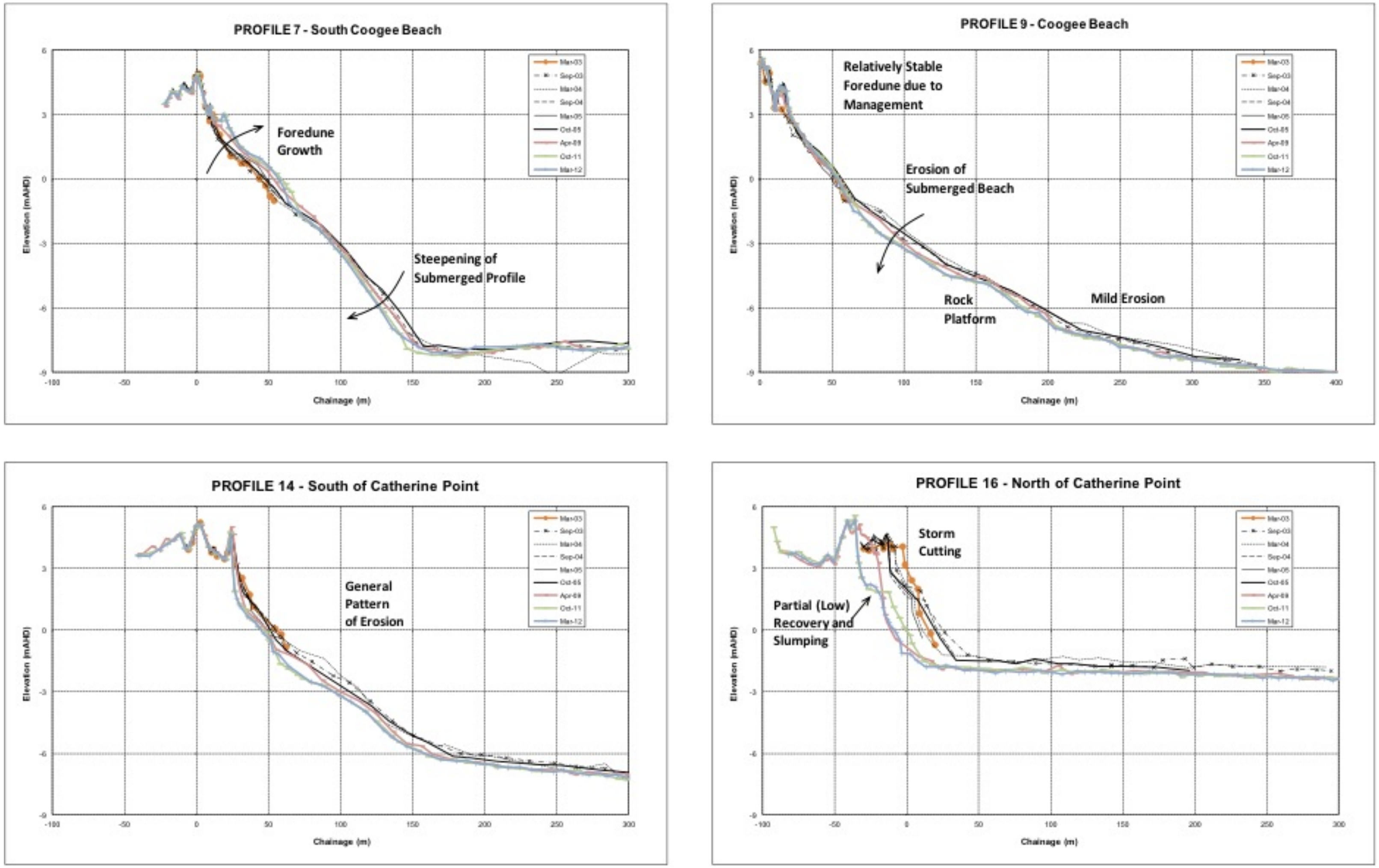

Figure 10: Illustration of Different Profile Types along OACS coast from March 2003 – March 2013 (Source: Cockburn Cement Ltd)

A summary of key attributes with respect to coastal landforms is presented in Figure 11 below. Of particular significance to the present study is the fact that the range of coastal landforms within the OACS coast are diverse, with a number of landforms behaving differently to those found on more exposed open ocean sandy coasts. This must be taken into account when attempting to describe the existing coastal dynamics of the area as well as undertaking modelling of future change. It will also dictate the range of management options that are potentially applicable (discussed further in Section 7).

KEY GEOMORPHOLOGIC ATTRIBUTES OF THE OACS COAST

Attributes:

- Majority of coastal landforms composed of relatively new material, as show by Fp (foredune plane – Figure 9).
- Tamala limestone outcrops are present along the coast at James Rocks in Owen Anchorage; from Russel Road to Naval Base and at Cape Peron in Cockburn Sound; and at Cliff Pont, Dance Head and Second Head on Garden Island
- A variety of coastal morphotypes exist. These respond in markedly different ways to spatial and temporal variations in winds, waves and water levels (Figure 10)
- Terrace systems affect wave transformation and interpretation of sediment transport regimes (Figure 10)

Implications:

- Low lying foredune planes along sections of the coast are prone to reworking and vulnerable to inundation
- A low-energy coast with large terrace features
- Sediment transport processes and coastal response different to an open ocean coastal zone
- Standard considerations for coastal management often do not apply

Key References:

Searle and Seminiuk, 1985; DALSE, 2003; Travers, 2007; Oceanica 2010a, b; Gozzard, 2011.

Figure 11: Summary of key coastal landform attributes for the OACS coast and associated implications for the present study

3.3 ENGINEERED CONTROLS

The OACS coast has a history of extensive modification within the coastal zone, with numerous coastal structures including groynes, jetties, breakwaters, boat ramps and intakes/outfalls (Figure 12, Figure 13 and Table 5). The presence of these structures has an important influence on local sediment transport patterns and nearshore hydrodynamics to varying degrees over time (Oceanica 2010a, b). Structures typically modify longshore sediment transport pathways, particularly when they extend offshore and hence their installation may affect shoreline stability within the surrounding sediment cell. In particular, large structures such as Garden Island Causeway and Woodman Point groyne have isolated Cockburn Sound from significant longshore feeds from the north or south. Wave reflection off artificial structures can also cause bed lowering in front and flanking erosion on adjacent beaches (Sumer & Fredsoe 2002).

Significant work has previously been undertaken to document the history of these structures and the known dredging and nourishment activities for the OACS coast. For example, detailed summary tables are available in reports prepared for Cockburn Cement by Oceanica Consulting (Oceanica 2010a, b). Figures providing an overview of the anthropogenic modifications of both Owen Anchorage and Cockburn Sound are presented below (Figure 12). Many of the structures installed along the OACS coast were deliberately installed either to improve coastal stability, or to isolate facilities that could be affected by sedimentation. The role of these structures for coastal management, in the context of a partitioned coast, is discussed in Section 7.

In the north of the OACS coast around South Beach, retention of sediment is apparent at the southern side of groyne-controlled sub cells, with a change of direction in the vicinity of Rollinson Road (Figure 12). The groyne at Catherine Point is saturated on its northern side, with other old structures between Catherine Point and Port Coogee completely smothered by sand. The more recently created 'infill' area between the Power Station and Port Coogee is actively accumulating sediment, at a forecast rate of 33,000m^3/annum (Hamilton & Hunt 2011). The influence of recent extension to Catherine Point groyne has not yet been established, although it is intended to increase the northward sediment supply and reduce the southward transport. Jetties along Coogee Beach do not apparently trap sediment at the present beach configuration.

Woodman Point has been highly modified through both groyne construction and reclamation activities (Figure 12). The reclaimer area at Woodman Point has a large influence on the coastal position. However, this is artificially managed and the coastal response is not considered a gauge of response to active coastal processes. West Beach, located between Woodman Point and Jervoise Bay Harbour, originally developed in response to groyne construction.

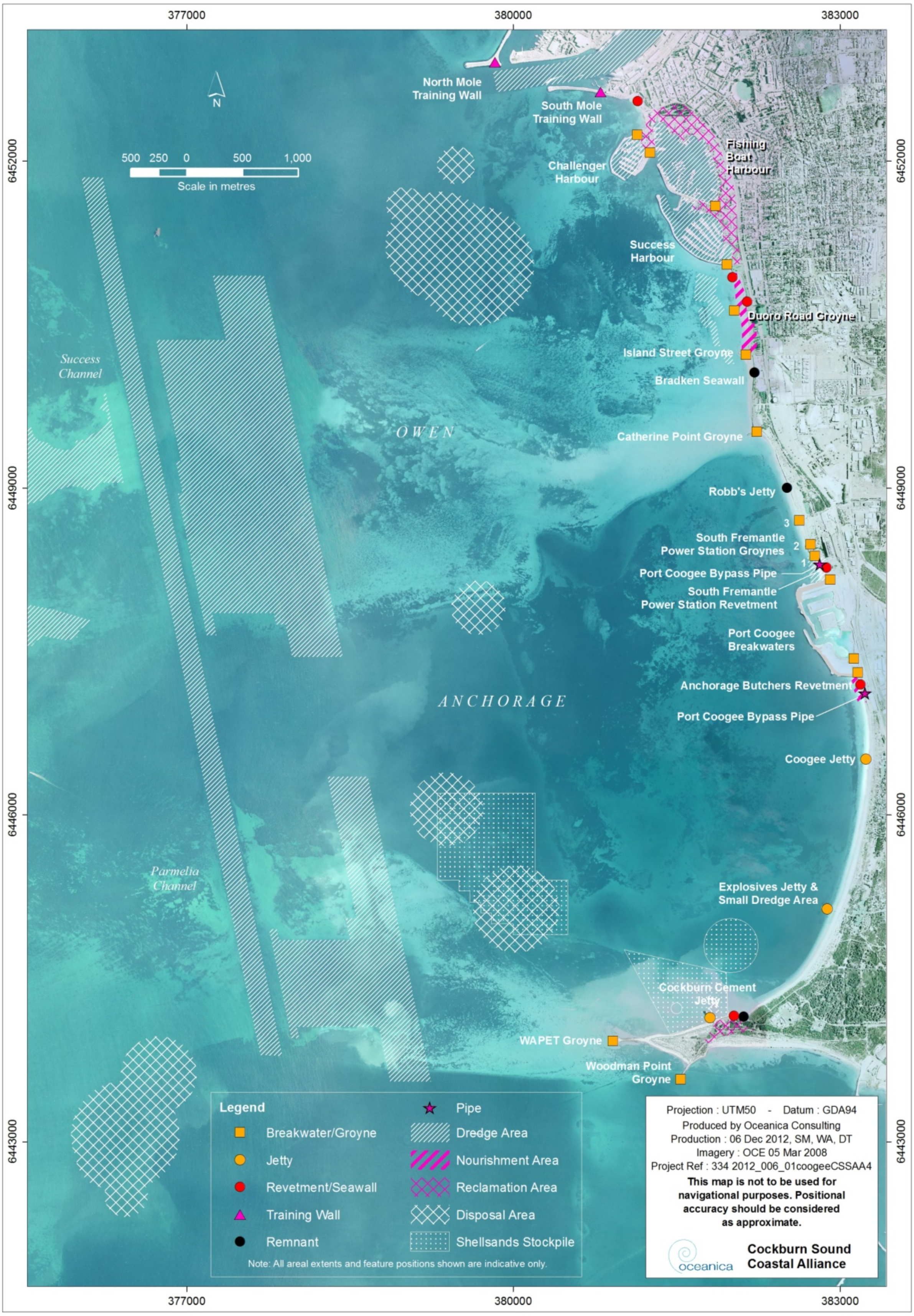

Figure 12: Anthropogenic Influences in Owen Anchorage. Source: Oceanica 2010a

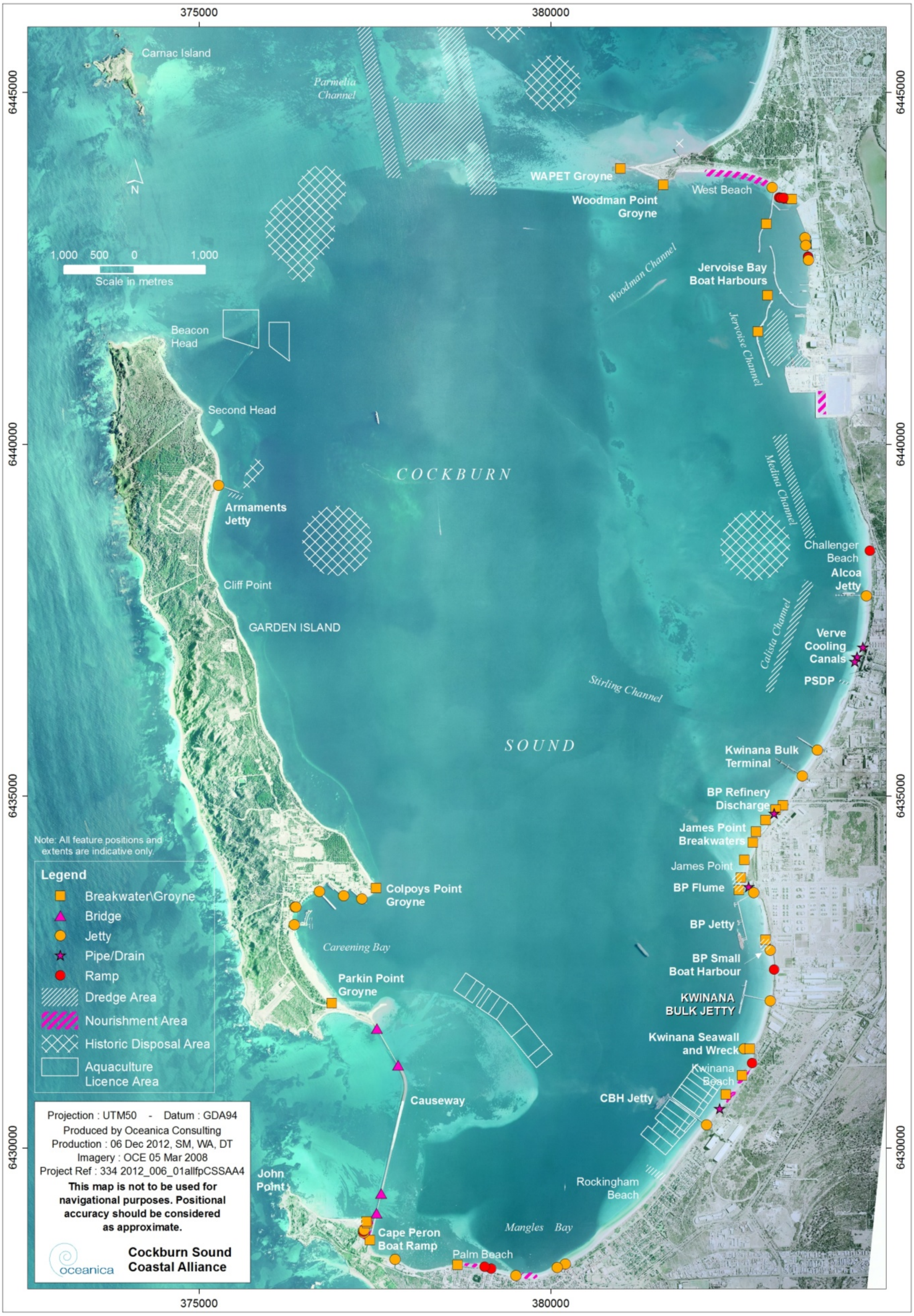

Figure 13: Anthropogenic Influences in Cockburn Sound. Source: Oceanica 2010b

Table 5: Existing Coastal Structures

Description	Year of Construction	Local Government	Cell	DoT Structures ID (2009)
Bathers Beach Block Seawall	1872 abutment of old jetty	Fremantle	22	S01
Success Harbour Southern Breakwater	1978-1979	Fremantle	22	
Seawall south of Fremantle Sailing Club	1995	Fremantle	22	S02
Duoro Road Groyne	1964 extended 1996	Fremantle	22	S03
Duoro Road seawall	1996	Fremantle	22	
Island Street Groyne	1962 extended 1996	Fremantle	22	S04
Catherine Point Groyne	1959/1964 (extension) and 2011 (extension)	Cockburn	22, 21	
SFPS Groyne 3	1949/1960 (extension)	Cockburn	21	S05
SFPS Groyne 2	1946	Cockburn	21	
SFPS Groyne 1	1946	Cockburn	21	
South Fremantle Power Station (SFPS) Revetment	1949	Cockburn	21	S06
Port Coogee Breakwaters	2006	Cockburn	21	S07
Seawall south of Port Coogee	2007	Cockburn	21	
Cockburn Cement Revetment	1913-1918, extended 1989	Cockburn	21	
Woodman Point Groyne 1 (WAPET groyne)	1913-1919	Cockburn	21, 20	S08
Woodman Point Groyne 2	late 60's	Cockburn	20, 19	S09
Woodman Point Seawall	1960's	Cockburn	19	S10
Jervoise Bay breakwaters	1913-1918, 1991-1997, 2001-2003	Cockburn	19, 18	S11
Challenger Beach Seawall		Kwinana	18	S12
Verve Energy Cooling Canal Outfalls	1970s	Kwinana	18	
Verve Energy Revetment		Kwinana	18	
BP Kwinana Outfall		Kwinana	18	
BP Headland 1	1970s	Kwinana	18	S13
BP Headland 2	1970s	Kwinana	18	S14
BP Headland 3	1970s	Kwinana	18	S15
BP Headland 4	1970s	Kwinana	18	S16
BP Headland 5	1970s	Kwinana	18	S17
BP Headland 6	1970s	Kwinana	18	S18
BP Headland 7	1970s	Kwinana	18	S19

Description	Year of Construction	Local Government	Cell	DoT Structures ID (2009)
BP Kwinana Flume	1953-1960	Kwinana	18, 17	
BP Kwinana Oil Refinery Jetty	1953-1960	Kwinana	17	
BP Kwinana Wharf Facility	1953-1960	Kwinana	17	
CBH Groyne		Kwinana	17	
CBH Rubble Revetment		Kwinana	17	
Kwinana Wreck	1959	Kwinana	17	S20
Kwinana Beach seawall	1981/1997(final stages)	Kwinana	17	S21
Kwinana Beach Headland 1	2008	Kwinana	17	S22
Kwinana Beach Headland 2	2008	Kwinana	17	S23
Rockingham Beach seawall	1898/1972/1982	Rockingham	17	S24
Rockingham Jetty seawall		Rockingham	17	S25
Bell Street Boatramp		Rockingham	16	S26
Palm Beach Timber Groyne 1	2002	Rockingham	16	S27
Palm Beach Timber Groyne 2		Rockingham	16	S28
Hymus Street Seawall	1975 progressively reinforced onwards	Rockingham	16	S29
Point Peron Yacht Club boat ramp and seawalls		Rockingham	16	
Cape Peron Boat Ramps	1985 (Americas Cup), 1994(upgrade plans)	Rockingham	16	
Causeway	1971-1973	Rockingham	16, 15	
John Point seawall		Rockingham	15	S30
Parkin Point Groyne		Department of Defence	GI2a	
Careening Bay Small Boat Harbour		Department of Defence	GI2a	
Naval Base 3 groynes and wharf facilities		Department of Defence	GI2a	
Colpoy's Point Groyne		Department of Defence	GI2a, GI1b	
Armaments Jetty	1972	Department of Defence	GI1a, GI4f	

It has subsequently been subject to a short erosive episode, but has not recovered, suggesting a cut-off of supply, and potentially acts as a sediment sink to any sediment bypassing the groyne. South of the Australian Maritime Complex (Figure 12), the coastline in the Henderson area is controlled by natural rock formation up to the Naval Base area. From there to James Point the jetties and other structures (generally small cross-shore length) presently demonstrate minor influence on the shoreline alignment, with some accumulation apparent on the northern side of Kwinana Power Station outflow chutes.

At James Point, shore-detached groynes (headlands) were installed to provide shore stabilisation following construction of Garden Island Causeway. It is understood that these will have reduced effect under sea level rise scenarios, particularly when associated with coastal recession. South of James Point, sediment accumulation is apparent on both sides of the BP supply base. However, there is a general pattern of accumulation on the northern side of structures, the most significant being the wreck of SS Kwinana, which required installation of two detached groynes to reduce the effect of downdrift erosion (DPI 2004). Structures in and around the southern part of the Sound are all short and generally saturated with sand on their western side. Some variation in transport directions has been identified in the Mangles Bay area, suggesting that it may have nearly a neutral direction of transport following installation of Garden Island Causeway (MP Rogers & Associates 2008; TABEC & JFA Consultants 2011).

Importantly, the history of active sediment management has largely been neglected in prior considerations of sediment budgets for the OACS coast. Because the coast is low energy in nature, there is a lag response to structural intervention and the system as a whole is likely to still be responding to some of the larger previous works.

Partitioning of the coast and associated implications for sediment transport regimes are a key consideration in formulating an accurate understanding of the physical process response relationships at play in the coastal system. For this reason, the structural controls exerted on discrete portions of the coast formed the basis of the spatial delineation of erosion hazard assessment discussed further in Section 5 below.

A summary of engineering control is presented in Figure 14.

ENGINEERED CONTROL & THE OACS COAST

Attributes:

- Coast has a long history of structural modifications
- Partitioned by engineered structures including groynes, jetties, breakwaters, boat ramps and outfalls
- Beach nourishment and sediment bypassing is conducted

Implications for Present Study:

- Modify longshore sediment transport pathways and result in the interruption of natural sediment cells
- Coast is largely responding to previous engineering works and active sediment management, biasing coastal response

Key References:
MP Rogers & Associates 2005a; Oceanica et al, 2008; Damara & Shore Coastal, 2009; Oceanica 2010a, 2010b.

Figure 14: Summary of factors relating to engineered controls along the OACS coast and associated implications for the present study

3.4 WATER LEVELS

The OACS coast is located within a microtidal (Figure 15a), mainly diurnal tidal region (Easton 1970; NTF 2000) which therefore increases the relative importance of non-tidal sea level processes, including the historic misnomer of 'meteorologic tide' for response to atmospheric conditions (Hodgkin & di Lollo 1958; Table 6). The synoptic climatology of the region is influenced by both tropical and mid-latitude pressure systems, with a range of storm types driving circulation, waves and storm surge (Steedman & Craig 1979, 1983). Variability of storminess in the region has been long identified (Fraser 1905), with monitoring frameworks progressively improving over time enabling gradually improved descriptions of storm fluctuations using a wider range of parameters (Steedman & Associates 1982; Hope et al. 2006; Haigh et al. 2010; Li et al 2010; Bosserelle et al. 2012).

This situation is consequently outside the range of conventional tide-surge integration (Pugh & Vassie 1980; Pugh 1987), which effectively requires dominance of either tide or surge (Jay & Flinchem 1999; Mendez et al. 2007) with extreme events associated with limited synoptic sub-types. A further strain on statistical extrapolation of historic data is brought about by the large ranging of mean sea level that has been observed over the 20th Century tide gauge record, principally associated with El Nino-Southern Oscillation climate variations (Haigh et al. 2011; Figure 15b). This relative complexity of water level phenomena has prompted detailed evaluation of the factors contributing to water level variability in the southwest region of Western Australia by the School of Environmental Systems Engineering at the University of Western Australia. A list of previously identified water level phenomena has been developed (Eliot & Pattiaratchi 2007; Pattiaratchi & Eliot 2008) and refined through further evaluation of individual processes and their interactions, with support through the WAMSI research program (Table 6).

The long 117 year record from the Fremantle tide station has provided the basis for investigation of water level phenomena over a wide range of scales, supported by other tide gauges from the Department of Transport's tide gauge network. This includes a comparatively short record since 2001 from Mangles Bay, within Cockburn Sound. The Highest Astronomical Tide (HAT) at Fremantle is 0.54mAHD (Department of Defence 2010). The highest recorded water level of +1.22mAHD occurred on 16 May 2003 when an extra-tropical storm caused sustained strong westerly winds, allowing the storm surge to superimpose upon high tidal conditions.

The very low tidal range experienced by the OACS coast enables other (non-tidal) sea level processes to be comparable in scale, including seasonal and inter-annual mean sea level (MSL) variations, storm surge, continental shelf waves, seiching, meteotsunami and inter-annual tidal modulations (Table 6; Eliot & Pattiaratchi 2007; Pattiaratchi & Eliot 2008). Furthermore, seasonal variations of tide, surge and mean sea level are almost coincident during May-July to produce high water levels (Eliot 2012; Figure 16). Within this environment, the simplification of equating tidal residual to storm surge is limited, as a significant proportion of the seasonal and inter-annual MSL ranges represent the response to changing weather or climate (Pattiaratchi & Buchan 1991; Feng et al. 2004; Wijeratne et al. In prep). The relative phase of tide and mean sea level during autumn months is also a major reason why tropical cyclones, which are capable of producing extreme surges when they travel parallel to the west coast (Fandry et al. 1984; Eliot & Pattiaratchi 2010), do not figure prominently in extreme water level records.

Table 6: Water level components for the OACS coast (Adapted from Eliot 2012)

Process	**Duration**	**Scale (m)**	**Reference**
Wave action	2–20 sec	~ 5	Lemm *et al* (1999); Li *et al* (2011)
Wave set-up	5–30 mins	~ 0.3	Bode & Hardy (1997)
Infragravity waves	2-60 mins	~0.3	
Seiches	30–90 mins	~ 0.2	Allison & Grassia (1979)
Pressure surge	1–3 hours	~ 0.2	Reid (1990)
Meteotsunami	1-6 hours	~0.4	Wijeratne *et al* (In Prep)
Wind set-up	3–6 hours	~ 0.2	Pugh (1987)
Tidal conditions	12–24 hours	~ 0.8	Easton (1970)
Sea breeze cycle	24 hours	undetermined	Masselink & Pattiaratchi (2001)
Pressure systems (cycle)	1–10 days	~ 0.8	Hamon (1966)
Continental shelf waves	3–10 days	~ 0.6	Eliot & Pattiaratchi (2011)
Fortnightly tidal cycle	2 weeks	~ 0.4	
Density changes	1-3 months	~ 0.3	Dept of Env. Prot. (1996)
Seasonal tide cycle	6 months	~ 0.2	
Leeuwin Current	Seasonal	~ 0.3	Pattiaratchi & Buchan (1991)
Oceanographic forcing	Years	~ 0.5	Church *et al* (2006)
Nodal tide	18.6 years	~ 0.15	Pugh (1987); Eliot (2011)
Climate variability	Decades	~ 0.2	Pariwono *et al* (1986)
Sea level rise	100 years	~1.0	Hunter (2007)
Interglacial influences	10^{3+} years	~ 10	Wyrwoll *et al* (1995)

Weather events acknowledged to cause extreme water levels locally include extra-tropical or mid-latitude storms (Haigh et al. 2010), tropical cyclones (Fandry et al. 1984) and meteotsunami (Wijeratne et al. In Prep). Mid-latitude storms are the most frequent of these phenomena, with the greatest likelihood of occurring coincident with high tide and mean sea level during winter. Tropical cyclones are comparatively infrequent, with only one cyclone travelling through the southwest per decade, on average in summer-early autumn; although more remote systems may act to force water levels in the southwest through continental shelf waves. Meteotsunami are produced by rapidly moving pressure jumps, such as thunderstorms, and are capable of producing extreme, albeit short-lived high water level events if they approach resonant characteristics of the basin across which they propagate. Extreme distributions for water levels around Australia have been developed as part of the Canute project, through a combination of tide gauge data analysis and tropical cyclone modelling (Haigh et al 2012, 2013). However, it should be recognised that the reliability of this Australia-wide study for representing tropical cyclone risk in the southwest is reduced due to its neglect of extra-tropical transition and propagation of coastally trapped waves.

The role of resonance to influence water level phenomenon has been previously identified (Allison & Grassia 1979; Molloy 2001; Ilich 2006), with more recent analysis presently in preparation (Pattiaratchi et al. in prep). This suggests that there may be a basis for the anecdotal perspective that enhanced surges can occur in Cockburn Sound, as the effect of a seiche may be to effectively sustain a water level signal longer than it period of generation, giving it more opportunity to superimpose with high tide. However, this proposition is not supported by comparison of the Mangles Bay tide gauge record with the longer Fremantle record.

The complexity of active phenomena along the OACS coast limits how well a conventional harmonically-derived separation of tide and surge represents Southwest water levels, and challenges the reliability of probabilistic methods for the analysis of extreme water levels (Hunter 2011). In particular, the period from 1990 to 2012 has experienced a significant increase in mean sea level, associated with a change from El Nino to La Nina climate phases. Over this period, the occurrence of high and extreme water level events in the southwest has increased, which along with the 18.6-year nodal cycle reduces the reliability of techniques based upon historic records (Eliot 2012). A consequence of the weakly defined extreme water levels is that use of 'representative design events' has remained locally in vogue, despite a global trend towards more probabilistic methods.

For mid-latitude storms, the likelihood of an extreme water level is affected by mean sea level, seasonal phase (tide and MSL) and inter-annual tidal cycles, in decreasing order of importance. These factors have not been in phase since the 1950s, which suggests that an extreme distribution based upon historic records is likely to underestimate likelihoods. A simulated extreme water level distribution, which includes several of the identified sources of variance, suggests a 100-year ARI extreme water level of 1.39m AHD for Fremantle (Haigh et al. 2012).

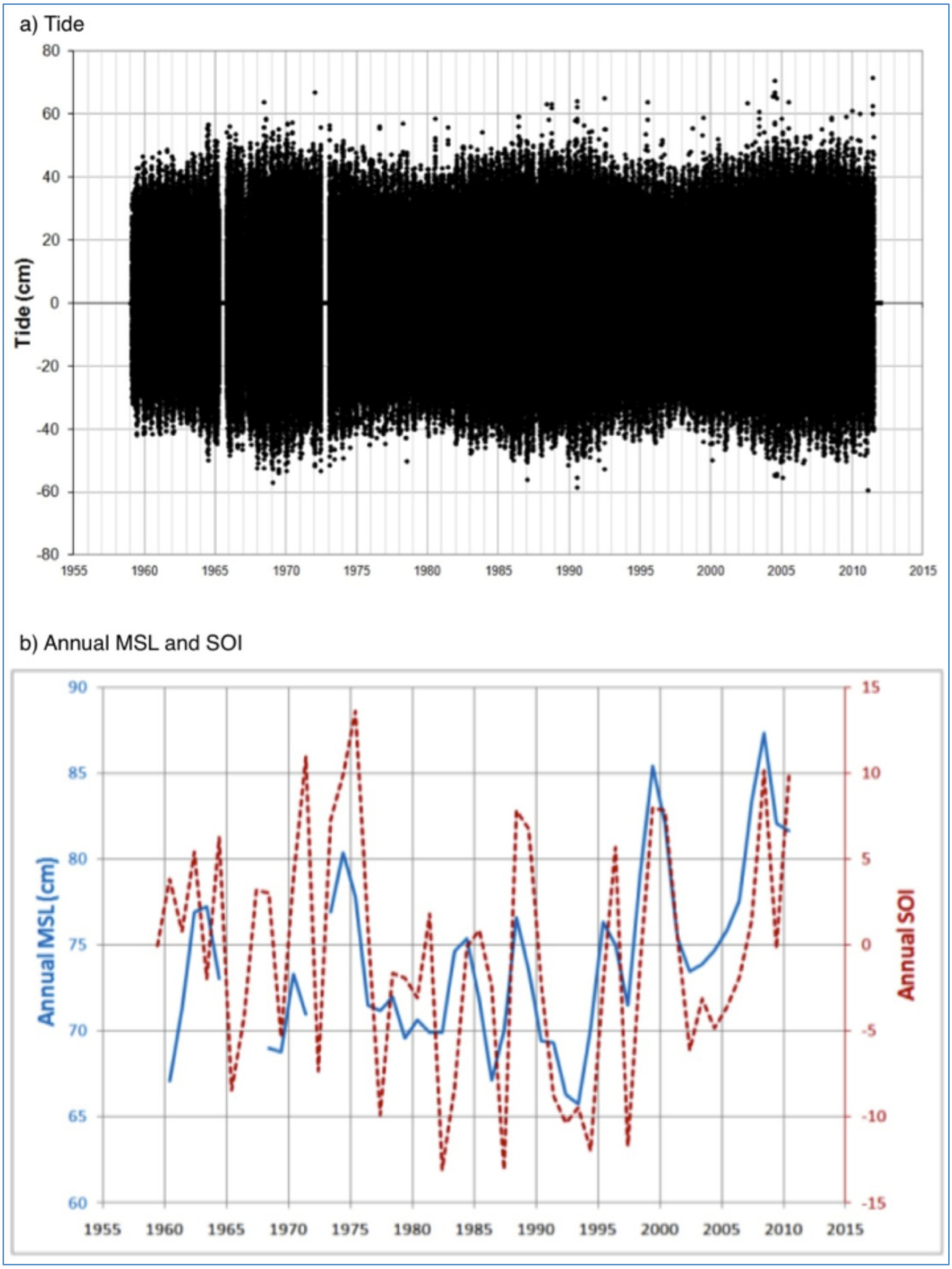

Figure 15: Times series of a) Tidal component of water level measurements and b) Annual MSL and SOI calculations for Fremantle

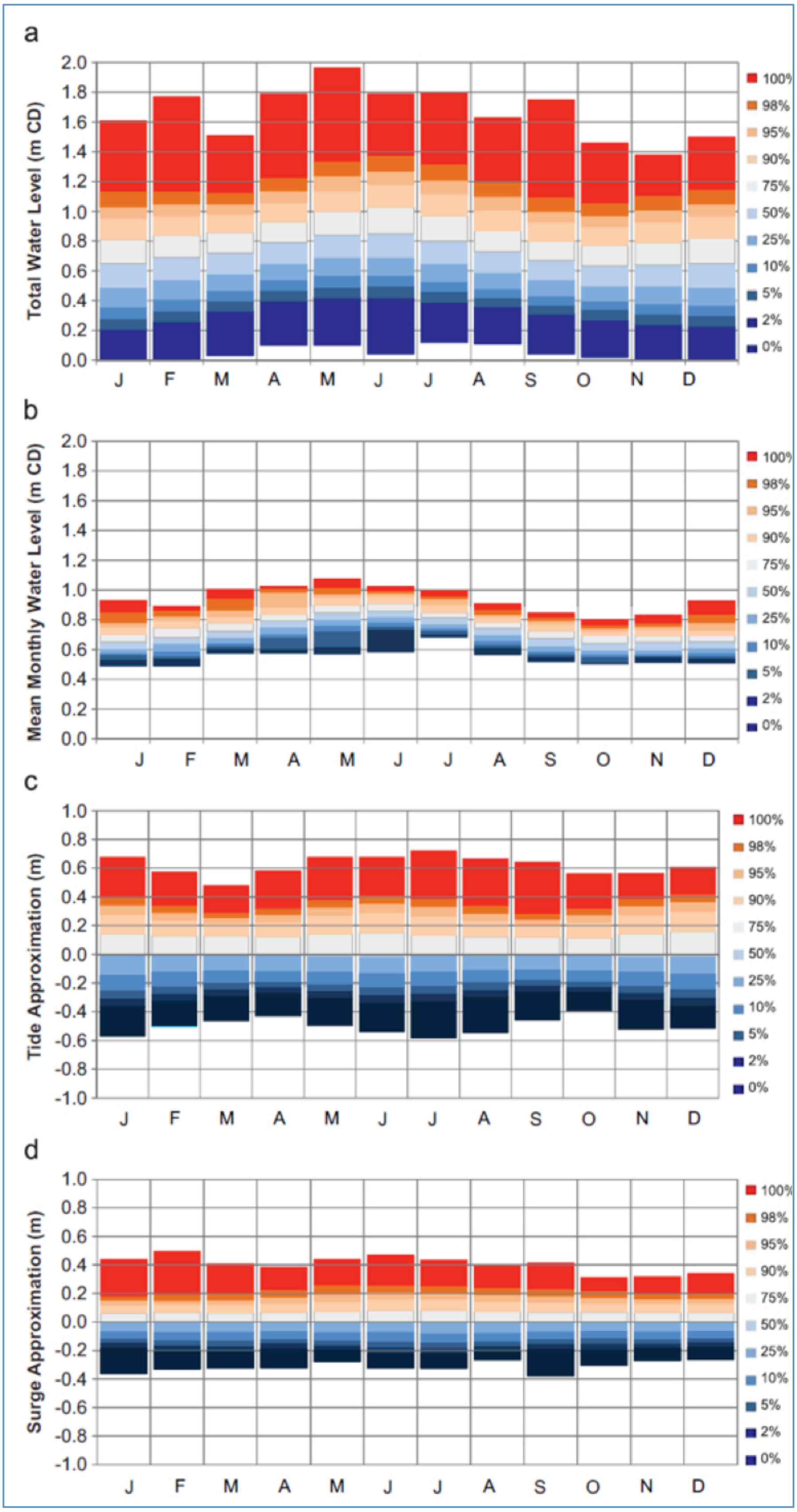

Figure 16: Seasonal distributions of decomposed water levels for Fremantle (Eliot 2012)

Tropical cyclones are rare events, even in tropical regions and therefore they are commonly parameterised using a range of meteorological characteristics including central pressure, radius of maximum winds, speed and direction of approach (Bode & Hardy 1997; Harper et al. 2009). This alone makes it difficult to describe likelihoods for southwest Western Australia, as such systems are too infrequent to define a reliable distribution of cyclone parameters, with the existing historic database affected by observational techniques (Damara WA 2006; Harper et al. 2008). However, their influence on water levels is considerably further complicated by extra-tropical transition (Callaghan 2005) and continental shelf wave generation (Fandry et al. 1984; Eliot & Pattiaratchi 2010). As a result, it is effectively impossible to assign a probability of extreme water levels in the OACS coast associated with tropical cyclones.

Overall, our existing knowledge base suggests that there is a very high degree of uncertainty associated with the estimation of flood likelihood, whether generated by mid-latitude storms, tropical cyclones or other phenomena. The key implication to future hazard mapping is that estimation of flood scenarios should make allowance for this uncertainty and clearly recognise the limitations of nominating an event recurrence interval.

A summary of water level fluctuations on the OACS coast is included in Figure 17.

WATER LEVEL FLUCTUATIONS & THE OACS COAST

Attributes:

- Non-tidal components often similar order of magnitude or greater than tidal components
- 19 year tidal cycle causes longer term water level shifts (Figure 16a)
- Strong La Nina event has recently contributed to high water levels (Figure 16b)
- Seasonal peak in May to June (Figure 16c)

Implications for Present Study:

- System will be responsive to higher water levels due to a small tidal range
- Very high degree of uncertainty associated with the estimation of flood likelihood
- Flood scenarios make allowance for this uncertainty.
- There are limitations of nominating an event recurrence interval.

Key References:
Ilich 2006; Eliot & Pattiaratchi 2007; Eliot & Pattiaratchi 2010; Oceanica et al 2010a; Eliot 2012.

Figure 17: Summary of water level attributes for the OACS coast and associated implications for the present study

3.5 WIND AND WAVES

The OACS coast is located within the temperate extra-tropical region, which experiences prevailing influence from diffuse high pressure systems, occasional influence from mid-latitude low pressure cells or fronts and the rare influence of tropical systems (Gentilli 1971). These synoptic conditions provide a distinct seasonal shift with a strong diurnal land-sea breeze cycle common during summer months and more variable conditions during winter months, typically swinging from mild northeast winds to intense westerlies associated with storm events (Steedman & Craig 1979; Masselink & Pattiaratchi 2001; Figure 18a, b). Storms may occur at any time of year although they are most prevalent during winter months.

Wave conditions affecting the wider southwest region are indirectly related to the observed wind patterns, with predominant waves generated by mid-latitude systems propagating from the southwest, resulting in a prevailing southwest swell offshore. Wave conditions outside the Garden Island ridge have been recorded and well reported through a permanent waverider buoy deployments offshore from Rottnest since 1994, measuring directional information since 2004 (Lemm et al. 1999; Li et al. 2009). Offshore wave conditions, as measured from the Rottnest waverider buoy, are typically 1–2m median significant wave height (Hs) during summer, and from 2m to 3m Hs during winter, with higher conditions during westerly (southwest through northwest) storm events (Figure 18c; ; Roncevich *et al.* 2009). The highest wave event recorded was 8.44m on 21 July 2009.

The offshore waves are modified before they reach the shore, through interaction with bathymetry, diffraction around islands and breaking across the extensive limestone reef chains and platforms (eg Figure 19). Further energy is introduced through local wind wave generation, of which the most distinct is produced by strong southerly sea breezes (Pattiaratchi *et al.* 1996). Sheltering by Garden Island and the outer reefs determines that the OACS coast has a wide variation in wave climate. Owen Anchorage is generally more exposed to ocean waves and Cockburn Sound (including Garden Island east coast) more exposed to wind waves, with the approaching wave fetches providing local changes in prevailing and dominant wave conditions that vary around the Sound (Travers 2007). Instrumentation to support ongoing operations (particularly for navigation) has been deployed at Owen Anchorage, Parmelia Bank and Stirling Channel, which provides an indication of spatial variation. However, local complexity of the wave fields has prompted the use of numerical modelling to explain spatial variations, with a range of comparatively short-term measurement programs to provide model validation for particular sites (Appendix 4). Validation of wave modelling within the Sound is generally more onerous than for a more exposed site, due to the need to resolve multiple active processes (refraction, diffraction, friction, breaking) and capture both swell and local wave generation appropriately.

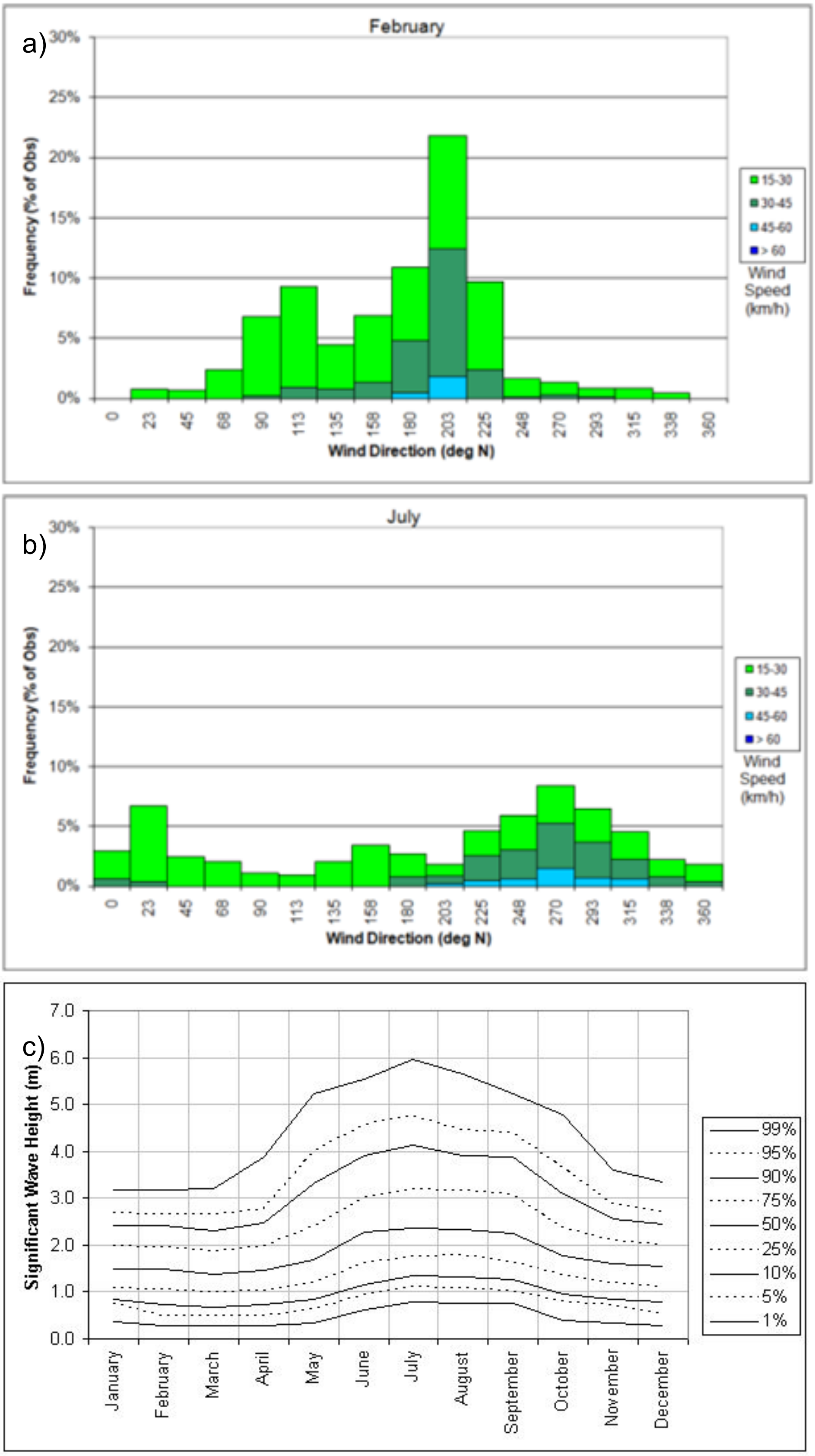

Figure 18: Summary of Garden Island winds (a & b) and Seasonal Wave Climate Variation (c)

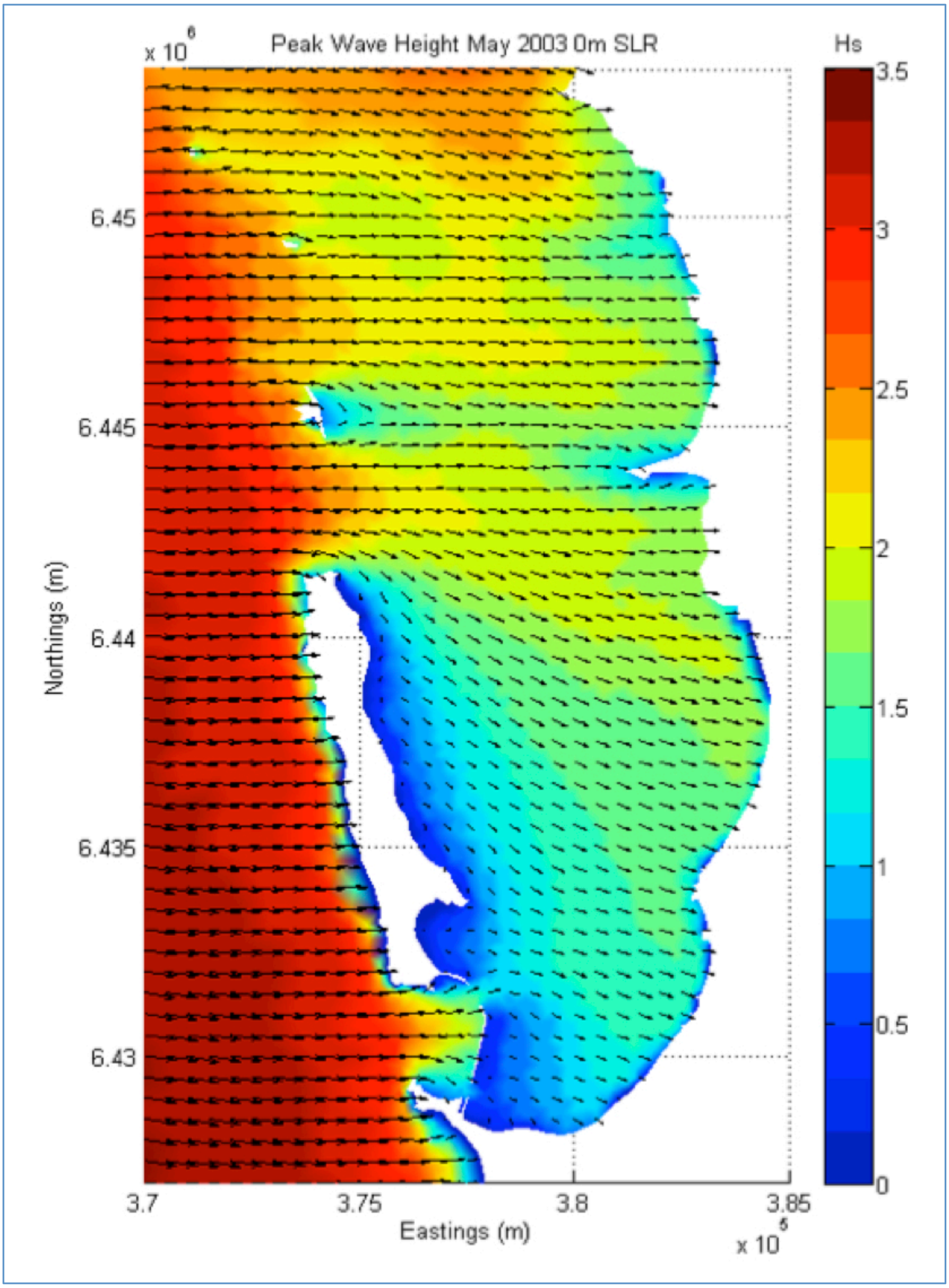

Figure 19: Distribution of peak wave energy through the study area, May 2003 storm, present sea level.

Numerical modelling of the local wave climate specifically to evaluate coastal sediment transport has been undertaken for various parts of the Perth metropolitan coast (Kay et al. 1996; MP Rogers & Associates 2007). Previous numerical modelling in the OACS coast using 2GWave has focused on the impacts of Cockburn Cement's dredging operations on the adjacent coast (MP Rogers & Associates 1996, 2007) and potential impacts of Port Rockingham Marina (MP Rogers & Associates 2008).

One major effect of the sheltered coastal environment for the OACS coast is the capacity for both seasonal and episodic changes in dominant wave direction. The balance between swell penetration (shifting from west through to northerly around the Sound) and wind waves from storms (westerly), sea-breezes (south-southwest) or easterly winds may be subtle, with fluctuations causing a large shift in the effective wave direction. The coastal response to such a change was dramatically and permanently illustrated at James Point following construction of Garden Island Causeway.

A summary of wind and waves on the OACS coast is included in Figure 20.

WIND AND WAVES & THE OACS COAST

Attributes:

- Sheltered from open ocean waves with locally variable wave climates
- Responsive to seasonal variability in metocean (wind, wave and water level) processes
- Local reversals in wave direction

Implications for Present Study:

- Implications of sea level rise on inshore wave climate over banks (Parmelia, Success and Southern Flats) could result in some local decrease and increase of wave heights, along with change in directions
- Change to the spectral spread of waves anticipated with sea level rise
- Difficult to really resolve processes inside OACS coast with numerical models

Key References:
Gentilli 1971; Riedel & Trajer 1978; Steedman & Associates 1982; Panizza 1983; Steedman & Craig 1983; Pattiaratchi et al. 1996; Lemm et al. 1999; Masselink & Pattiaratchi 2001; Li et al. 2009; Roncevich et al. 2009; Oceanica et al 2010a.

Figure 20: Summary of wind and wave attributes for the OACS coast and associated implications for the present study

3.6 COASTAL CHANGE

Interpretation of aerial photographs (eg Figure 21; Figure 22), profile data (eg Figure 23) and LADS bathymetry was undertaken to establish the major mechanisms of coastal change along the OACS coast. Key characteristics include:

- The underlying geological framework determines coastal partitions (sediment cells) within which coastal change exhibits strong connectivity;
- Focused supply of sediment to the OACS coast occurs at discrete locations, which includes Catherine and Woodman Points, along with supply south of Garden Island that has been partly interrupted by construction of the Causeway;
- Significant anthropogenic changes have occurred, including massive deposition of sidecast dredged material, and installation of coastal structures (Section 3.3). In general, these works have acted to redistribute the alongshore sand supply, with larger structures such as Garden Island Causeway, Catherine Point groyne and Port Coogee acting to modify the sediment cells;
- Infilling around Broun Bay and formation of Careening Bay spit provide evidence of supply to this area, with a sand ribbon adjacent to the north of the Causeway also demonstrating local sediment transport;
- Wave driven alongshore transport is the dominant process with absence of tidal landforms suggesting little contribution from currents, except the Careening Bay spit;
- The coastal configuration is spatially consistent with the relative balance of swell waves and locally generated wind waves. A portion of the observed change relates to short (storm) and medium (1-5 year) term perturbations of this balance, resulting in erosion-recovery cycles; and
- Terraced beaches, which occur on Garden Island east coast and southern Cockburn Sound are characteristic of low-energy coast, which may experience erosion-recovery imbalance. Sediment transport and associated coastal change may be distinctly different between the shore and the terrace margin.

Overall, there is a change in morphodynamics from the south to the north of Cockburn Sound and Owen Anchorage, shifting from characteristic low-energy behaviour towards swell-dominated conditions. Under low energy conditions, coastal change tends to be more episodic, and discrete between inner and outer margins of the terrace. Coastal change for the swell-dominated coast is more connected between the dune, beach and submerged parts of the profile. Along the east coast of Garden Island, southward transport is dominant under swell, with apparently limited influence of wind waves, which are mainly from the east.

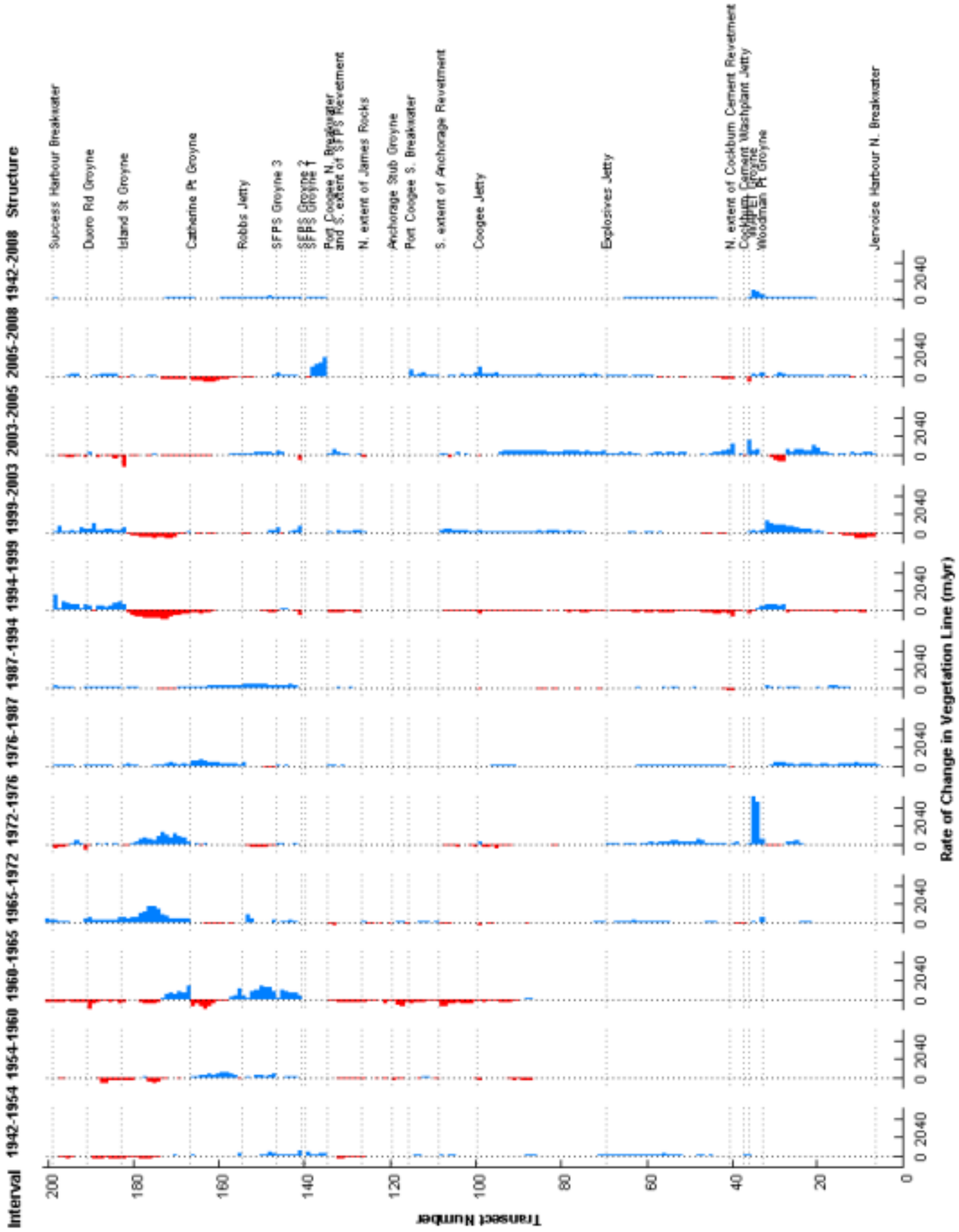

Figure 21: Vegetation line changes in Owen Anchorage (Source: Oceanica 2010a)

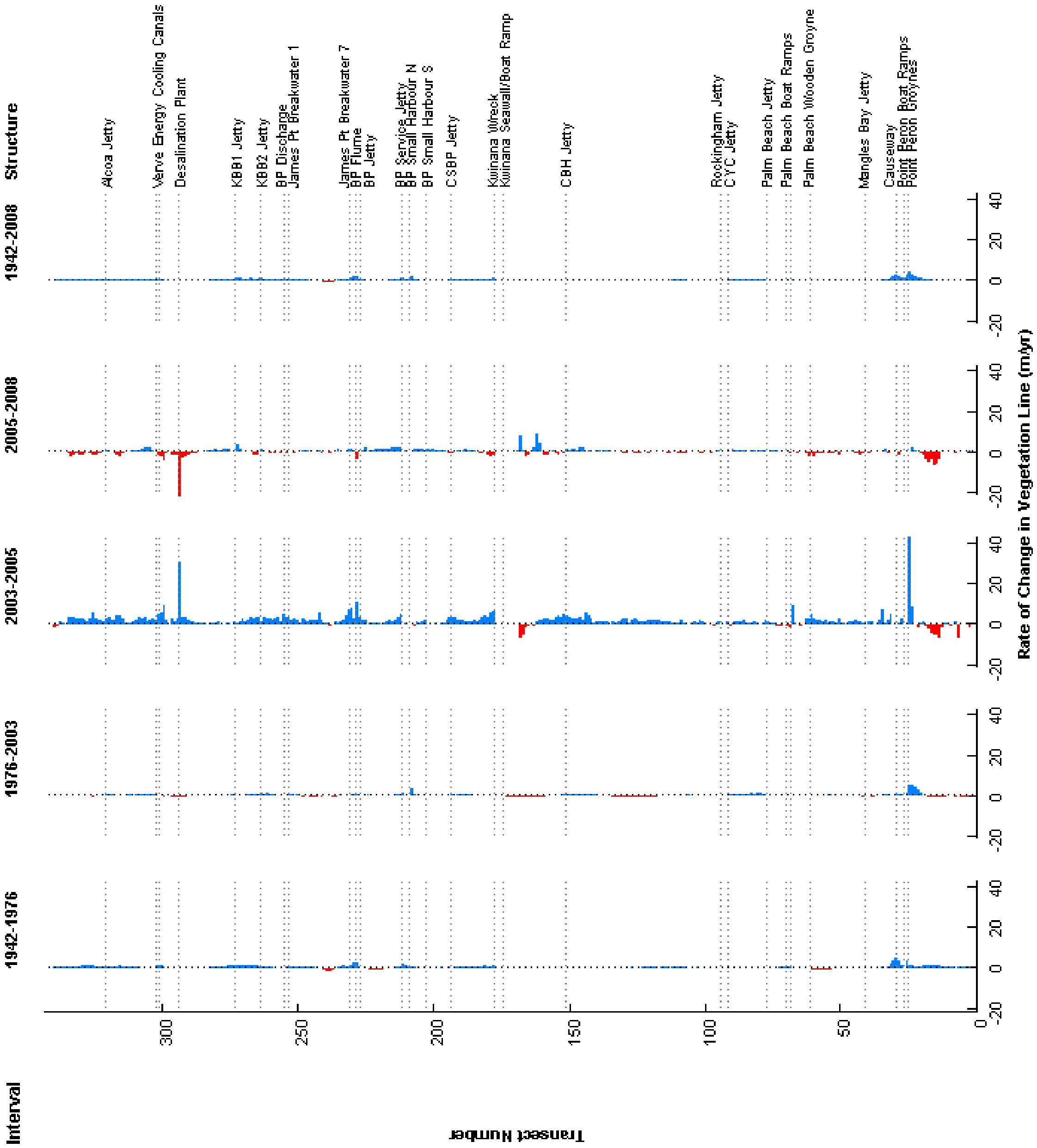

Figure 22: Vegetation line changes in Cockburn Sound (Source: Oceanica 2010b)

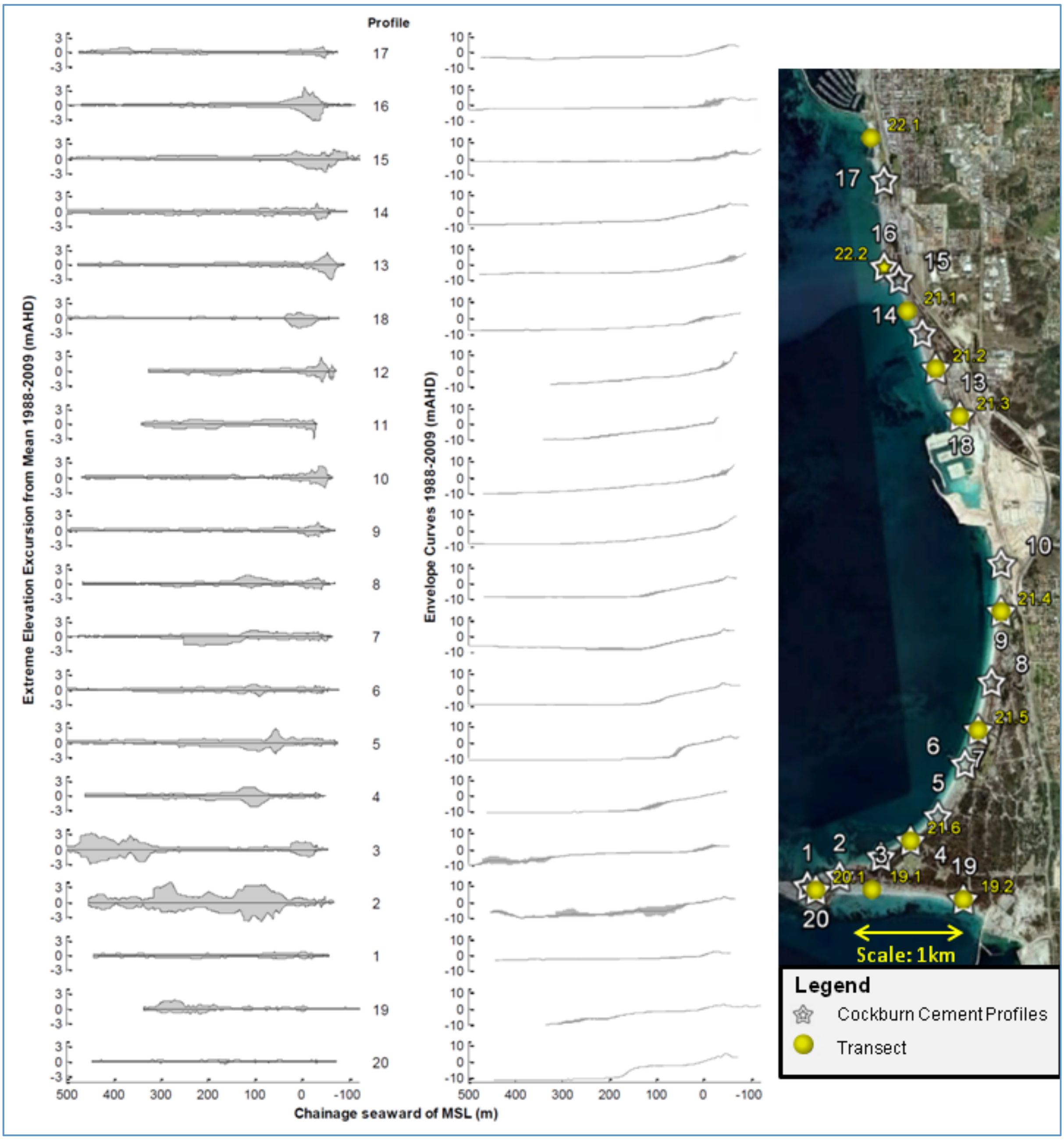

Figure 23: Profile changes in Owen Anchorage (After: Oceanica 2010a)

Pathways and relative rates of sediment supply into Cockburn Sound and Owen Anchorage were evaluated based on review and interpretation of existing information for the OACS coast including:

- Interpretation of late Holocene sand shunts suggested by stratigraphic and sedimentological records (Collins 1988; Semeniuk & Searle 1986; Skene *et al*. 2005);
- Analysis of historic erosion rates and coastal management works, including renourishment along Kwinana foreshore (DPI 2004);
- Review of studies on modern sediment process and budgets for the Sound (MP Rogers & Associates 2005b; Oceanica *et al.* 2010a, 2010b; Hamilton & Hunt 2011; TABEC & JFA Consultants 2012);
- Work undertaken by Damara regarding sand accumulation and drifts on southern Garden Island for the Royal Australian Navy (Damara WA 2005); and
- Interpretative analysis of historical aerial imagery for the OACS coast, including response following installation of structures.

Discrete onshore and alongshore feeds were identified from a review of several sediment budgets produced for the area (Oceanica *et al.* 2010b Figure 5.1), supported by interpretation of sub-surface features from Department of Planning LADS and LIDAR. Four major pathways are apparent, with two through the gaps in Garden Island Causeway at Careening Bay (1) and Cape Peron (2). Onshore sediment feeds occur to the north of Garden Island across Parmelia (3) and Success (4) banks.

Sand supply south of Garden Island has not been quantified, but anecdotally has caused extensive infilling to the west of the Causeway over the last 40 years (Waterman *et al*. 2004). Surface expression of the sedimentation is apparent through accretion at Broun Bay, Careening Bay and Peron boat ramps (Department of Transport 2009). At Peron boat ramp, sediment accumulating onshore is transported east by wave action, where it is artificially trapped by a groyne and managed mechanically.

High feed rates calculated for the North of the OACS coast need to be interpreted with care due to the difficulty in separating anthropogenic influences upon shoreline change (Figure 21; Figure 23). This includes construction and removal of coastal protection structures, and onshore sediment supply due to dredging and renourishment. Renourishment works at South Beach in 1996 are a known source of sediment feed. Less quantified and potentially more significant sand feed occurred following extensive dredge spoil disposal during excavation of the Success and Parmelia shipping channels in the 1950s. Material disposed north of Success Bank apparently came slowly ashore over decades in the vicinity of South Beach (WS Andrew, photo record; Oceanica *et al.* 2008). Previously analyses of coastal change for the Owen Anchorage area (MP Rogers & Associates 2005a; Oceanica 2010a) do not clearly identify whether anthropogenic influences have been taken into account, and therefore it is possible that supply rates for early reported periods (1942-2003 and 1972-1994) are artificially high (Oceanica *et al.* 2008).

The interpretation is presented as indicative sediment pathways for Owen Anchorage (Figure 24) and Cockburn Sound (Figure 25). Potential transport rates are presented as High, Moderate or Low based upon relative wave exposure and the apparent active depth of change observed from monitoring profiles. Particular note should be made for pathways that are 'subject to reversal' or 'supply controlled' as response to any imposed coastal change (natural or artificial) in these locations may not be reflected by the historic volumetric change. In simple terms, these pathways represent the likely net direction of transport if unconfined material were deposited at that location.

The indicative sediment pathways require suitable interpretation for coastal change assessment. Three different phenomena are apparent within the historic record, including:

- Net sediment transport;
- Episodic response, to storms or moderate-term climate variability; and
- Variability of the offshore sand supply.

The pathways may be used to estimate change by considering how modification of one arrow would affect the relative balance to adjacent arrows (e.g. 'turning off' the sand supply at Catherine Point would cause erosion both north and south of the groyne). In addition to the historic phenomenon, the indicative pathways may provide an indication of the possible spatial distribution of sea level rise response, through consideration of cross-shore profile adjustment as a sediment demand (Figure 26).

Overall, the sediment pathways identified within the OACS coast are unlikely to change significantly as a result of elevated water levels (in the order of 1m change). However, dramatic changes are likely to occur with respect to the rates at which sediment is supplied to discrete areas Sensitive locations are likely to occur where the sand presently feeds onshore (Catherine Point, Woodman Point), and towards the downdrift end of a compartmentalised beach sequence (James Point, Coogee Beach). There is some potential for erosion to shift to updrift areas in zones of high transport (e.g. south of Catherine Point).

Figure 26 schematically illustrates the effects of sea level rise upon a partitioned (controlled) coast. Under present-day conditions, supply into the cell is almost balanced by loss out from the cell. Cross-shore profile adjustment due to sea level rise creates a sediment deficit, which 'uses up' the sediment supply until there is net erosion within the cell. The position within the cell for which this occurs varies, with transport that is supply-determined preferentially experiencing erosion downdrift (the supply 'runs out' before reaching the downdrift end of the cell); and rate-determined transport likely to experience erosion updrift (sediment is preferentially retained downdrift). Potential locations for rate-determined transport are south of Catherine Point and north of Woodman Point.

A summary of interpretation of coastal change on the OACS coast is included in Figure 27.

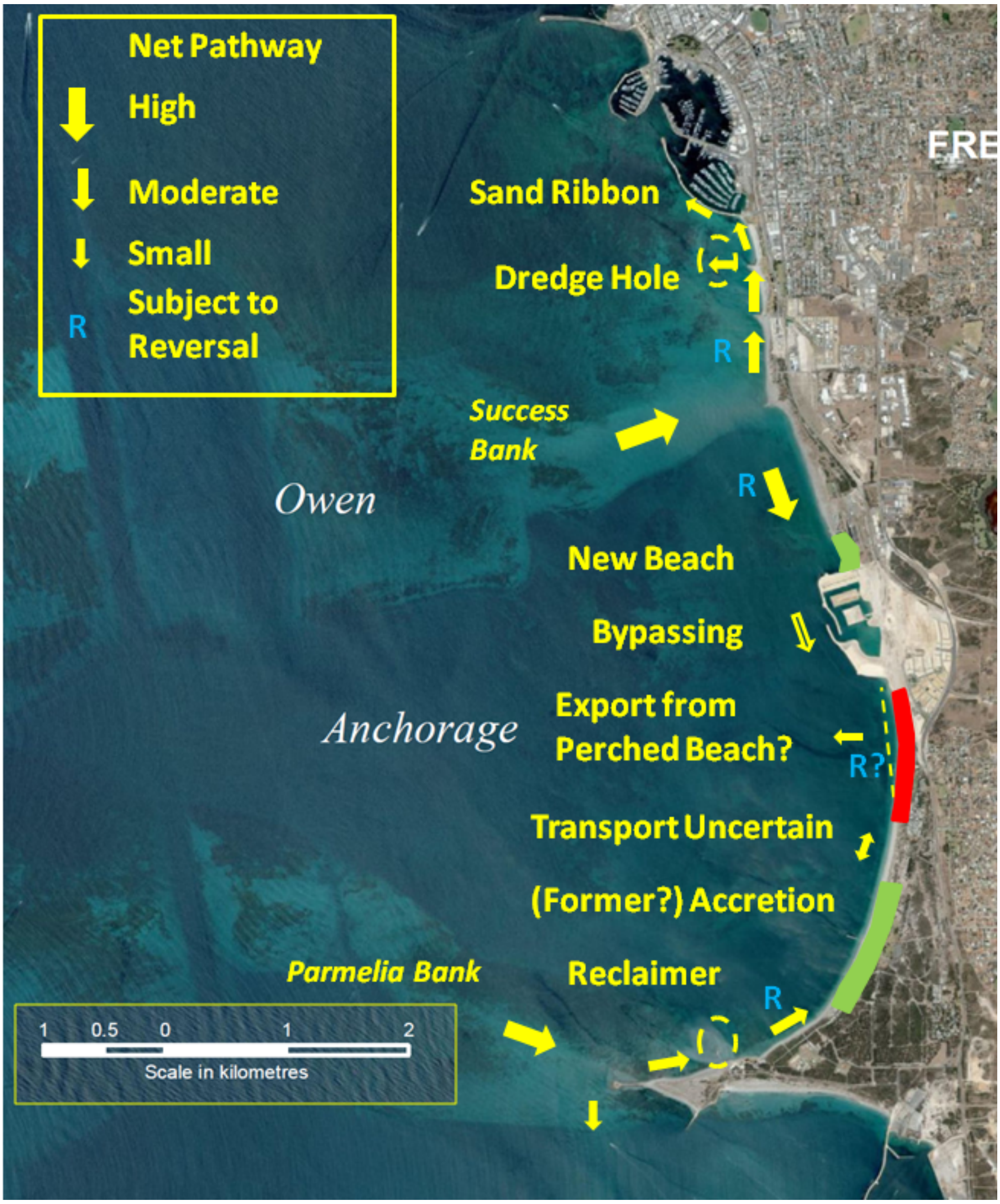

Figure 24: Indicative Sediment Pathways for Owen Anchorage

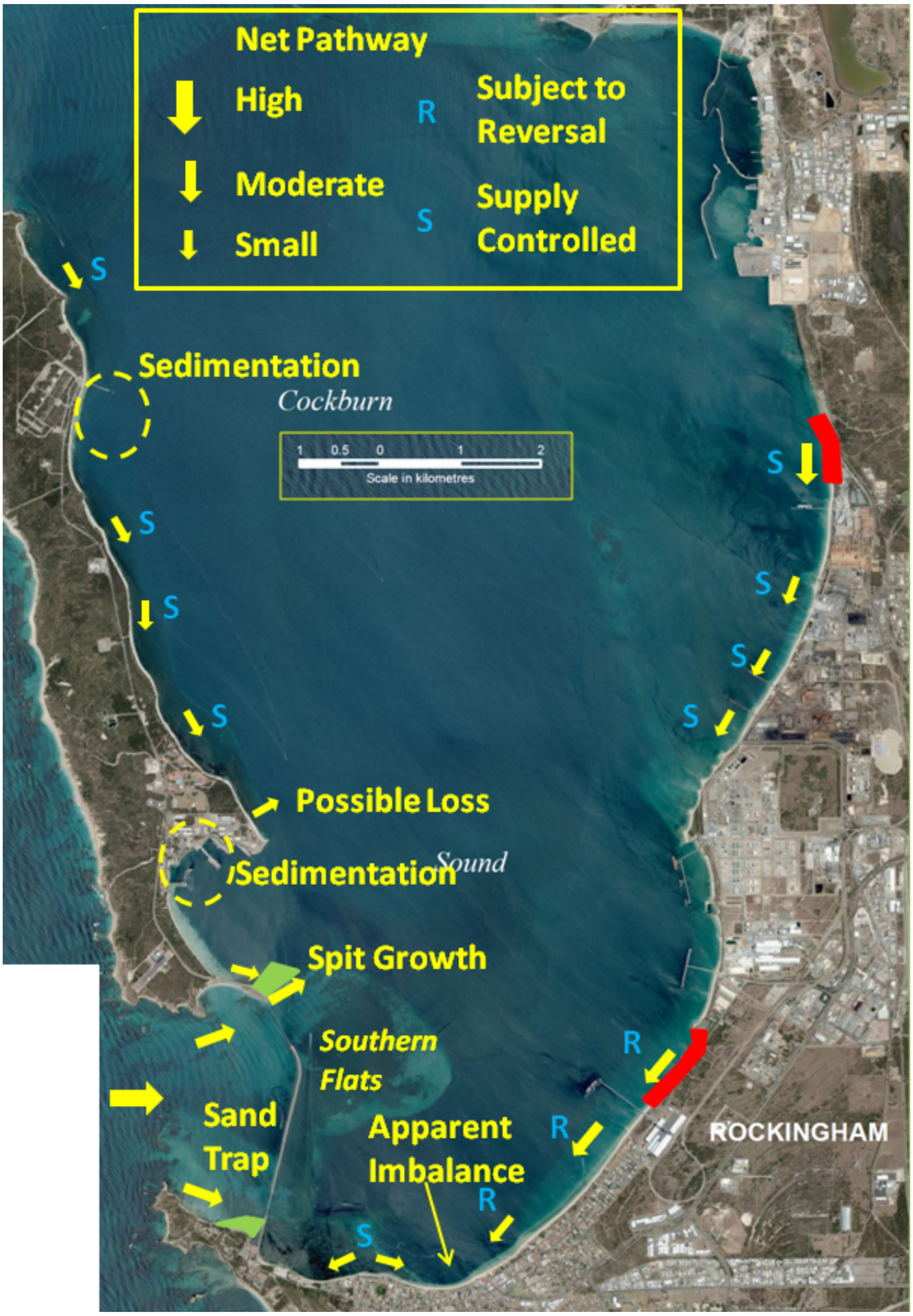

Figure 25: Indicative Sediment Pathways for Cockburn Sound

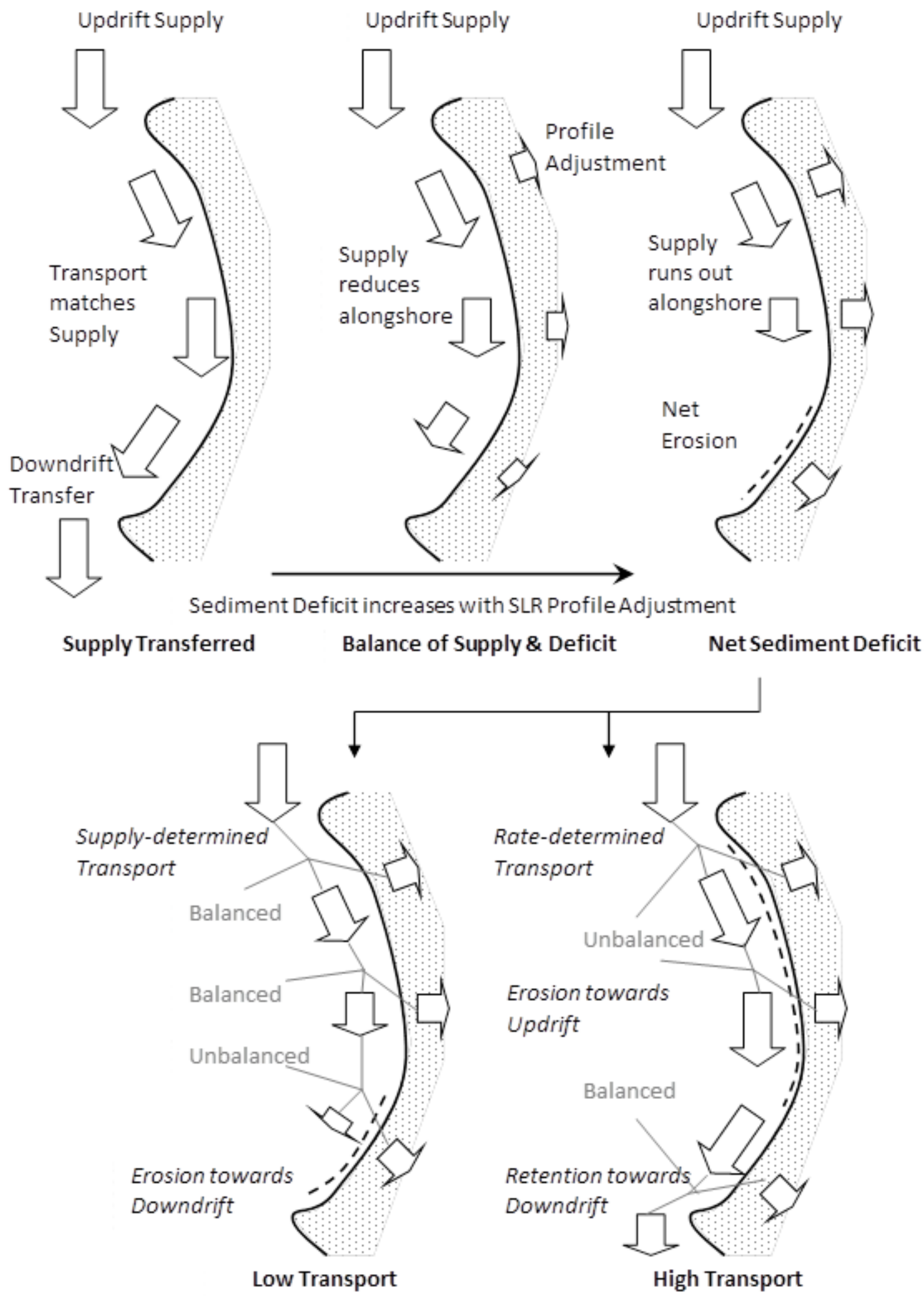

Figure 26: Coastal Response to Sea Level Rise Profile Adjustment (Schematic)

COASTAL CHANGE & THE OACS COAST

Attributes:

- Extensive record of profile data collected at locations through the OACS coast including march and September 2003 measurements
- Discrete modes and levels of change associated with different profile morphotypes that vary with aspect, exposure and terrace structure
- Limited natural change on the upper profile. Response to storms is registered with limited bulk trend indicated by vegetation line analyses
- Vegetation line analyses largely captures response to beach nourishment and engineered structures
- Long term change observed on the terrace and terrace slope

Implications for Present Study:

- Approaches applied to assessment of coastal change on open ocean coasts has limited applicability
- Understanding the terrace behaviour is important to interpreting potential future change
- Caution required in selecting analysis techniques to ensure the correct process response relationships are captured to the relevant scale
- Methods for the assessment of coastal hazard vary for different sediment cells due to the complexity of the morphology of the OACS coast. Assumptions applied to homogenous coasts are not appropriate
- Coast is considered to respond with internal redistribution to changes in forcing

Key References:
PWD 1979, 1989; MP Rogers & Associates 2005a, 2005b; Oceanica et al, 2008; Oceanica 2010a, 2010b

Figure 27: Summary of coastal change attributes for the OACS coast and associated implications for the present study

3.7 SUMMARY OF EXISTING COASTAL DYNAMICS

The OACS coast is anticipated to behave differently in the future to how it has behaved in the past, complicating interpretation of coastal datasets and prior analyses. The OACS coast is:

- Not wholly in equilibrium with present day environmental forcing. It is an old basin with relict features and large sediment banks
- Controlled by rock at varied elevations
- Partitioned by changes in aspect, submarine landforms, rock, sediment supply and large geomorphic features. The broadest separations are at Garden Island Causeway, James Point and Woodman Point/AMC.
- Further partitioned by engineered structures
- Largely responding to prior engineering works and active sediment management
- Supplied by onshore feeds in Owen Anchorage with unknown unreliability
- Comprised of low-lying foredune plains in some sections vulnerable to inundation

- Sheltered from open-ocean waves with locally variable wave climates. The wave climate is anticipated to alter with sea level rise
- Responsive to higher water levels due to a small tidal range
- Responsive to seasonal variability in metocean (wind, wave and water level) processes
- A low-energy coast with large terrace features, with sediment transport processes and coastal response different to an open coast. Coastal response occurs on the terrace, the beach and in the dunes.

The combination of this understanding requires different approaches to considering coastal hazard for each section of coast. A basis for sectioning the coast was to use the eight mainland and three Garden Island secondary cells denoted by DoT (Stul et al. 2012) as there is a degree of similarity in processes and coastal attributes within each cell. Key attributes of each of the cells are summarised in Table 7.

The basis for sediment cell identification considered the presence of rock, width of the sub-tidal terrace, the height of the dunes and coastal orientation, and therefore provides a preliminary spatial clustering. This suggests that, at a minimum, at least one transect (cross-shore profile) is required for each sediment cell. However, it was recognised that aggregation at a cell-scale effectively ignores sub cell-scale variations of morphology or wave climate. Consequently, analysis of the LADS and LIDAR data was undertaken to provide an initial disaggregation with supporting interpretation of the extensive profile data for OACS coast.

The OACS coast was separated into 35 transect 'zones' that each required a minimum of one transect to suitably represent the spread of observed coastal response (Figure 28 and Figure 29). Actual transect locations were selected to match previous monitoring program survey lines (DALSE 2003; Oceanica 2009) for comparison with measured data. In general terms transects were located toward the central portions of each zone, to reduce updrift or downdrift influences when comparing modelled and measured responses, as modelling for present-day conditions only captures cross-shore erosion (S1).

A process of aggregation and disaggregation of data through upscaling and downscaling is required to capture the most relevant temporal and spatial scales for each site. This is discussed further in pertinent components of Sections 4 & 5 that follow

Table 7: Attributes of Coastal Cells per Local Government Area.

Cell number and boundaries	Attributes	Local Government Area
22: Catherine Point groyne to South Mole Fremantle	Supply to the north from Success Bank onshore feed at Catherine Point. Broad shallow nearshore associated with Success Bank. Transport interrupted by Success Harbour.	City of Fremantle and City of Cockburn
21: Woodman Point (WAPET groyne) to Catherine Point	Supplied by material from Success and Parmelia Banks. Material transported south from Success Bank and north from Parmelia Bank. Significant interference by Port Coogee constructed on rock platforms and outcropping of the Spearwood Ridge.	City of Cockburn
20: Woodman Point groyne to Woodman Point (WAPET groyne)	Artificial coast with sediment from Parmelia Bank impounded on structures.	City of Cockburn
19: Australian Maritime Complex to Woodman Point groyne	Compartmentalised coast with no direct sediment supply. Groyne structures extend beyond terrace.	City of Cockburn
18. James Point to Australian Maritime Complex	James Point lacks a contemporary sediment supply, controlled by a change in aspect and rock features. Coast is part of the partially infilled basin of Jervoise Bank. Coast has a terrace, with the coast partitioned through individual engineering works.	City of Cockburn and City of Kwinana
17: Palm Beach Rockingham to James Point	Low-lying foredune plain coast has a change of aspect with beaches more exposed to the northeast. There is a narrow terrace in Mangles Bay, with a deeper and broader terrace to the east underlying the narrow terrace. James Point lacks contemporary sediment supply and is controlled by a change in aspect and rock features.	City of Kwinana and City of Rockingham
16: Garden Island causeway to Palm Beach Rockingham	Low-lying foredune plain coast with behaviour influenced by marine features, exposure to the north and the Causeway. Broad terrace width increases to the west of the cell.	City of Rockingham
15: Cape Peron to Garden Island causeway	Foredune plain located between large rock outcrops as part of the Garden Island Ridge. Recent foredune plain growth associated with the Causeway. Influenced by pulses of sediment supply through the Garden Island Ridge. Causeway has modified local wave climate.	City of Rockingham
GI2: Parkin Point to Colpoys Point	Careening Bay is altered by the Causeway, facilities and dredging. Loss of material from the coast is partially transferred to Parkin Point spit. No significant supply to the beaches and limited capacity of recovery.	Department of Defence
GI1 : Colpoys Point to Dance Head	Coast is sheltered from most extreme events with shallow embayments controlled by rock outcrops from the Garden Island Ridge and marine features of variable extent and depths. Limited capacity for storm recovery.	Department of Defence
GI4: Dance Head to Beacon Head	Some sediment supply transported around Garden Island south past Beacon Head with reworking. Coast controlled by rock outcrops and marine features.	Department of Defence

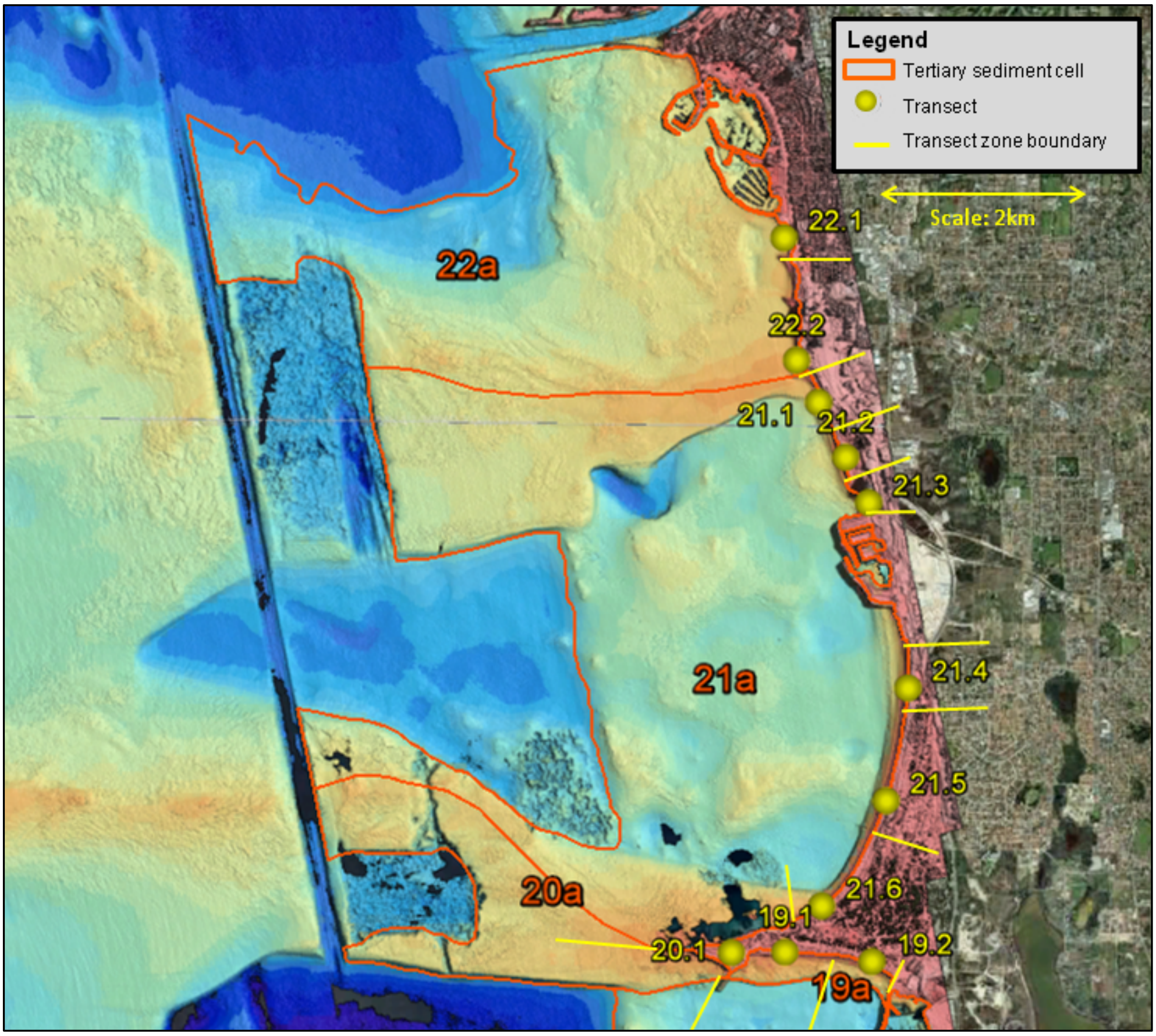

Figure 28: Cells and transects, Owen Anchorage

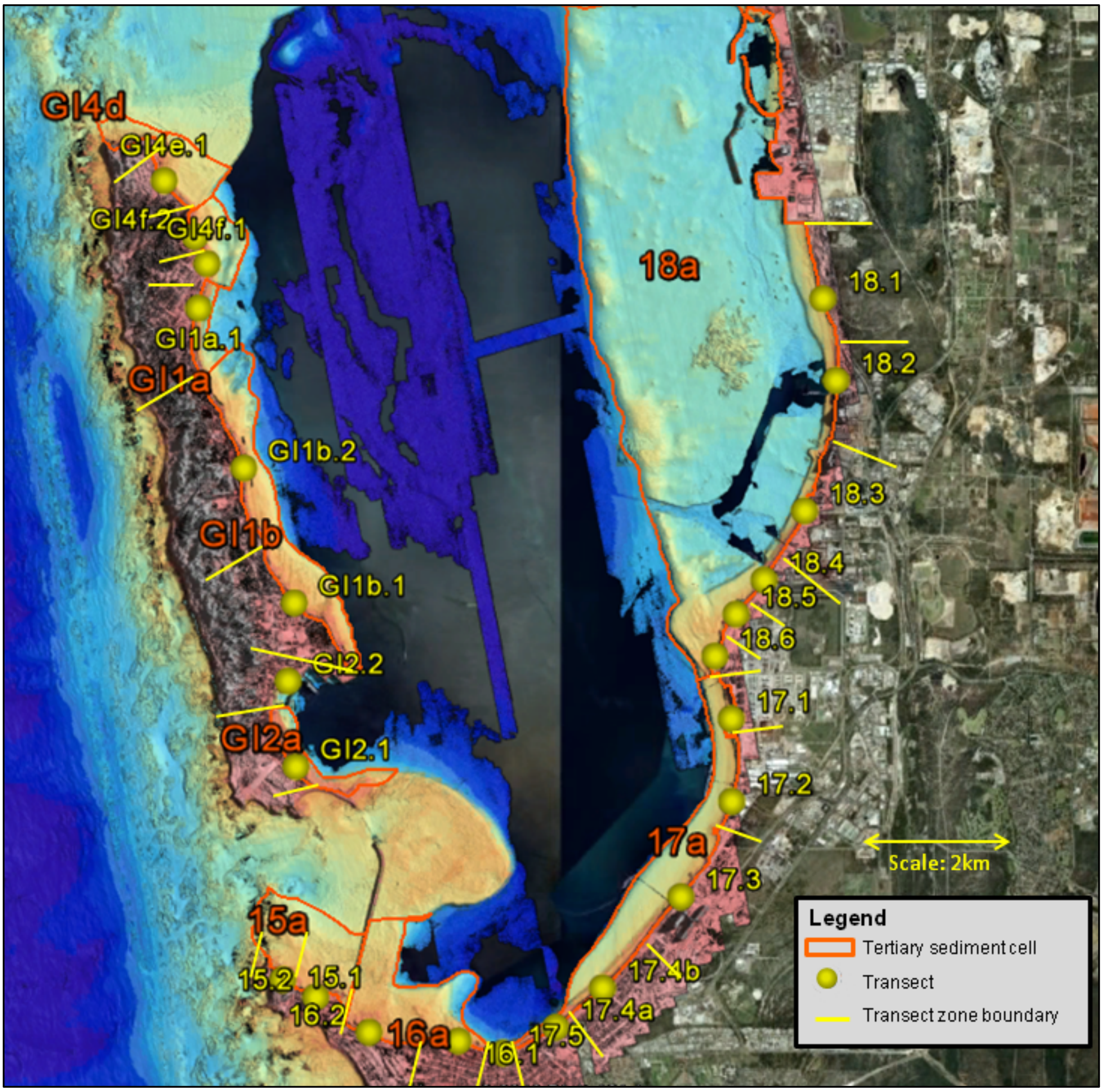

Figure 29: Cells and transects, Cockburn Sound

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4. Methodology

The Project Scoping phase was used to identify methodologies that could provide a practical representation of coastal hazards affecting the OACS coast and their change due to sea level rise. An important constraint was the effective use of modelling (which identifies spatial variance), compared with available relevant data sets (Figure 30), and their potential role in model validation. Acute response modelling requires 1 or 2 short periods of hydrodynamic modelling, which can therefore be effectively captured within the ambient modelling, which requires at least four individual months over a year to describe seasonal variations. However, to develop an understanding of the spatial variation of extreme events requires modelling of multiple (30+) short periods, with model validity only able to be evaluated at discrete locations or a limited part of the available record.

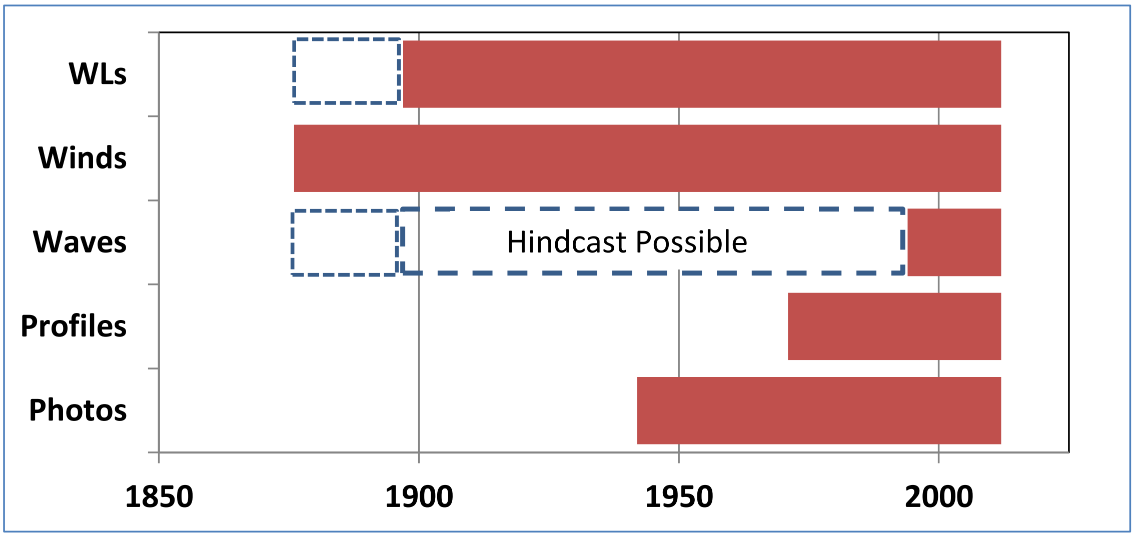

Figure 30: Length of Available Relevant Datasets

Information available for validation of inundation modelling was effectively restricted to Fremantle (1896-2012) and Mangles Bay (1991-2011) tide gauges. Comparison of extreme water levels for the two locations demonstrated insufficient range to justify the use of hydrodynamic modelling to estimate spatial variation (Figure 31). The absence of coastal waterbodies also implied a relatively small variation of inundation levels, as flood lag through estuary entrances typically causes the most significant variation (e.g. MacPherson *et al.* 2011).

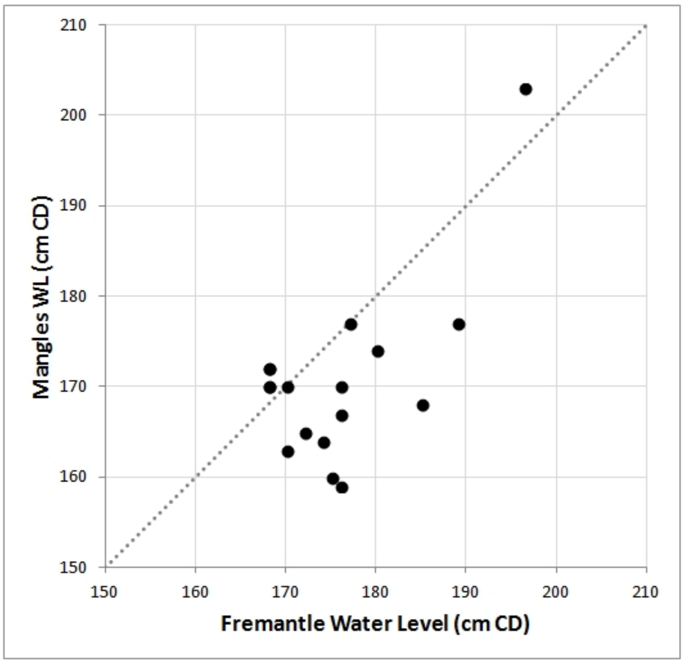

Figure 31: Comparison of Peak Hourly Water Levels During Extreme Events Overlapping at Mangles and Fremantle (1991-2011)

Following the terminology outlined in Table 8, a ‘Secondary’ level of assessment was applied, with focus upon the topography. This is colloquially referred to as a ‘bathtub’ assessment, which are commonly disparaged when applied to estuarine areas, or when wave setup or runup is included in the evaluation – neither of which is the case for this study. The inundation assessment approach was selected due to the availability of high resolution topography, the relatively discrete areas of low-lying land and the relative simplicity of available extreme water level information.

Table 8: Types of Inundation Assessment (Adapted from Damara WA 2009)

Assessment Classification	Assessment Type	Additional Information Needs	Decision Making Use
Primary	Numerical	Water level observations	Regional planning / Site selection
	Empirical	Bathymetric cross-section	
	Parametric	Storm parameters	
Secondary	Oceanographic	Bathymetry	Development / Structure siting
	Inundation	Topography	
Tertiary	Tidal inundation	Tidal characteristics	Structural / Risk assessment
	Morphodynamic	Sediment mobility	

In contrast to the inundation assessment, the Project Scoping phase indicated that a more complex representation of erosion was required. The OACS coast displays changes in process-response characteristics over relatively small spatial scales and demonstrates coastal behaviour that reflects the legacy of extensive artificial manipulation. Evaluation of the observed patterns of change suggests that much of the coastal response to changing conditions occurs through adjustment internal to coastal sediment cell scales. Coastal response to sea level rise has been evaluated through overall cell behaviour, locally downscaled by incorporating the influences of sediment transport controls, both natural and artificial.

The varied characteristics of the coastal zone mean that no one-size-fits-all approach is appropriate for analysis. Rather, it was necessary to adopt a multi-scaled assessment approach in the context of coastal sediment cells of the OACS coast, with smaller scale effects due to sediment transport controls. Between the different erosion components, the reliability of available information provided constraints to process estimates. The most extreme constraint was provided by the lack of available data to validate wave modeling inside Cockburn Sound. As a consequence, the modeling process represented significant spatial extrapolation from a single point of validation at Owen Anchorage Wave Buoy. Whilst qualitative efforts were undertaken to assist the reliability of the wave modeling, its performance for low to moderate energy conditions was deemed unsatisfactory, hence limiting the model use to generation of extreme wave conditions for acute erosion modeling.

An overview of key project efforts is provided in Table 9. Tasks associated with these efforts are aligned to the constituents of coastal change outlined in the State Governments Coastal Planning Policy Guidelines (SPP 2.6) where S1 relates to the acute erosion response; S2 refers to the historic trend of shoreline movement and the cause for this movement while S3 relates to erosion caused by future sea level rise.

Table 9: Project Efforts & Relationship to S1, S2, S3 Components

Summary of Key Project Efforts

Ambient Metocean Modelling (Addresses S3)
- Modelled over whole of OACS coast for extended time frame.
- Used to identify spatial variations to change in wave climate (height & direction) with SLR
- Used to describe change in sediment budgets with SLR.

Extreme Metocean Modelling (Addresses S1)
- Modelled for whole of Sound for short time frame for known erosion event (May 2003)
- Used to define boundary conditions for 1D SBEACH Modelling

SBeach 1D Modelling (Addresses S1 and contributes to S3)
- Modelled for 35 individual transects for short time frame of May 2003 event/
- Used to identify cross-shore response (S1) including overwash and profile adjustment to SLR/changing wave climate (S3)
- Transect selection based upon geomorphic and metocean similarity. Attributes used to consider transect selection include Geology / Coastal Alignment / Nearshore Bathymetry / Dune Topography / Spatial Wave Variation (sediment cell basis implies a degree of similarity).
- Used to identify distributed cross-shore responses, including overwash and profile adjustment to SLR/changing wave climate (S3).

Sediment Budget Interpretation (Addresses S2 and contributes to S3)
- Considers sediment budget for each sediment cell
- Uses change in ambient waves to indicate change from historic transport patterns
- Uses geomorphology to describe variation of sediment deficit
- Uses retentive capacity of controls (including cell boundaries) with updrift/downdrift patterns of response

Elements contributing to Acute Coastal Change assessment (S1)
- SBeach 1D Modelling
- Extreme Event Metocean Modelling
- Survey Profile Interpretation
- LIDAR / LADS Interpretation

Elements contributing to Coastal Evolution assessment (S2)
- *Ambient Wave Modelling*
- Geomorphic Interpretation
- Sediment Budget Interpretation
- Survey Profile Interpretation
- Aerial Photograph Interpretation
- Coastal Geology and Stratigraphy

Elements contributing to Climate Response assessment (S3)

- *SBeach Modelling*
- *Ambient Wave Modelling*
- Geomorphic Interpretation
- Sediment Budget Interpretation
- Sediment Deficit Analysis
- Survey Profile Interpretation
- Aerial Photograph Interpretation
- LIDAR / LADS Interpretation

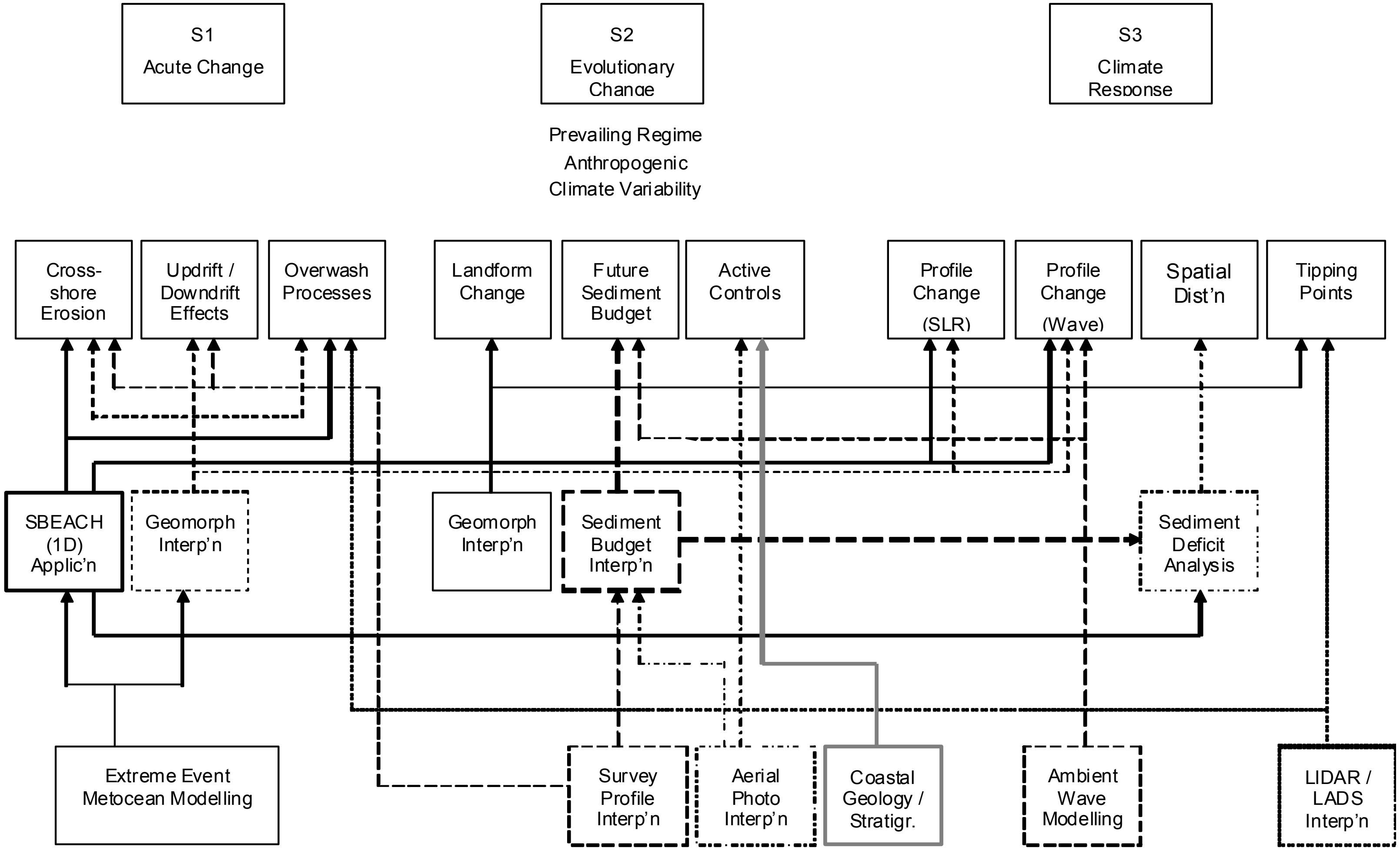

Figure 32: Coastal Process Flowchart[14]

[14] Elements of the erosion hazard analysis undertaken are aligned to the terminology applied in State Planning Policy SPP 2.6

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One aspect of the work completed was separate presentation of erosion and inundation hazards. The decision to adopt this approach rather than a composite hazard map was taken at the outset of the Project because impacts of erosion and inundation require different adaptation planning[15]. Consequently, separate hazard mapping for erosion and inundation provides an appropriate input to Phase II of the Cockburn Alliance Coastal Vulnerability Study.

It is relevant to note that whilst both inundation and erosion are best expressed probabilistically (i.e. in terms of average recurrence interval), comparison of event likelihoods should be undertaken carefully, due to differences in the associated impacts and the relative importance of typical of extreme events. For the OACS coast, over planning time scales up to 100 years, adverse impacts of inundation is generally associated with acute processes (trend plus >10 year ARI events), whereas erosion is more strongly affected by gradual processes (trend plus 1-5 year ARI events). This distinction has implications for management, with gradual erosion more readily managed through avoidance or maintenance of adequate buffers (Dekker *et al.* 2005; Larson *et al.* 2009). The potential for acute erosion remains an important consideration, particularly where it may destabilise coastal barriers (rare on the OACS coast), or where coastal barriers are not able to migrate landward due to lack of coastal reserve.

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 5) . 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.

4.1 INUNDATION HAZARD

Work undertaken to complete the inundation hazard assessment involved the following steps:

1. **Primary analysis of topography** – an initial evaluation of the coastal topography was conducted, to determine the presence and extent of depressions that may be subject to coastal inundation under sea level rise. This step was undertaken to identify viable approaches for inundation

[15] Development of a composite hazard map requires that it corresponds to an equivalent form of hazard mitigation. Most commonly, this is associated with setback definition, where mitigation is provided by hazard avoidance.

assessment, such as whether erosion of coastal barriers needed to be considered. The rising topographic structure and limited presence of extensive depressions below the dune crest indicate that a simple analysis using ocean water levels would give meaningful results.

2. **Analysis of existing water level datasets** – following work undertaken by Eliot (2012), the historic water level record was identified as likely to understate the hazard of extreme floods. Consequently, estimation of inundation levels with 1 year, 10 year, 100 year and 500 year Annual Recurrence Intervals (ARIs) for the OACS coast were based upon the Fremantle record, but including additional allowance based upon the statistical confidence interval. The water level reported excludes wave effects (runup and setup) as these are relevant specifically at the coast and effectively captured in the erosion assessment. This deliberate focus for the inundation assessment was to identify areas which may be treated with adaptation measures separate from erosion mitigation.

3. **Addition of projected sea levels for specified climate change scenarios** – influence of sea level rise upon coastal flooding was incorporated by adding a time-varying sea level allowance in accordance with the recommended sea level curve (Department of Transport 2010). The curve is consistent with the A1FI climate change scenario adopted by IPCC. An additional scenario of +1.5m sea level rise was included to test for high end sensitivity.

4. **Application of inundation levels to high resolution topography** – the identified sea levels were compared with a digital elevation model (DEM) developed from the Department of Water's Light Detection and Ranging (LIDAR) dataset to determine areas with direct connection to the coast where inundation will occur.

Inundation hazard was evaluated for each of the three timeframes selected for the study (present day, 2070 and 2110) and corresponding projections for changes in mean sea level (i.e. 0, +0.5m, +0.9m, +1.5m). The approach to inundation assessment was deliberately less severe than that of addressing erosion hazard due to the potential for minor damage to occur during low flooding, whilst any erosion reaching infrastructure is likely to cause failure.

- Coastal inundation mapping has been based upon tide gauge observations at Fremantle, from 1896 to 2011. Limitations of this database for extrapolation to future conditions have been previously identified, with recognition of the roles of tidal phase and modulation (Eliot 2011), non-tidal cycles (Haigh et al. 2011; Eliot 2012) and inter-annual variability of synoptic conditions (Haigh et al. 2010). Consequently, an extreme distribution based upon historic data was modified (Figure 33) to provide allowance for these additional sources of variability. Four inundation events relative to present day mean sea level were identified, covering the probabilistic range from

0.2% to 63% annual exceedence probability (1 to 500 years ARI; Table 10). Present-day 100-year inundation scenarios are comparable with the observed total flood levels (including wave action) during 16 May 2003 event. Wave runup was not included in the analysis, as due to its near-coast nature, its effect upon inundation declines very rapidly with landward propagation. Future scenarios were considered to result from the direct addition of these inundation events to the mean sea level rise allowances of +0.5, +0.9 and +1.5m.

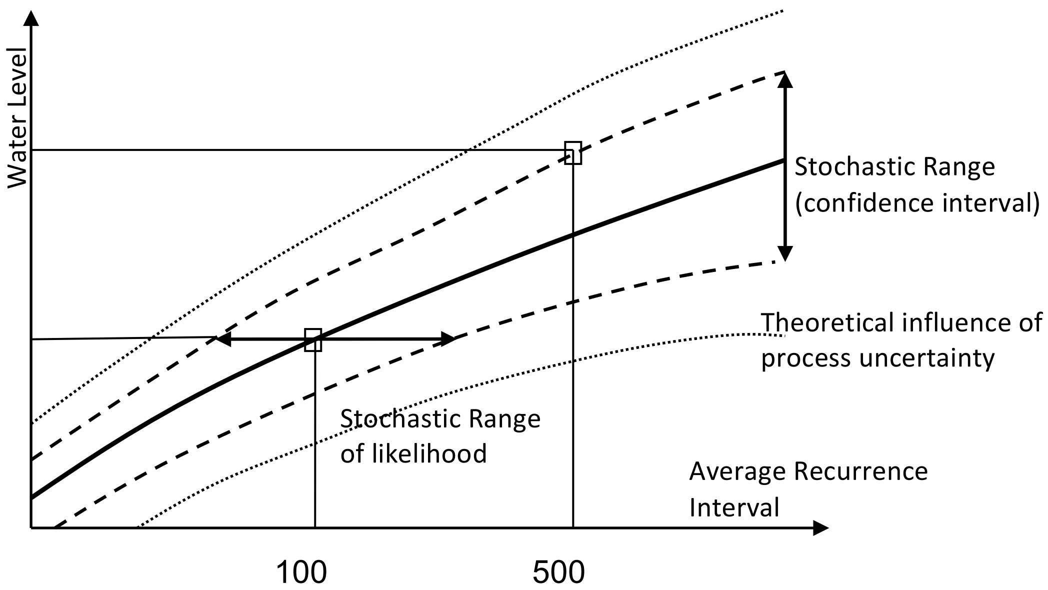

Figure 33: Schematic Showing Definition of Inundation Scenarios

A shorter available data set from Mangles Bay (1991-2011) was used to consider spatial variation (Figure 31). This generally showed slightly smaller extremes than the Fremantle record, although the difference is within the likely effects of synoptic variability when comparing 20 and 100 year data sets (Haigh et al. 2010).

Increased in storm event intensity or frequency were not incorporated into the storm inundation levels for future conditions. Available forecasts e.g. CSIRO 2007) are equivalent to the uncertainty of increased sea level rise as it would not significantly alter the inundation levels. For example, an increase in the storm component of an inundation level by 10% would only translate to a 4cm (3%) increase in a 1 year ARI level, which corresponds to only 8% of a 0.5m sea level rise. The increased storm intensity of frequency would not significantly alter the inundation levels, the threat to values or the need for adaptation.

Table 10: Inundation Scenarios

	Present Day	+0.5m SLR	+0.9m SLR	+1.5m SLR
1 year ARI 63% AEP	1.00m AHD	1.50m AHD	1.90m AHD	2.50m AHD
10 year ARI 10% AEP	1.16m AHD	1.66m AHD	2.06m AHD	2.66m AHD
100 year ARI 1% AEP	1.34m AHD	1.84m AHD	2.24m AHD	2.84m AHD
500 year ARI 0.2% AEP	1.48m AHD	1.98m AHD	2.38m AHD	2.98m AHD

Small differences between the ARI levels for inundation scenarios highlight the subtlety of flood risk and suggest the need to use high resolution topography for the assessment. High resolution data also enables the identification of hydraulic connections between the coast and lowlands, which are commonly narrow channels which may be obscured in coarse resolution topography.. Inundation levels were applied to the Department of Water LiDAR high-resolution topography from 2008, captured at a 1m spatial resolution with a ±0.1m vertical accuracy. Modifications to dune levels, seawalls or structures since 2008 are not captured in these maps. Inundation levels for Garden Island will require mapping by Department of Defence using a detailed Digital Elevation Model because the Department of Water LiDAR does not cover Garden Island. The incomplete Digital Terrain Model from the Department of Planning LADS was not of sufficient accuracy to capture the inundation hazard (Figure 33).

The inundation values in Table 10 are higher than those available in the on-line sea level rise decision-support tool available from the Antarctic Climate & Ecosystems CRC [16], a revised Canute 2 tool from the ACE-CRC[17] (+1.2mAHD for present day 100-year ARI event) and the Ozcoast website maps (+1.2mAHD, +1.4mAHD and +1.8mAHD)[18], but are lower than those suggested by MP Rogers & Associates for finished floor levels (+3.8mAHD for +0.9m SLR scenario)[19]. These differences are largely methodological, with the MP Rogers & Associates levels incorporating wave components and an additional safety margin freeboard.

[16] ACE CRC's Sea Level Rise Decision-Support Tool http://slr.sealevelrise.info/cms/Decision-Support%20Tool

[17] ACE CRC's Canute Sea Level Rise Decision-Support Tool.

http://canute2.sealevelrise.info/slr/About%20%20Canute

[18] http://www.ozcoasts.gov.au/climate/Map_images/Perth/mapLevel2_North.jsp

[19] MP Rogers & Associates (2011).

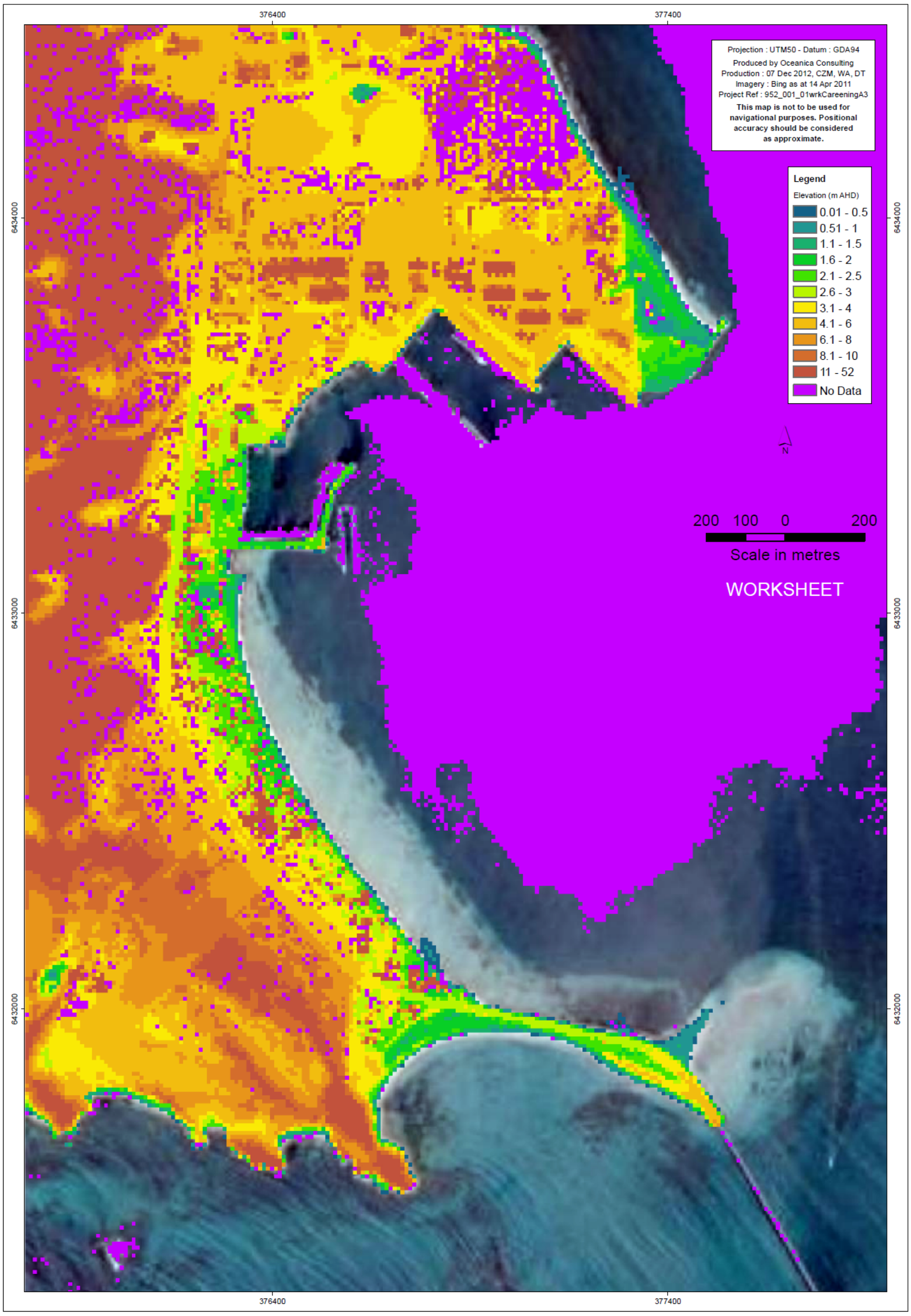

Figure 34: Example of Topographic Levels on Garden Island derived from LADS. Note that buildings, trees and 'missing' data constrain use of the DTM for inundation mapping

ACE-CRC use of the joint probability method (integrating combined tide and tidal residual distributions) to derive extreme water levels. This simple method is biased in south-west WA by the simulation of surge by tidal residual, with up to 50% of the tidal residual being associated with mean sea level anomalies. As a consequence, the ACE-CRC method creates opportunity for combining (slightly) exaggerated non-winter tidal residuals with high winter tide and mean sea level.

The Canute tool (Mason *et al.* 2012) used a GEV distribution and used a simple representation of non-tidal processes that affect total water level distributions at Fremantle, potentially resulting in an underestimate of the reported ARI values. For illustration, the reported 10 and 100 year ARI levels of +1.00m AHD and +1.22m AHD have been exceeded 12 times and twice in the last 70 years, which is not statistically supportive. It is worth recognising that the Canute tool methodology was developed for the whole of Australia and therefore detailed representation of non-tidal processes was impractical.

Ozcoast maps are presented as +0.5, +0.8 and +1.1m SLR scenarios above Highest Astronomical Tide (+0.64mAHD; Department of Defence 2010), without consideration of other water level processes, such as storm surge and meteotsunami, that are often of similar order of magnitude to tidal fluctuations. These values are mapped on a coarse-resolution DEM that is of insufficient resolution to capture the implications of the small differences between the ARI levels.

The high finished floor level values in the MP Rogers & Associates (2011) investigation presented a 100-year ARI level of +1.2mAHD at 6m depth, with a setup between 6m depth and the coast of +1.2m, a 0.9m allowances for sea level rise and freeboard of 0.5m to a total finished floor level of +3.8mAHD. The large discrepancy between this study and the MP Rogers (2011) investigation is due to the wave setup component and an additional freeboard. It is noted that the wave setup component is large given its short distance of generation, and the relative complexity of the coast, which will distribute some of the energy to circulation rather than solely to setup.

4.2 EROSION HAZARD

Observations of change suggest that there are several different mechanisms for coastal change. Some of these are locally relevant, such as downdrift erosion immediately adjacent to structures; whereas other active processes are effectively distributed across segments or reaches of coast of different size. Storm response often affects the coast at the scale of a sediment cell through beach rotation (hundreds of metres to a few kilometres), whilst the effects of sea level rise are active over the whole coast, albeit distributed more locally. There is a general relationship between time and space scales.

Assessment of erosion hazard for the OACS coast was undertaken by considering the anticipated change in sediment availability at varying spatial scales and considering local controls (namely coastal structures). The approach to the analysis may be summarised as follows:

- Assessment of potential short-term (acute) erosion, due to both storm response and fluctuations of environmental conditions over typical intervention time scales (1-2 years)
- Assessment of more gradual changes in shoreline position, including response to sea level rise
- Evaluation of the amount of sediment removed from the shore, as calculated through Step 1 and 2 of the analysis, to project landward retreat of the shoreline (erosion) within each section of the coast.

This information was used as the basis for establishing erosion hazard lines for each scenario considered in the study.

The complexity of coastal response identified within the historic record of profiles and vegetation lines (Oceanica 2010a, 2010b) demonstrated several attributes that influenced the erosion modelling methodology:

- The role of sand feeds at Success and Parmelia Banks is evident, with sediment distributed alongshore. This behaviour is consistent with longer term patterns indicated by sediments and morphology inside Cockburn Sound (Skene *et al.* 2005);
- An extensive legacy of coastal manipulation, including the effects of coastal protection works, dredging and dredge spoil disposal has dominated coastal changes;
- Larger coastal structures have provided compartmentalisation along the coast, whereas bypassing has occurred at the majority of smaller coastal structures;
- Change is not uniform along the profiles, suggesting that vegetation lines provide a limited representation of coastal change along the OACS coast, which has implications for estimates of alongshore transport and sand feed rates.
- Some recent observed change includes steepening of the submerged part of the beach profile, which obscures management and 'primes' the coast for enhanced response to acute erosion.

The erosion assessment approach recognised the multi-faceted nature of change along the OACS coast and the potential constraints of applying numerical modelling. Specifically, it was identified at the outset of the project that the low energy morphology (Travers 2007) with a highly partitioned coast, challenged the representations provided by open coast cross-shore and alongshore models. As a consequence, an evidence-based approach was used both to identify active processes and evaluate model performance.

4.2.1 Overview of Approach

The approach to undertaking the erosion assessment follows a sediment budget approach to establish volumetric changes. The assessment was conducted at varying scales incorporating:

- Sediment feeds from Success and Parmelia Banks
- Partitioning and control by rock features and engineered structures.
- Acute and chronic response, both cross-shore and alongshore.
- Capacity for change considering site-specific attributes, such as length of coast, depth, wave exposure, shoreline orientation and observed differences between behaviour of surface and submerged sections of the beach profile.
- Spatially distributed response to sea level rise, incorporating varying profile change and the influence of partitioning.
- .Evaluation of the volumetric loss of sediment as a result of acute erosion (S1), chronic erosion (S2) and sea level rise (S2 & S3) to calculate horizontal distance of retreat for each sediment cell.

An overview of the component parts to the volumetric assessment outlined is presented in Table 11. Tasks associated with these efforts are aligned to the constituents of coastal change outlined in the State Coastal Planning Policy (SPP 2.6) where S1 relates to the acute erosion response; S2 refers to the historic trend of shoreline movement and the cause for this movement while S3 relates to erosion caused by future sea level rise.

The acute response relates to change induced under storm conditions, both alongshore and cross shore response. Acute response was determined by interpretation of beach response modelling in the context of the actual morphology of discrete coastal reaches and by considering local control exerted by structures or rock. Cross-shore beach response modelling was conducted using wave model output. Longer-term response interpreted previous sediment transport and sediment budget rates, previous response to engineered structures, potential wave climate response to sea level rise and the broader response of the coast to sea level rise. Erosion is considered separately for acute erosion and chronic erosion because acute erosion is essentially a surface response (sand moves cross-shore, often raising the nearshore bed), whilst chronic erosion represents a permanent shift of the whole beach profile.

Table 11: Summary of analysis undertaken to determine likely erosion hazard (as a horizontal distance of retreat) per coastal cell.

	ATTRIBUTE	APPROACH	OUTCOME	EROSION CONTRIBUTION
1.0	**Acute Response**			
1.1	**Cross Shore**	Interpretation of SBEACH model output for May 2003 extreme event for specified water level scenarios (i.e. present day conditions, +0.5m, +0.9m, +1.5m).	Maximum shoreward extent of erosion under storm conditions at selected profile locations per cell for each water level scenario under consideration.	15-60m typical
1.2	**Alongshore**	Applied beach rotation (based upon sensitivity, changes in volume, rates of change) for extreme alongshore sequence (e.g. year of strong NW storms or strong seabreezes).	Potential alongshore changes in cell structure as a result of extreme events under given water level scenarios.	10-15 m
2. 0	Gradual Response			
2.1	**Evolution**	Interpretation of existing profile information and vegetation line analysis to establish decadal scale evolution (i.e. where is material being transferred from/to) & determine how this might change under specified water level scenarios.	Observed patterns of evolution were used to determine alongshore distribution of shoreline erosion associated with net coastal change driven by SLR and acute erosion.	(spatial distribution of 3.2 and 3.3)
2.2	**Structures**	Consideration of existing structures and their present holding capacity (i.e. sources, sinks, level of saturation) to inform assessment of potential future function under changes in water level.	Determination of likely future controls per sediment cell – i.e. which structures are likely to provide active partitions and have the capacity to modify alongshore transport under given water level scenarios.	(spatial distribution of 3.2 and 3.3)
3.0	**Sea Level Rise Response**			
3.1	**Geometric Change**	Assessment of profile geometry to determine the likely change in shoreline position within each cell solely as a result of increased water level for each specified scenario.	Estimation of likely erosion contribution due to shoreward shift in water level along indicative profiles for each sediment cell.	Composite value for 3.1 and 3.2 ranged from 15-50m across analysed profiles
3.2	**Bruun-type response**	Assessment of multiple SBEACH model runs for each profile to determine potential change in shoreline position (loss of sediment from the beachface and redistribution offshore .	Determination of likely loss of sediment from the beachface as a result of sea level rise for each sediment cell under given water level scenarios.	
3.3	**Supply Change**	Identification of local features associated with onshore sand feeds from aerial photo analysis & subsequent assessment of likely changes as a result to modified sand supply with changes in water level.	Estimation of potential modifications to shoreline configuration under altered onshore transport regimes.	~10m in the local vicinity of Catherine and Woodman Points.

4.2.2 Evidence-Based Coastal Change Modelling

All forms of coastal modelling are developed around certain sets of assumptions and physical conditions, that have an associated domain of validity. When applied towards the limit of this domain, there is increasing opportunity for spurious model outcomes. Evidence-based verification is one possible means of identifying potentially spurious results and when applied carefully, provides a framework for defining an 'extended' domain of confidence. The multi-faceted nature of coastal change on the OACS coast, and the potentially tenuous representation of low energy beach dynamics using available models suggested the use of evidence-based verification was appropriate for this study. This may be applied at a range of levels (Table 12) with higher levels providing greater opportunity to identify limits of model performance.

Table 12: Levels of Model Validation and Evidence-Based Verification

Assessment Level	Model Validation	Evidence Based Verification
Primary	Model compared statistically with measured environmental conditions, to calculate error band	Compare overall scale of physical response (e.g. erosion) with model outputs
Secondary	Performance of individual model elements evaluated (e.g. tide, surge, wind response)	Compare physical response for each of the identified processes (e.g. cross-shore, rotation, alongshore, supply loss)
Tertiary	Systematic evaluation of individual model elements (e.g. how model fit changes with storm severity)	Assess spatial or temporal pathways for physical responses to each process (e.g. response only low on profile; terrace growth simultaneous with dune loss)

The concept of evidence-based verification, as illustrated by Figure 35, is to identify the situations under which an aspect of the modelling represents a spurious result. In this way, the modelling can be corrected, re-interpreted, or the functional model limit flagged. Importantly, the divergence does not mean that the model is incorrect, it just indicates the evidence considered does not support the behaviour.

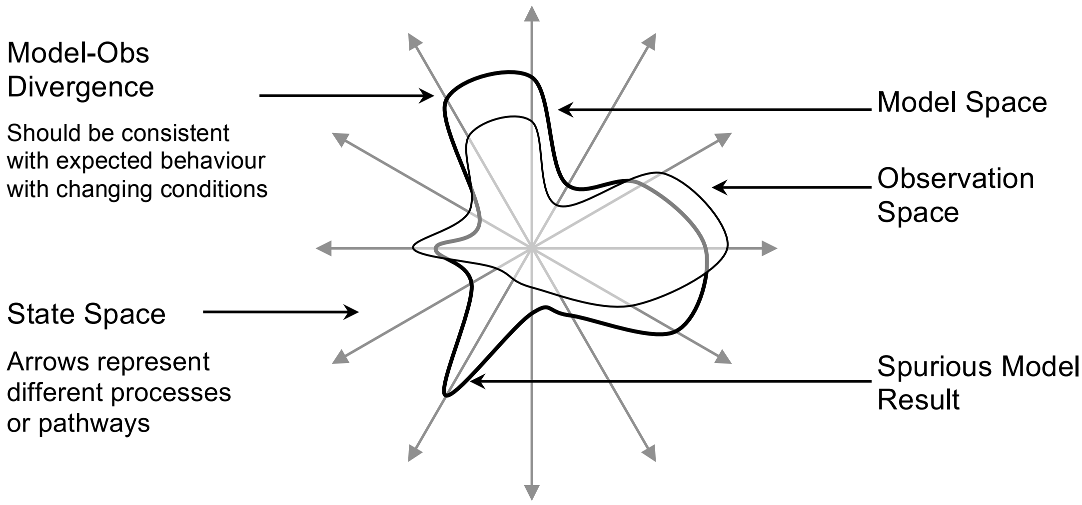

Figure 35: Conceptual Representation of Evidence-Based Verification

4.2.3 Assessment of Potential Short-Term Erosion

This involved interpretation of SBEACH modelling of profile response to the May 2003 storm event with varying mean sea levels; combined with evaluation of likely alongshore variations in sediment cell structure. The potential for alongshore variation was calculated as rotation of selected beach segments, with allowance for relative storm wave energy, capacity for differing wave directions and the degree to which observed coastal change above and below mean sea level has been consistent. Short-term erosion is generally a result of local profile or plan-form adjustment to extreme or unusual conditions (e.g. a season of strong sea breezes), with the capacity for significant recovery between events.

Wave Modelling

Wave modelling was conducted as part of the erosion hazard assessment to investigate the the spatially varying nature of beach profile response to both acute storm response and for more gradual change related to profile adjustment due to sea level rise. Modelling was conducted for each of the sea level rise scenarios outlined in Section 2.2.

Wave height, period and direction were modelled for an extreme event and over a period of 12 months. The extreme event was used for input to beach response modelling to estimate acute storm response (S1) while the 12 month period was generated to determine trends in altered alongshore wave power and sediment transport (subsequently considered for S2 and S3).

The principal justification for selecting 2009 as the 12 month period was to use existing model datasets where possible (Foo 2011) , although it was recognised early in the project that the previous modelling had significantly overstated wave penetration into Cockburn Sound. The year 2009 had relatively mean and monthly water levels compared to other years partially correlated to a strong La Nina event (Figure 36, Figure 37). The median significant wave heights were similar for 2009 to the longer record from 1994-2009, with a higher proportion of extreme wave heights in 2009 than the period 1994-2009 (Figure 38 and Table 13). This suggests that selecting 2009 may have biased the results to a more erosive condition than average due to the higher mean water levels and extreme wave conditions. However, the wave model misrepresented the non-storm conditions and restricted the ability to analyse for changes in sediment transport with increased sea level. This information was not used significantly in the determination of the erosion hazard lines.

Two storms were modelled to represent extreme events likely to cause erosion in the OACS coast. The first storm, May 16 2003, was a high water level event that caused known erosion (Figure 39, Figure 40, Figure 41). The second storm was a recent northerly event in June 2011 with sustained winds along the longest fetch. The storm event that affected the OACS coast on May 16th 2003 was selected for the purposes of analysis as it was a known event that caused up to 10m erosion along the OACS coast and the associated datasets were available to allow consideration of model performance and actual storm response. No further information is presented for the June 2011 storm because it was not identified as causing dramatic erosion, which was supported by cross-shore erosion modelling.

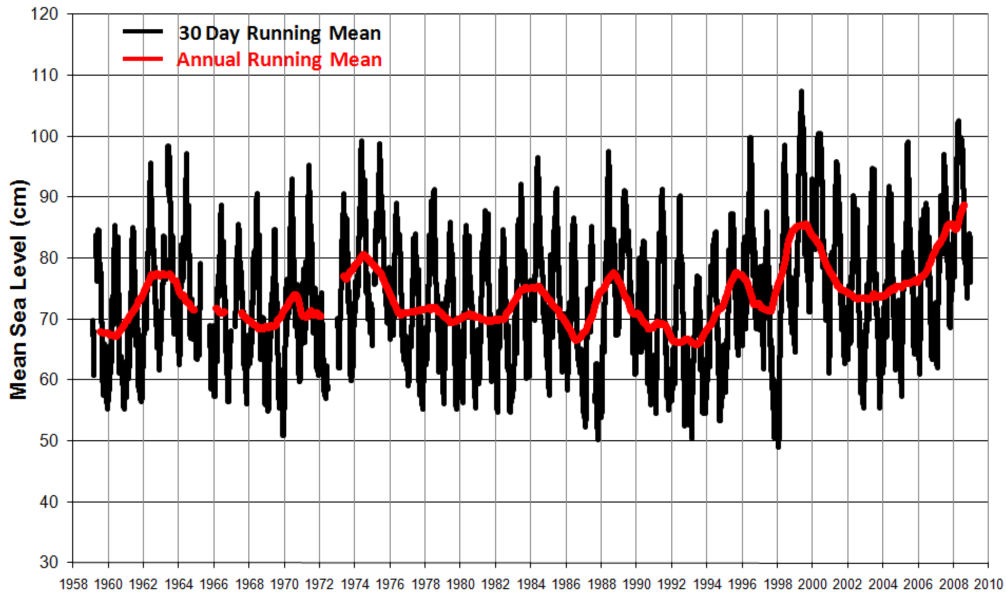

Figure 36: 30-Day Running Mean and Annual Mean Sea Level (1959-2008)

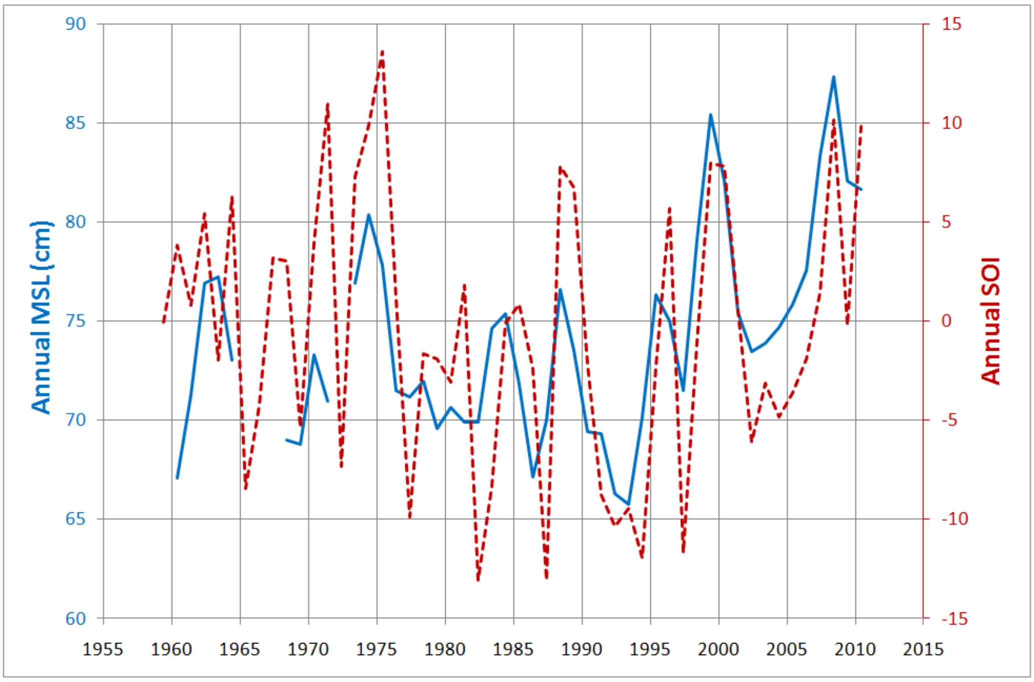

Figure 37: Correspondence between the Annual Means of Fremantle Mean Sea Level and SOI (1960 to 2010)

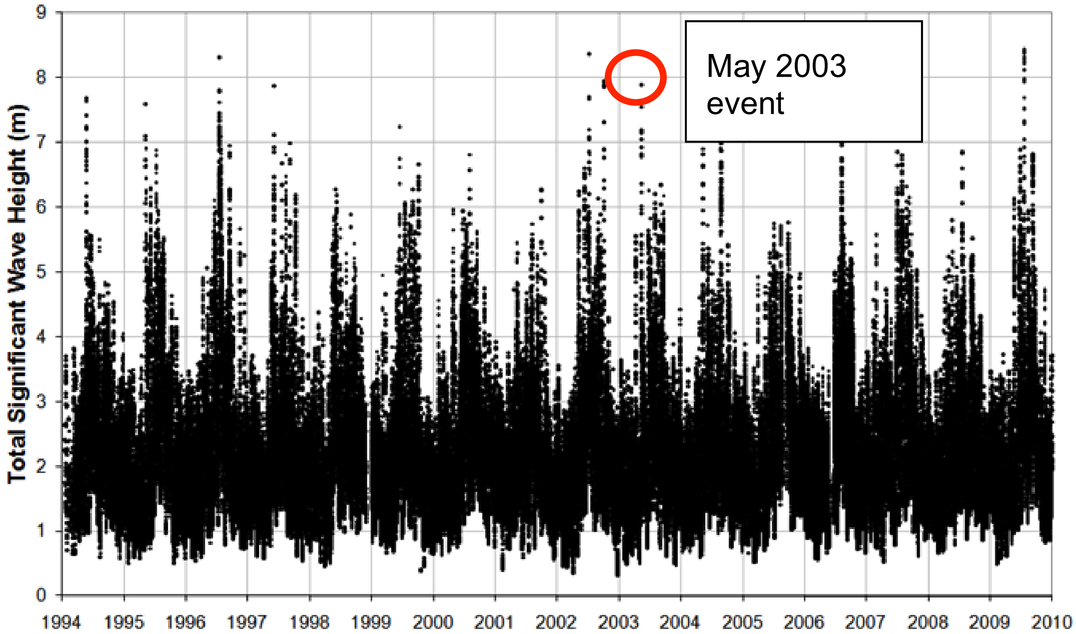

Figure 38: Rottnest Offshore Wave Heights (1994-2009) (Source: Department of Transport)

Table 13: Median and 1% Significant Wave Heights

Location	Depth	Period	Median H_s (m)	1% H_s (m)
Rottnest	48m	January 1994 to December 2009	2.0	5.3
Rottnest	48m	2009	2.0	5.8

The 2003 storm did not rate highly in the ranking of total wave power (TWP) which has been recently discussed as an important consideration in selecting storm for storm response modelling (Li et al. 2009; and Ilich et al. 2009). However, total wave power is a measure of wave height at Rottnest that neglects the influence of depth limitation in shallow, sheltered inshore waters, and consequently TWP is considered likely to be a weak proxy for erosive capacity on sheltered parts of the OACS coast. The controlling influence of water levels on storm erosion has been identified for Cottesloe (CZM & Damara 2008). The May 2003 storm provided the highest water level recorded at Fremantle. The storm duration and magnitude are represented in Figure 40 and Figure 41. Consecutive runs of the storm were considered for erosion modelling.

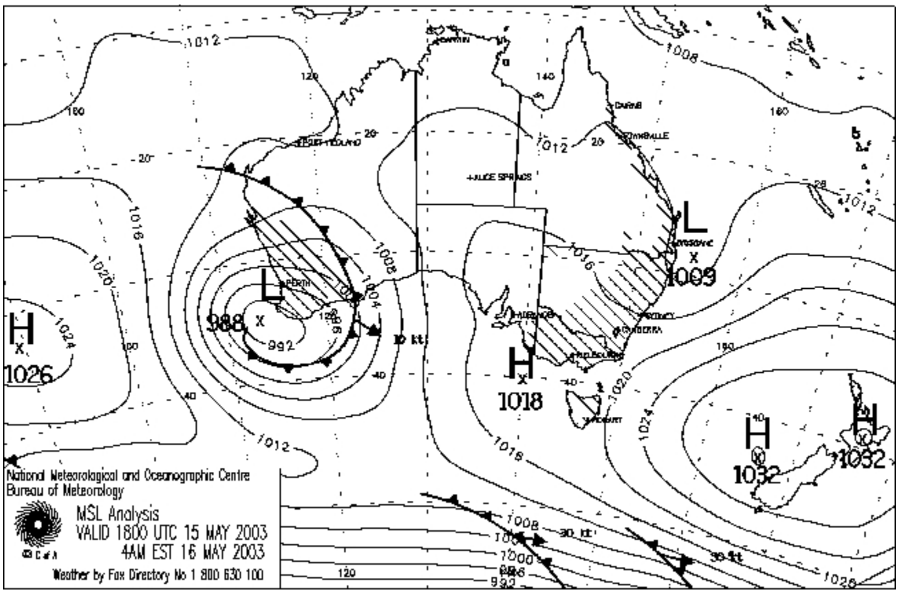

Figure 39: Synoptic Chart with Mid-Latitude Depression for 16 May 2003 (Source: Bureau of Meteorology)

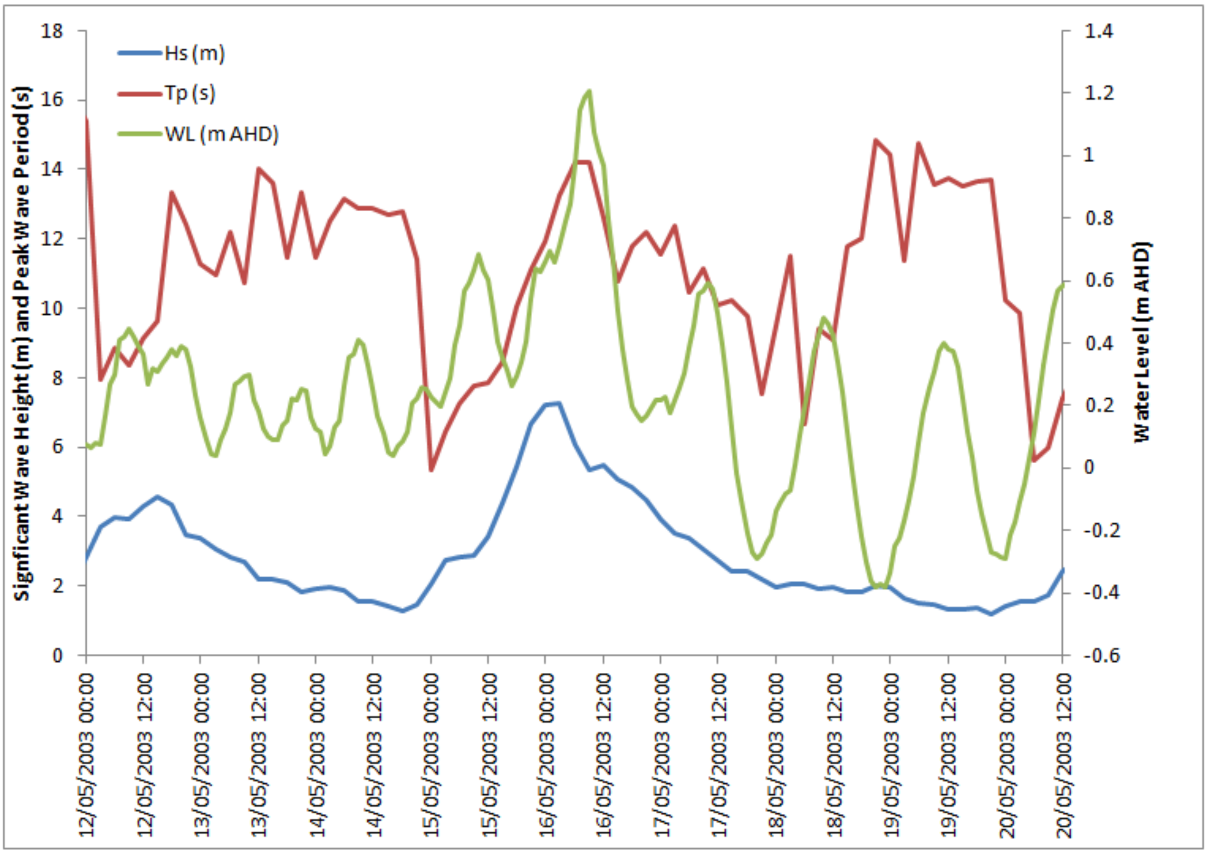

Figure 40: Wave Height, Period and Water Level at Rottnest for 16 May 2003 Storm (Source: Department of Transport)

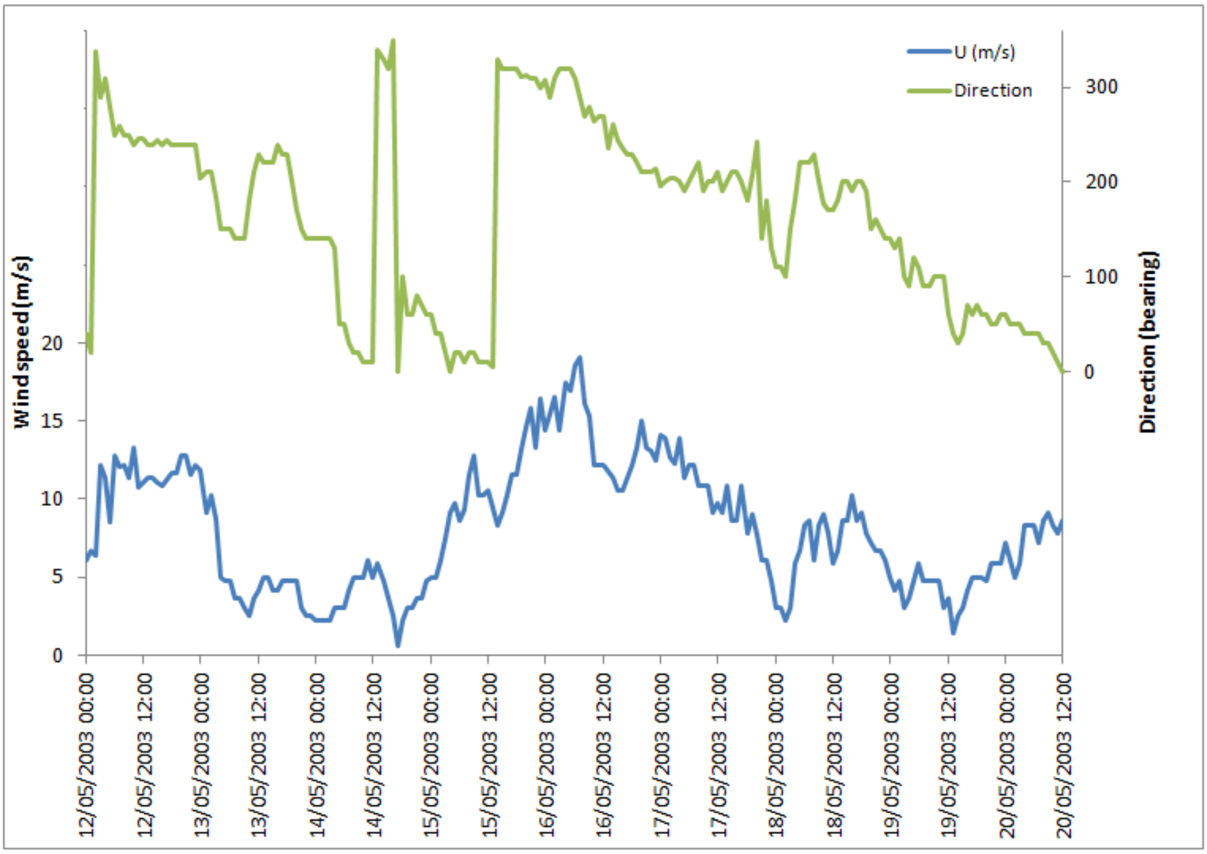

Figure 41: Wind Speed and Direction at Garden Island for 16 May 2003 Storm (Source: Bureau of Meteorology)

Information was exported as time-series at 34 sites at the nearest bathymetry point seaward of the terrace, at Owen Anchorage buoy and at 10 deeper sites for model performance queries (Figure 42, Figure 43; Appendix 5; Appendix 6).

The wave model was based on solving the depth averaged, shallow water form of the Navier-Stokes equations for momentum conservation and mass conservation. The model is depth-averaged and the spatial domain is discretised using a finite volume in the form of an unstructured triangular mesh. The advection is computed using an approximate Reimann solver and the time integration is computed using an explicit scheme. The wave model includes processes such as wind wave growth, wave dissipation through white-capping, bottom friction and breaking, wave refraction and wave-wave interaction. The model computes the propagation of wave energy in geographical space, the time domain, the frequency domain and the directional domain by solving the wave action balance equation.

The wave modelling undertaken by the modelling team at SESE provided sufficient information to conduct the storm response modelling (Appendix 6) and determine focal areas for changes in wave climate with sea level rise scenarios (Figure 44).

A limitation of the modelling undertaken is an inability to verify the processes of wave transformation that occur on the banks, terraces and basins. Calibration datasets at multiple locations were not obtained for use in this project, with the focus of the modeling on the May 2003 event, when the Owen Anchorage buoy was not installed and Rottnest buoy was non-directional. The model over-estimates wave heights, most significantly for ambient conditions, and is likely to have wave heights higher than those calculated using any formulas. Increasing the friction variability across the model grid would have improved this model bias. Only output for the high wave energy events was considered useful for the coastal erosion analysis because the over-estimated wave heights are appropriate for conservative storm response modelling.

The application of ambient wave modeling to alongshore transport estimates provided results that varied dramatically between adjacent transects. This prompted qualitative (interpretative) use of the relative wave energy for different sea level scenarios, rather than incorporating wave direction and period. For example, the model does not adequately account for the local sea breeze. This is largely due to the time-step issues in the modelling and the lack of a spatial grid of wind data, with the time-steps of any numerical modelling limited by the timesteps of in input data. Sea-breezes are a rapid forming, and often short-lived, event in numerical modelling timescales.

Future improvements for wave modelling in the OACS coast could focus on:

- ensuring the model represents the wave transformation processes occurring for the interest of the project. In the OACS coast there tends to be a discrepancy in model performance between extreme and ambient conditions. It may be worth focusing efforts on model performance for either extreme or ambient.
- improve the representation of bed interaction with waves. This may involve higher resolution bathymetric mesh/grids (<25m spacing over banks and reefs) or improved bed friction mapping. improve the resolution of the bathymetric grid.
- attempting to test model performance on a time period where multiple directional wave datasets are available. Appendix 4 contains details of some known wave measurement device installations and the dates available.
- installation of at least three water level recording instruments in the area (Fremantle, Mangles Bay and one other).
- improve temporal resolution of wind and wave inputs (presently 3 hourly) to improve model representation of the seabreeze.

Figure 42: Wave model output locations for Owen Anchorage (Image: GoogleEarth). Note: OAB is the Owen Anchorage Buoy.

Coordinates of wave model outputs is included in Appendix 5 with summary of wave model outputs in Appendix 6.

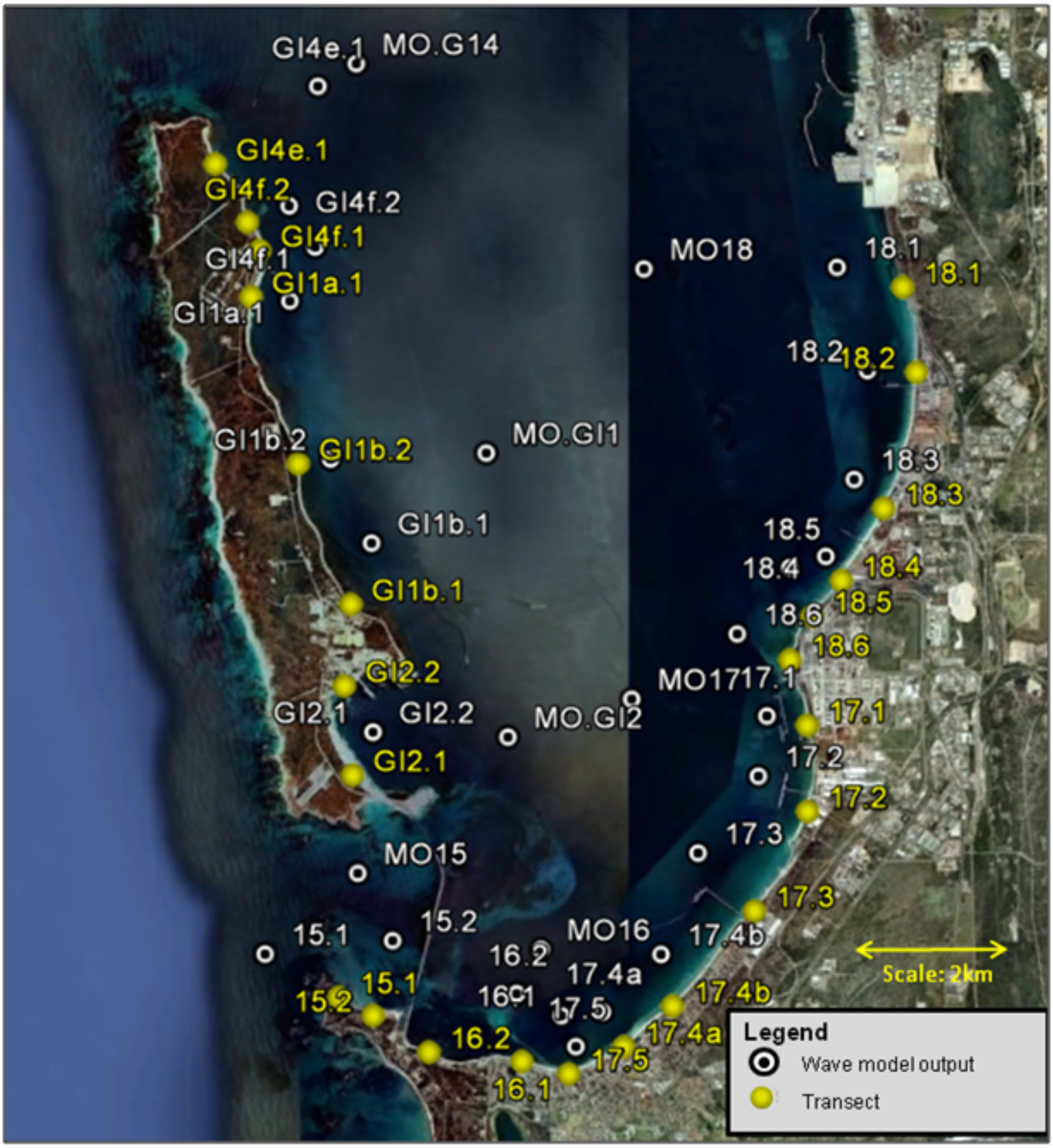

Figure 43: Wave model output locations for Cockburn Sound (Image: GoogleEarth).

Coordinates of wave model outputs is included in Appendix 5 with summary of wave model outputs in Appendix 6.

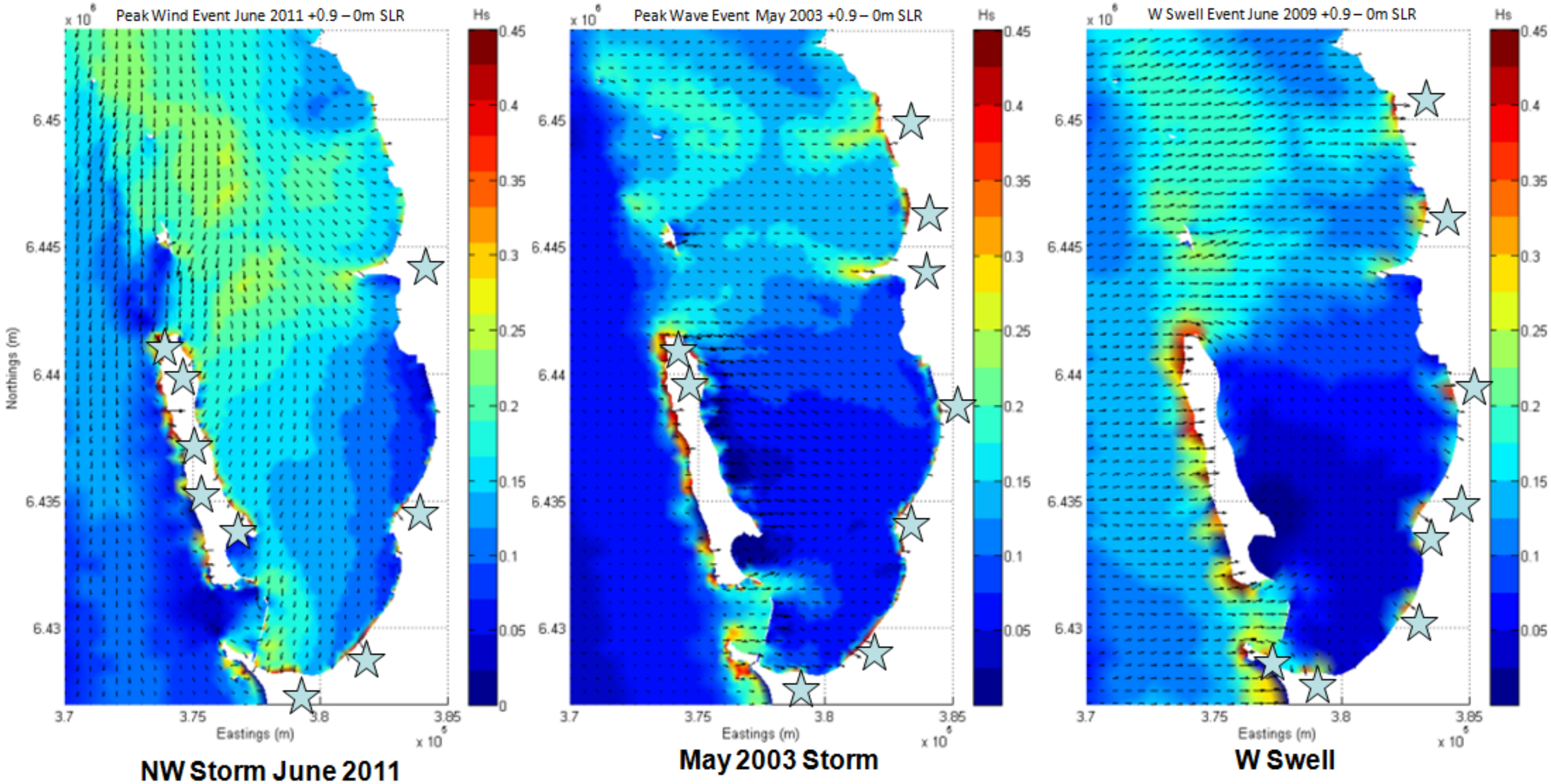

Figure 44: Locations of largest modelled wave height change shown in stars between 0m and +0.9m sea level rise scenarios

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Storm Response Modelling

Coastal response to storms was modelled with varying sea level rise scenarios using the wave model output. Numerical modelling was conducted at each of the 35 transects using profiles created through visual amalgamation of extracted data from LADS and LiDAR (Appendix 4; Appendix 5; Appendix 6).

At the outset of the work undertaken it was intended that the XBEACH numerical model would be used to complete this aspect of the erosion assessment along the OACS coast. However, initial model testing showed that XBEACH failed to provide meaningful results for short period waves onbeach profiles with terrace structures and steep banks. The long model times associated with XBEACH were prohibitive to a timely deliverable without significantly improving the accuracy of the product.

Comparative analyses of outputs gained from XBEACH and SBEACH were undertaken at four profiles around the coast (GI1b.1, 17.5, 18.3 and 21.4; Figure 28 and Figure 29). A comparison of the modelled significant wave heights at the four model output locations is included in Figure 45 for context. A simulated intense storm event of a 3 day run (Hs 2m, Tp 7s, U 25m/s) was run for 0m and +0.9m sea level scenarios at the four profiles (Figure 46). The simulated storm produced similar order of magnitude erosion results with SBeach and XBeach for the extreme storm, with XBeach giving smaller response to the 2003 event (Figure 46; Figure 47).

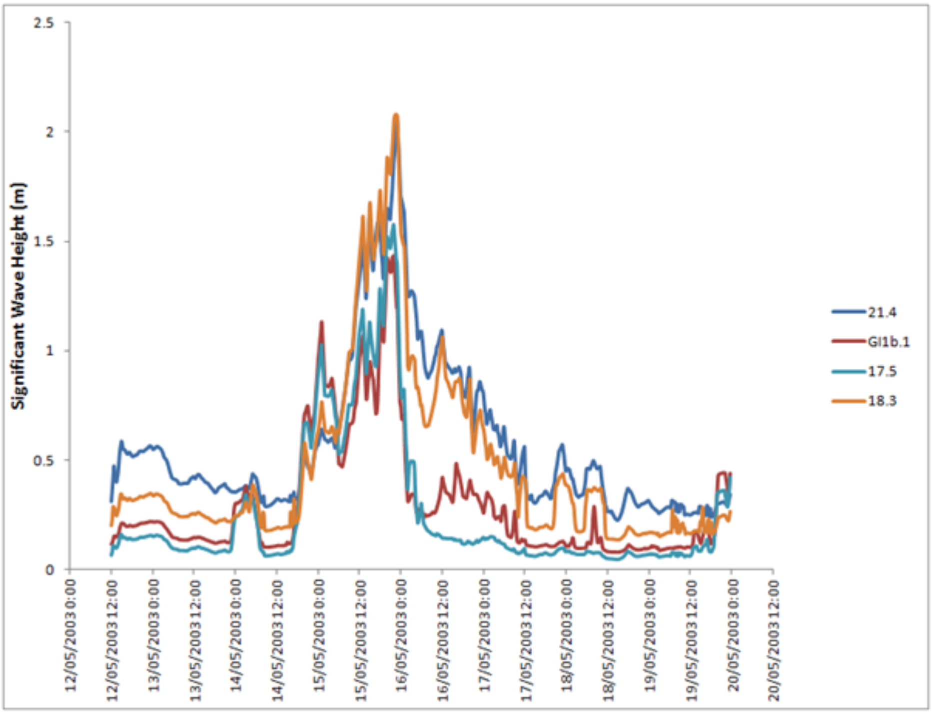

Figure 45: Modelled Significant Wave Heights for the Four Locations used to Compare SBeach and XBeach, for the existing mean sea level scenario.

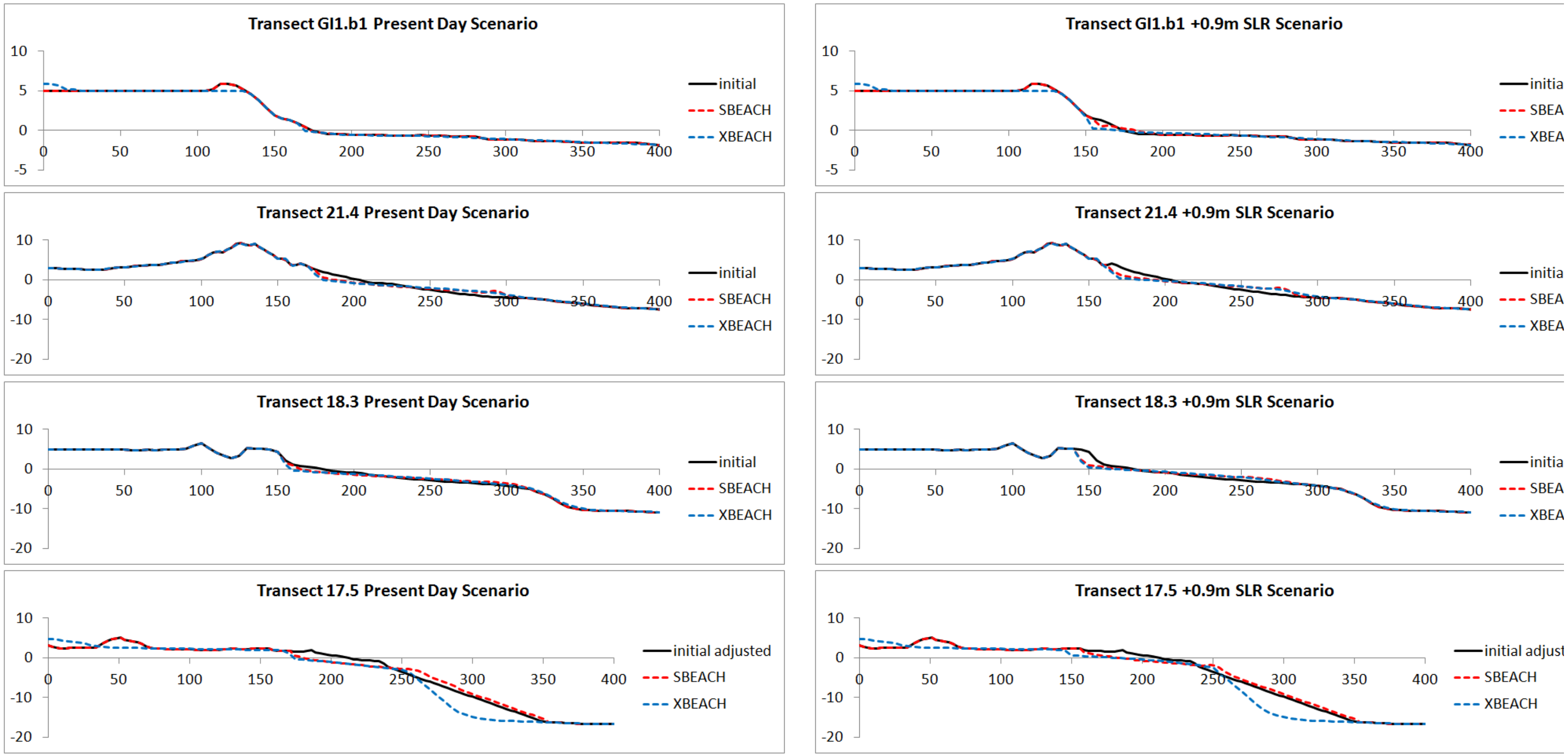

Figure 46: SBeach and XBeach Comparison

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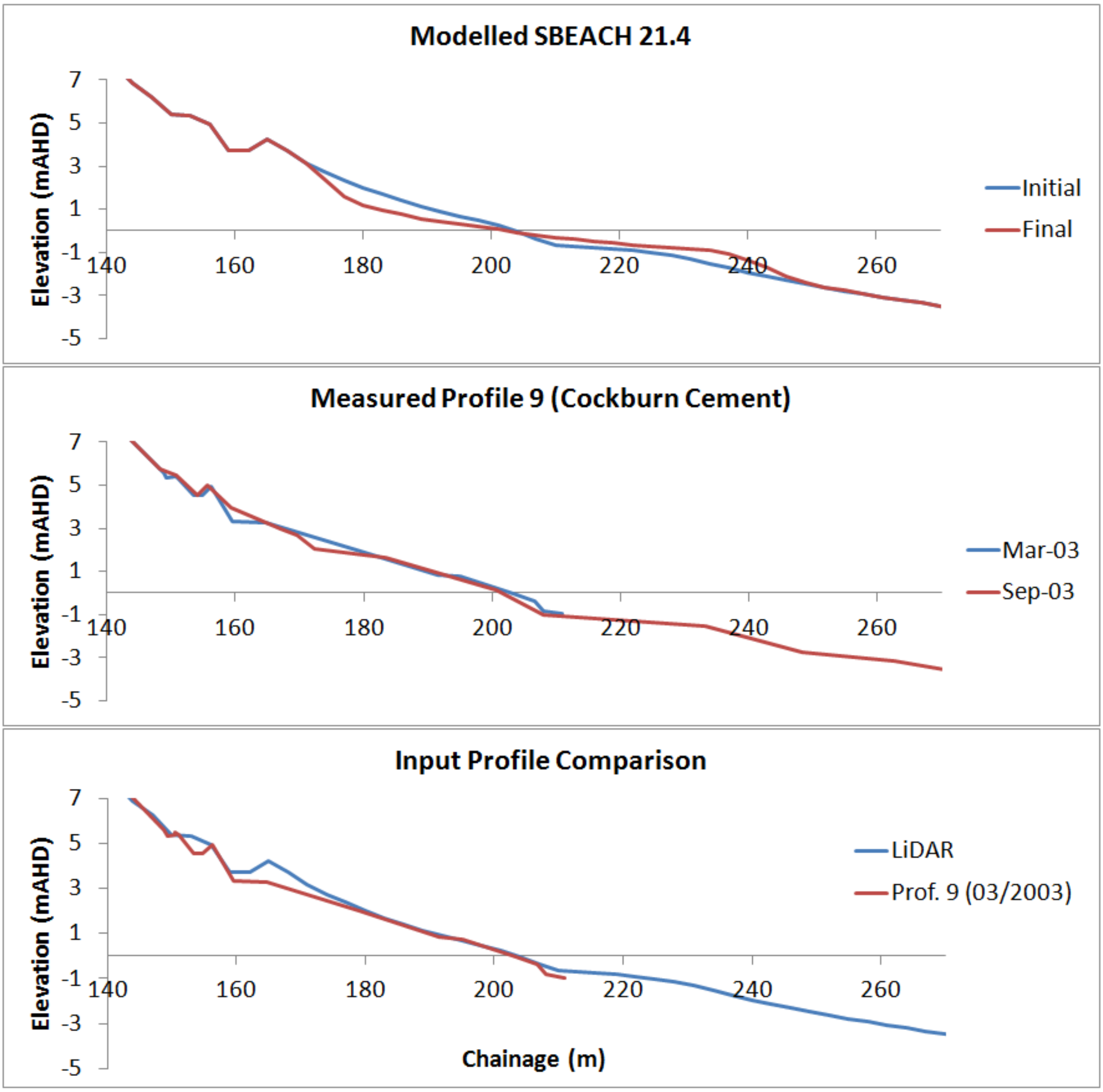

Figure 47: Example of SBeach model and March to September 2003 Measured Profiles at 21.4

SBEACH was selected to model the storm response element of the analysis because the model converged for most profiles and it had a short run-time allowing for easy manipulation of parameters. The modelling and interpretation was undertaken with a recognition of the limitations of SBEACH in a low-energy environment and cognisant of difficulties encountered by the model to represent nearshore friction (Komar *et al.* 1995). The model output is representative of what processes are included in the model and do not always represent reality.

The modelling process using SBEACH can be summarised as follows:

- SBeach modelled for 0mAHD May 2003 for 1 run to compare to the measured profiles.
- SBeach modelled for one, three, five and ten consecutive runs of the storm to consider response to multiple storms.
- SBeach modelled for three runs at 0m, +0.5, +0.9 and +1.5m SLR scenarios using the storm output for each scenario at each profile.
- Volumetric erosion response calculated (Figure 48).
- Acute storm response considered cross-shore response and alongshore capture capacity of each of the controls with downdrift variation.

The interpreted cross-shore and alongshore capture capacity were combined to provide the 'acute' erosion scenario.

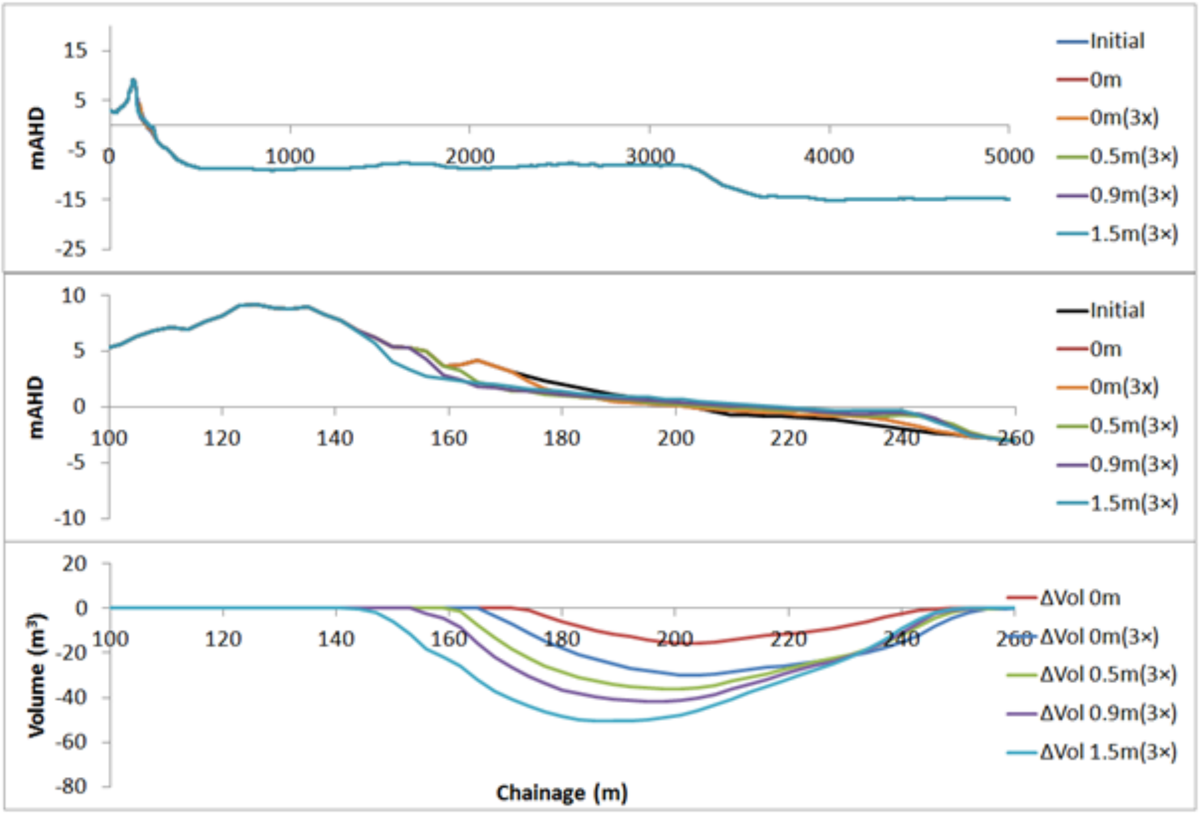

Figure 48: SBeach model output and volumetric interpretation for 21.4. Acute response of 60m used. Similar model results for all other Profiles is included in Appendix 6

Storm Erosion Interpretation

The 'acute' erosion relates to change induced under storm conditions, both alongshore and cross shore response. Acute response was determined by interpretation of beach response modelling for three consecutive runs of the May 2003 storm at each of the sea level rise scenarios was calculated as a volumetric erosion response. The cross-shore response was interpreted in the context of the actual morphology of the discrete coastal reaches considering alongshore retention capacity of sediment by local controls of engineered structures and rock. The volumetric allowance was converted to a horizontal distance buffered from the 1mAHD contour to provide an indication of the relative sensitivity to acute erosion, without other forms of coastal management.

This acute distance was subsequently considered along with that calculated for long term response to sea level rise (summarised below) to provide an assessment of the possible extent of erosion under given timeframes and sea level scenarios for each section of the OACS coast. Each long-term scenario has an acute response added to it to allow for storm response in addition to the long-term sediment demand.

4.2.4 Gradual Change in Shoreline Position

Observed coastal change has demonstrated that there has been a gradual onshore supply of sediment from onshore sand feeds at Parmelia and Success Banks. This supply has been utilised for active coastal management along the OACS coast, with redistribution of material through the influence of coastal structures. Historic behaviour has demonstrated that the influence of individual structures is time-limited, determined by how long it takes for each structure to become 'saturated' by sediment. The resulting behaviour is for coastal change to occur within segments, with smaller coastal structures only having a local influence.

Response to sea level change within a partially controlled coastal system is non-uniform, with structures preferentially holding sediment, whilst more exposed segments are likely to have shoreline erosion associated with profile adjustment. The relative distribution of shoreline change is therefore affected by alongshore sediment supply and structures, with a relative sediment deficit accruing toward downdrift. This form of representation was considered essential for a suitable representation of hazard along the OACS coast.

The capacity for change of discrete sections of coast was established considering site-specific attributes, such as length of coast, height, shoreline orientation and volume. An assessment of existing structures and their current holding capacity (i.e. sources, sinks, level of saturation) was undertaken to inform assessment of their potential future function and ability to control shoreline position under changes in mean sea level.

4.2.5 Long-term Response including Sea Level Rise

Sea level changes causes adjustment to the nearshore patterns of waves and currents, which therefore suggests potential corresponding changes to the coastal structure, above and beyond inundation of the existing form. Scientific progress in coastal morphodynamics has defined three fundamental approaches, which represent increasing system complexity (Figure 49):

- Primary Landform elements and active processes are assumed to continue unchanged;
- Secondary Landform elements are assumed to remain constant, but a change in the balance of active processes is expected;
- Tertiary Relationships between landform elements are considered to be dynamic, resulting from changes in active processes.

For practical reasons, the majority of coastal change assessments use the simplest approach, with the alternative approaches only applied where it is apparent that simpler methods are invalid. Evaluation of these techniques and their relevance to the OACS coast is discussed in detail below, with the general conclusion that a secondary or tertiary approach is required to adequately represent the dynamics demonstrated by modern observations and the stratigraphic record.

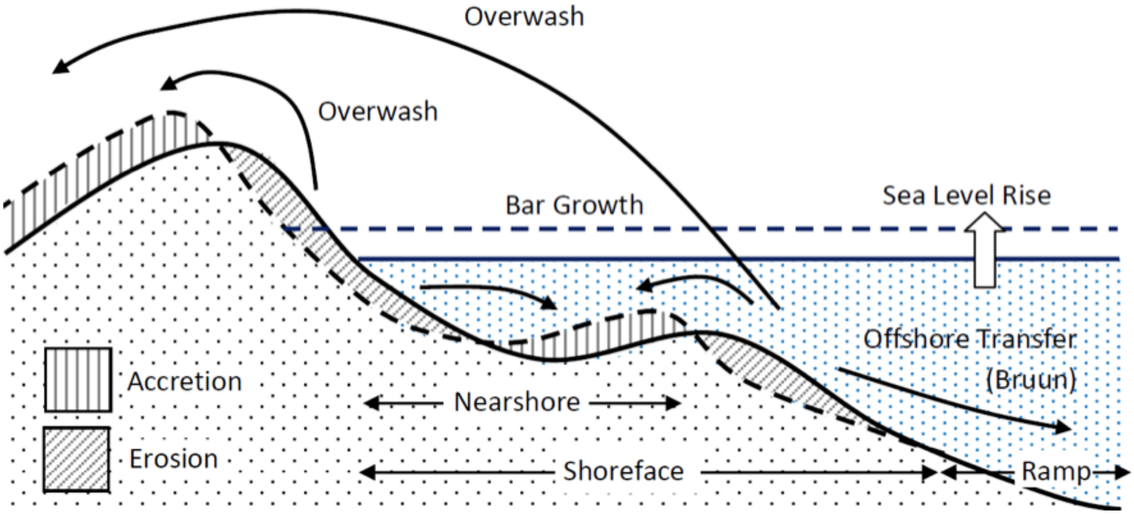

Figure 49: Alternative Pathways for Coastal Response to Sea Level Rise. Modified from Dubois (1992)

Primary Approach to Coastal Change Assessment

The simplest form of coastal change assessment is to consider that the existing coastal configuration represents a state of equilibrium[20] with respect to prevailing conditions, hence allowing assumption that the landform elements and active processes are assumed to continue unchanged. Mobile coastal landforms are assumed to shift in elevation and position, such that the existing balance of coastal stresses and landform is maintained.

This concept of equilibrium is intrinsic to the widely-applied Bruun model (Bruun 1962, 1988), which considers the specific case of a sandy coast which is cross-shore equilibrium. Landward and upward movement of an exponential-shaped profile is assumed to balance erosion of the beach and dune with infilling of the deeper section, down to the limit of wave action, termed the depth of closure. This results in a simple formula, which has the form $\Delta X = L_C / hR$, where ΔX is the horizontal recession, L_C is the depth of closure, h is the active height of change and R is the sea level rise. Typically L_C / h is in the order of 50-100, which results in common application of the further simplified formula $\Delta X = 100\ R$. The model relies upon a balance of seaward sediment transport during storm events against landward transport under ambient conditions.

The Bruun conceptual model with a ratio of 100:1 is in-built to the Western Australian policy for coastal development setbacks, and therefore has been widely applied to the Perth Metropolitan coastline. Variation of the ratio to account for local topography and wave base was considered by Jones (2005), giving a ratio of 250:1 for a dune height of +12m AHD. A similar approach was undertaken by Cowell & Barry (2012) for the coast between Cape Naturaliste and Cape Peron, excluding rock stratigraphy from the volumetric balance, which gave recession up to 800m for a 1m sea level rise. The latter methodology is considered to be highly conservative, as the influence of rock upon shore-shelf sediment transfer was not considered, with infill calculated as equal to the depth of sea level rise across the inner continental shelf (30-50km).

The Bruun conceptual model has reduced validity in southwest Western Australia, where the presence of lithified former shorelines provides considerable control on coastal response to changing environmental conditions. Much of the coast is perched upon rock platforms, trapped updrift of cross-shore features, or landward of offshore sheltering, including reefs and islands. The validity of the Bruun model is further constrained in Cockburn Sound and Owen Anchorage, where the morphology and sedimentology suggest coastal response to drowning during the late Holocene was limited to the coastal margin (Skene *et al.* 2005). Dominant coastal landforms, including the sandbanks (Parmelia, Success and Southern Flats) and the low energy beach terraces (Rockingham to James Point and along the east

[20] Coastal equilibrium is a concept only, as environmental conditions are highly variable, causing mobile coastal features to constantly adjust. The concept is representative when, under the majority of conditions, there is a self-stabilising tendency toward a suite of similar coastal states, occasionally termed dynamic equilibrium. The concept loses meaning if there are alternative configurations which may develop under the same conditions, or if the 'equilibrium' form is strongly influenced by variation of available sediment.

side of Garden Island) are characteristic of non-equilibrium conditions, although the previously extensive presence of seagrass beds suggests change is gradual.

The 'Bruun' approach can be applied on several scales to Cockburn Sound, to give an indication of the scale of this potential mechanism. However, it is acknowledged that there is no evidence to support the physics implicit to the Bruun conceptual model. Four possible applications are presented, none of which are wholly satisfactory:

- Basin Infilling. At the largest scale, it could be assumed that the whole Sound is subject to infilling, proportional to sea level rise, on the basis that the offshore wave climate suggests sediment transport may be active out to a depth of 50m. This outcome gives a 'Bruun ratio' of 350:1, which is highly unrealistic, as it requires sufficient wave and current energy to effectively disperse sediment across the Sound. The existing sedimentology (Skene et al. 2005) demonstrates that post-flooding late Holocene sedimentation has occurred as sand accumulation on the margins of the Sound, and mud accumulation within the central basin;
- Margin Infilling. At a moderate scale, modern sediment deposits could be assumed to represent the area capable of experiencing future sedimentation. Applying in a simple cross-shore fashion, this implies 'Bruun ratios' varying from 15:1 (no terrace) through to 90:1 (broad terrace at Naval Base). Again, this interpretation represents an unrealistic outcome, as the terrace width is more strongly representative of rock presence than stresses on a mobile sediment feature. Also, the broad terraces provide coastal sheltering through friction and refraction, and therefore act to reduce the potential for cross-shore exchange – meaning that a wider terrace can be less prone to infilling, contrasting with the Bruun model, which implies greater infill;
- Deepwater Infilling. A similar approach to basin infilling, but acknowledging the difficulty of transferreing sediment offshore, the Bruun model could arguably be considered to apply locally at those sections of coast where there is a relatively direct connection between the shore and deeper water, giving an average Bruun ratio of 1:60. However, as at the largest scale, it is acknowledged that the deeper water represents an area that has not been subject to significant deposition, and therefore it does not represent a realistic outcome.
- Equilibrium Profiles. Variation of the wave conditions throughout the OACS coast suggests potential differences in the extent to which coastal sediments may be mobilised offshore. This characteristic has been estimated through the numerical wave modelling, with coastal profile modelling (SBEACH and XBEACH) undertaken to estimate the spatial extent of response. This analysis demonstrated significant sensitivity to both profile structure and modelled wave climate, reflecting the model schematisation (Komar et al. 1995). SBEACH, calculates an equilibrium profile from the point of wave breaking upwards, therefore increasing coastal response with wave

height, with dramatic increase if the point of breaking is on the face of a sub-tidal terrace. Equivalent Bruun ratios calculated using this approach varied from 1:12 to 1:60, in addition to geometric movement up the profile. Modelling results for this process have been included in the overall erosion assessment, interpreted so as to limit the effects of terrace collapse or dune failure.

- The use of Equilibrium Profiles has been incorporated within the erosion hazard assessment as the mechanism most consistent with observed behaviour and existing landforms. However, it is important to acknowledge the other mechanisms are possible, and if they occurred, could potentially cause erosion that is in the order of six times greater. In the face of such potential uncertainty and severe outcomes, it is appropriate to evaluate change through ongoing monitoring. Requirements for a suitable monitoring program are outlined in Section.

Secondary Approach to Coastal Change Assessment

This approach assumes that landform elements (e.g. sub-tidal terrace, beach, dune) retain presence, but that the relative balance of active processes shifts. Alternative conceptual models for response to sea level rise are available, including bar formation, barrier transgression and alongshore transfer (Dubois 1992; Fitzgerald et al. 2008).

Bar formation causes reduction of the shore wave climate, and therefore is likely to result in a smaller volume of material loss from the dune system. The erosion response is further reduced on a terraced beach if the material is sourced from the seaward margin, which is likely to occur when storm wave breaking occurs at this edge.

Barrier transgression includes overwash and breaching processes, and represents an additional net loss of sediment from the dune system. The height of the dune system throughout the OACS coast and the tendency for generally rising topography limits the issue of barrier transgression to a few limited areas, particularly Rockingham and Woodman Point. These areas are identified as being affected by "Tipping Point" behaviour (Section 4.2.7), as when inundation occurs, it will facilitate drastic local erosion.

Alongshore transfer occurs when the change to environmental conditions modifies the potential for sediment transport. For the OACS coast, the major mechanism for such change is through alteration of the wave climate. Modelling of the changing wave conditions (Section 4.2.3) shows discrete areas of change, particularly with wave height increases occurring in the vicinity of Catherine Point and Woodman Point. The influence of these changes to onshore sediment supply that occurs at these locations is likely to be dominated by the increased water depth, so that overall there is a reduction of sediment supply.

A second aspect of changing alongshore sediment transport due to sea level rise is developed through alongshore variations in coastal response. That is, relatively exposed locations will experience greater loss, with the material transferred to more sheltered areas. The discrete nature of changes suggested by the modelling indicates that this mechanism is not likely to be broadly active, although alongshore transfer remains a key process.

Tertiary Approach to Coastal Change Assessment

Capacity for change due to sea level rise occurs through a number of possible pathways, which may not necessarily be the result of cross-shore equilibrium. A modern approach towards assessment of coastal dynamics is consideration of landform-landform interactions, in response to changing processes (Whitehouse et al. 2009). This technique requires interpretation of how individual landforms may respond to change, and determining the relative exchange of material between landforms, such as preferential accumulation updrift of a rock headland, at the expense of an adjacent beach. As such, it represents a three-dimensional extension of the Bruun conceptual model, with a much broader consideration of landform features. Whilst this concept is simple, the application requires considerable interpretation, extending observation evidence of coastal behaviour into conditions that are outside the modern range of conditions. Palaeomorphology, particularly associated with the sea level highstand around 2,000 years ago (Searle & Semeniuk 1986a, b) provides some further indication of dynamics, but it is recognised that there is significantly less mobile sediment available in the present regime (Semeniuk 1995).

The landform structure in both Owen Anchorage and Cockburn Sound has a distinctive sequence, which is a function of both ongoing sediment supply and the presence of lithified former shorelines (Figure 7 and

Figure 9). Bank structures occurring at Catherine Point, Woodman Point and the interrupted pathway at Cape Peron provide onshore sediment supply, which is transported alongshore by wave action, towards perched beach areas at Port Coogee, north of Challenger Beach and near James Point. This suggests a coastal configuration which is resilient to variations in sediment supply:

- Enhanced sediment supply cannot be held by the perched beach, and therefore is dropped into deeper water;
- Although reduced sediment supply may causes the perched beach to retreat slightly, the presence of the rock base limits how much erosion can occur, transferring the response updrift, with the result that the net loss is distributed across a broad area, producing a small coastal change.

The nature of this sequence has been incorporated into the erosion response modelling by estimating the capacity for material transfer into deeper water. As the loss is ultimately determined by how much material can be pushed towards the perched beach zones, it is constrained by the alongshore transport rate and the availability of sediment – which will be reduced in response to profile adjustment.

An estimate of the rate of alongshore loss has been calculated for each sediment cell, based upon estimated rates of alongshore transport and net sediment supply (MP Rogers & Associates 2005b; Oceanica 2010a, 2010b). Typically this is equivalent to a Bruun ratio in the order of 50:1 for the wider coast,, with higher ratios north of Catherine Point and along Kwinana industrial area; and lower ratios along Garden Island. Importantly, this pathway for change, where the capacity for loss to offshore is constrained by alongshore transport rates, gives behaviour that is consistent with the structure of the OACS coast, with only limited infilling of the deep basin areas.

The loss rate has been assumed to be distributed evenly across the cell, although it is likely that there will be a spatial bias in the distribution, which is a combined result of sediment supply, transport and coastal management, including defences. A preliminary interpretation of the change has been developed through the alongshore consideration of supply, transport and sediment deficit (due to profile adjustment). This analysis suggests that sea level response will primarily be at the downdrift end of sediment cells (South Beach, south of Port Coogee, James Point, Kwinana Wreck) except south of Catherine Point, where the potentially high rate of transport suggests a tendency for updrift erosion (south of Catherine Point). This potentially implies a change in management requirements at South Beach and south of Port Coogee.

Comparison of the supply estimates and sediment deficit suggests that between 2060 and 2100, the sediment deficit will outstrip the supply. However, estimates of supply, transport and deficit are very simply determined, and cannot be considered reliable. This further reinforces the need to monitor the coastal behaviour and identify patterns of change, rather than relying upon assumed patterns of behaviour.

Adopted Methodology for Response to Sea Level Rise

The overall methodology used to estimate response to sea level rise uses a combination of primary, secondary and tertiary approaches. In particular, these include:

- Equilibrium profile response, calculated using SBEACH, with exclusion of terrace collapse or dune transgression;
- Offshore transfer at limited locations, constrained by alongshore transport rates;
- Local reconfiguration due to loss of supply (Catherine Point, Woodman Point);

The analysis suggests several critical “tipping points” of behaviour, which are likely to be important for active coastal management:

- Breaching of low-lying dunes and consequent landward transgression;
- Sediment supply reducing below the quantity required for profile adjustment, which consequently results in a sediment starved condition.

4.2.6 Key Uncertainties and Unknowns

Projection of potential erosion outcomes for the OACS coast has been developed through a series of estimates and assumptions. Whilst significant effort has been used to obtain evidence to support these conceptual model elements, several of them contain ambiguity or uncertainty that may contribute to model performance. It is valuable to identify the perceived key uncertainties and unknowns, to suggest possible knowledge gathering pathways that may help refine projections and to help assist with interpretation of future observed behaviour. Table 14 summarises identified key uncertainties and unknowns used in the erosion projections.

Table 14: Key Uncertainties and Unknowns in Erosion Predictions

Model Element	Uncertainty	General Bias	Implication
SLR projections	Contain considerable uncertainty, which is suggested by SLR estimates (Section 4.2.4)	Exaggerated High	Possible impacts brought forward in time
Wave conditions	Wave model validated at Owen Anchorage buoy, which allows systematic bias in Cockburn Sound	Unknown	May increase or decrease both cross-shore and alongshore transport
Onshore sand feeds	Estimated based upon previous sediment budgets, which include anthropogenic effects and the assumption of closure depth	Exaggerated High	'Sand starvation' time frame is over-estimated
Closure depth	Used to relate vegetation line change to volumetric change. Profiles show significant variance, with strong median bias	Exaggerated high	Over-estimates volumes (feed and transport rates)
Alongshore transport	Have been estimated based upon sediment budgets and wave modelling. Does not incorporate apparent seasonal beach rotations	Unknown	May affect alongshore sediment transport gradients and capacity for erosion recovery
Terrace response	Modelling based upon SBEACH, which generally assumes limited sand transfer from the front of the terrace	Unknown	Capacity for increased sediment deficit if sand moves offshore. Reduced deficit if terrace margin erodes
Presence of rock	Isolated areas of exposed rock have been identified from LADS and LIDAR	Unknown	Presently obscured rock may restrict sand transport, or may provide local retention, which spreads deficit across smaller length of coast

4.2.7 Geomorphic Tipping Points

Geomorphic tipping points occur when there is a dramatic change in the incremental coastal response to a change in environmental forcing. Typically they occur when an environmental parameter reaches a threshold at which there is a fundamental change in active geomorphic processes (e.g. Figure 50). In the context of sea level rise, considered a major climate change vector for this study, there are several geomorphic tipping points for the low energy beaches common to the OACS coast.

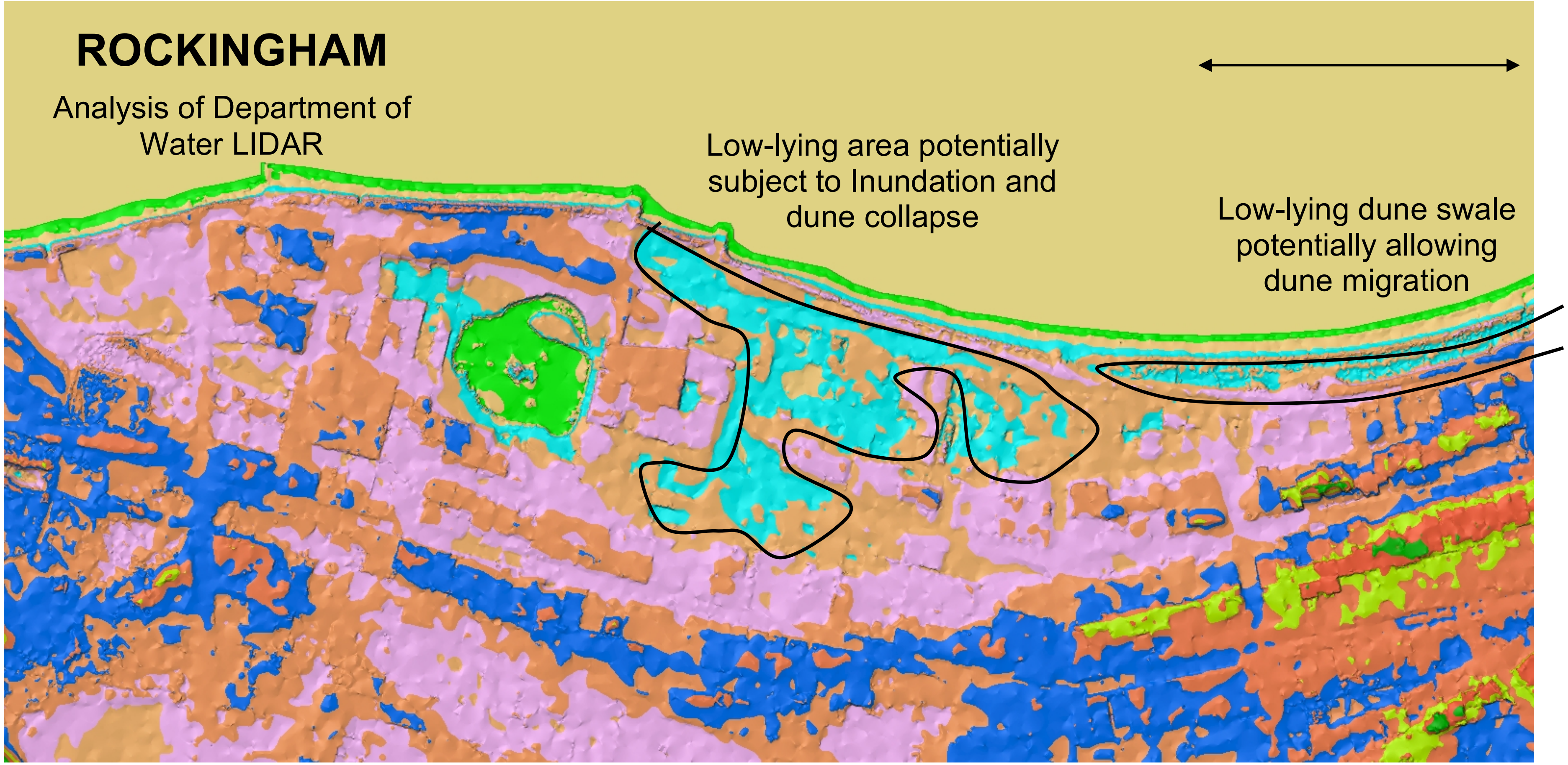

Figure 50: LIDAR analysis for Simple Identification of Tipping Points - High contrast colouring used to identify local variations at 0.5m interval

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The most apparent geomorphic tipping points related to sea level rise correspond to vertical thresholds on the shore profile such that the change in active or dominant processes acts to reinforce the effect of sea level rise. One such threshold is the dune crest, where a sea level rise may potential shift active processes from Aeolian to marine, thereby causing dune crest deflation and consequently amplifying the morphologic change. Figure 51 schematically indicates several vertical zones in which different processes are dominant, with rapid geomorphic change potentially occurring if the landform elements in this zone cannot adjust sufficiently rapidly to sea level rise. Other forms of dune 'tipping points' may occur, depending upon the elevation and width of the primary coastal dune (Table 15). The other commonly occurring vertical threshold is associated with the depth of the subtidal terrace, which occurs on several parts of the OACS coast. Tipping point behaviour may occur where there is a shift of the wave base relative to the terrace margin, or the effect of wave depth limitation across the terrace reduces.

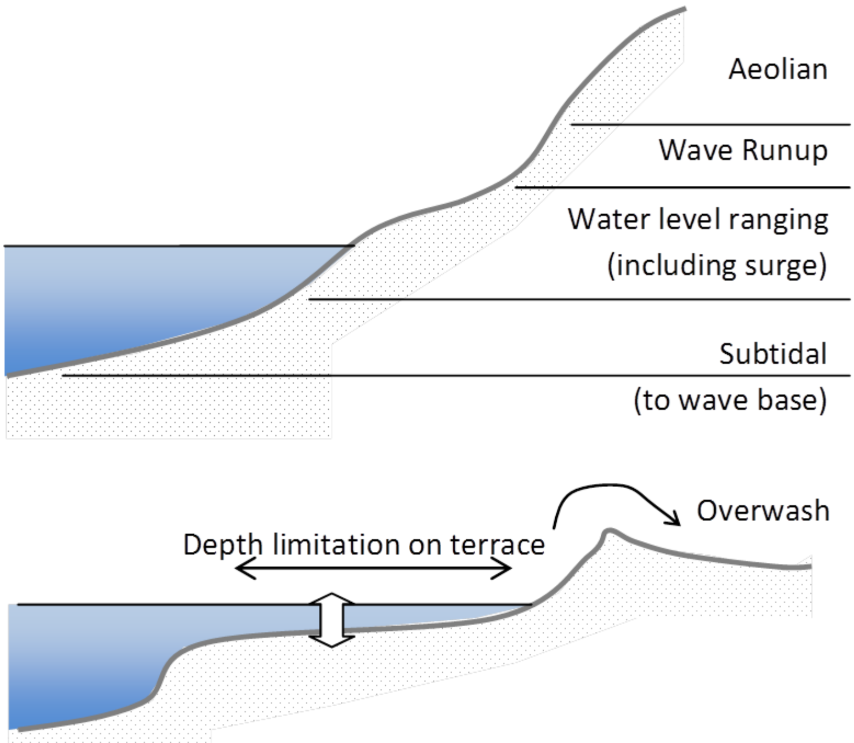

Figure 51: Schematic Zonation of Dominant Coastal Processes

Other forms of rapid coastal regime shift that have been historically evident on the OACS coast include dramatic fluctuation of supply-determined sand features (Catherine and Woodman Points) and response to the installation of large coastal structures (examples include Garden Island Causeway and Woodman Point groyne). These are not strictly geomorphic tipping points, but illustrate the fine balance that may occur between active coastal processes. For many of the changes potentially occurring, forward indicators may occur, such as steepening of profiles below low tide level south of the Armaments Jetty.

Table 15: Indicator of Structural Change and Process Shifts

Structural Change	Landform Element	Process Shift	Indicator	Poss. Location
Dune Overwash	High Dune	Aeolian -> Runup	Scarp or storm limit near crest	General
Dune Breaching	Barrier Dune	Runup -> Surge	Dune trough near vegetation level	Pt Peron & Rockingham
Dune Migration	Narrow Dune	Runup -> Overwash	Dune back slope gently graded	General
Terrace Cut	Terrace Limit	Rise of Wave Base	Increased sediment	Rockingham-Kwinana; GI*
Terrace Toe Scour	Terrace Limit	Increased Waves	Deepening off terrace	Rockingham-Kwinana; GI*
Deepened Terrace	Terrace Surface	Depth Limitation	Increased sediment flux	Rockingham-Kwinana; GI*
Basin Infilling	Depressions	Dry -> Surge	Sediment rills on basin edge	Rockingham, Fremantle
Basin Expansion	Depressions	Surge -> Tidal	Surge flooding cuts out	Rockingham
Channel Cutting	Channels	Drain -> Tidal	Channel wider and deeper	(not identified)
Sand Bank Loss	Sand Bank Edge	Reduced Supply	Edge of sand bank flattens	Catherine & Woodman Pts
Sediment Sink Infill	(Structural)	Net to Gross Transport	Seasonal reversal not observed	Port Coogee & Catherine Pt

* The deeper terrace offshore within Jervoise Bay is not a sub-tidal terrace, with the western boundary held in place by rock features.

The nature of terrace (or perched beach) response is illustrated schematically by Figure 52, which suggests how the non-linear relationship between wave height and the tendency for onshore-offshore sediment movement contributes to the changing morphology.

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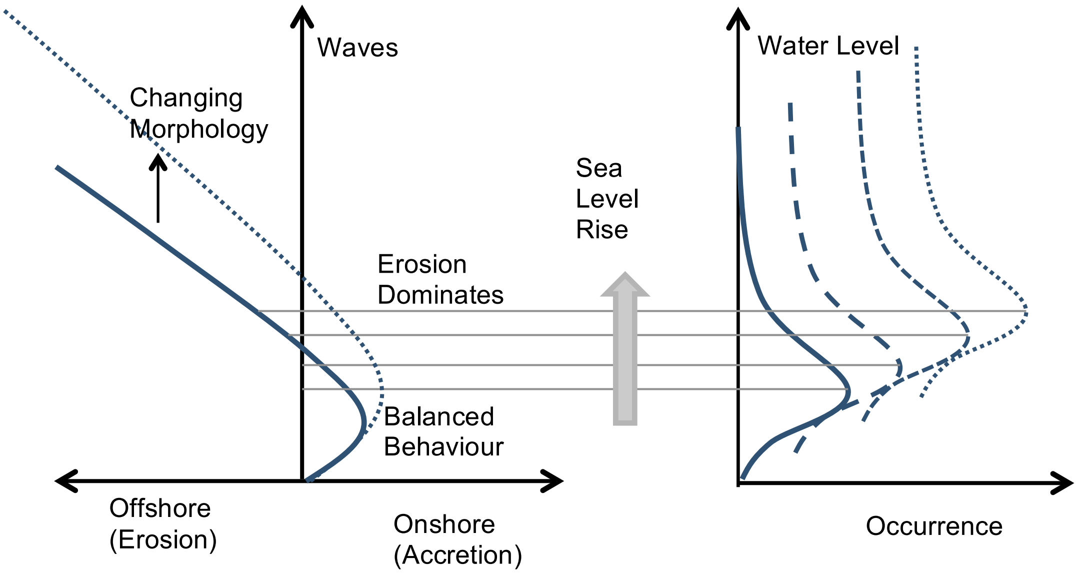

Figure 52: Nature of Terrace or Perched Beach Response

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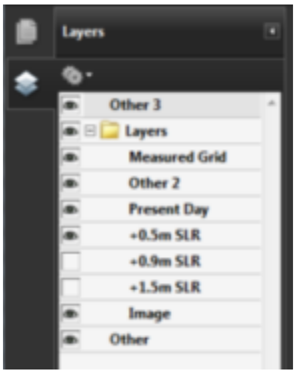
5. INUNDATION HAZARD REPRESENTATION

Four inundation events with different probabilities of occurrence in any one year were selected as the basis for the inundation mapping (Table 10; See Section 4.1 for further detail). These inundation levels were applied to the Department of Water LiDAR high-resolution topography from 2008, captured at a 1m spatial resolution with a ±0.1m vertical accuracy.

5.1 INUNDATION MAPPPING PRODUCTS

Inundation Hazard Maps are presented as a series of four interactive pdf maps provided as separate attachments and as a series of ArcGIS shapefiles (see Appendix 7 for further explanation and full map products The interactive maps allow the user to view the likely area impacted by inundation for each Annual Recurrence Interval scenario (1 year, 10 year, 100 year and 500 year) and each Sea Level Rise scenario (present, 0.5m, +0.9m and +1.5m). The user may turn on or off layers of the maps as appropriate to view the inundation hazard under their preferred scenario selection. To view layers in interactive pdf in Adobe acrobat software:

- Turn on the layers by either locating the navigation panel on the left side of the Acrobat window and clicking the layers icon in the panel or choose View>Navigation Panels>Layers.
- View the layers by clicking the plus symbol adjacent to the 'Layers' folder.
- Turn layers on and off by clicking the eye-shaped symbol next to the layer of interest.



Two examples are provided for using these datasets, demonstrating sea level rise effects and increased event severity respectively. The examples presented are for the three areas of highest inundation hazard 'hotspots' (Figure 53):

- Reclaimed land and the three harbours of Fremantle (Cell 22 in City of Fremantle);
- Woodman Point and small areas of Australian Maritime Complex (Cells 18-21 in City of Cockburn); and

- Southern Cockburn Sound including large areas of Rockingham (Cells 15-16 in Town of Rockingham).

The increased inundation hazard with sea level rise for a certain annual exceedance probability event are included in Figure 54, Figure 56 and Figure 58, for an event that has a 63% probability of occurring in any one year (1 year ARI). The increased extent of inundation with event severity (reduced annual exceedance probability or raised ARI) is demonstrated in Figure 55, Figure 57 and Figure 59 for a +0.9m SLR scenario.

The increased likelihood of coastal flooding with sea level rise is demonstrated by the two example images combined with Table 10. Inundation during a 500 year ARI event in present conditions would become the equivalent of a 1 year event with a +0.5m SLR.

Overall, the hazard assessment shows increased inundation hazard with sea level rise. The potential shift of inundation zones due to sea level rise along the OACS coast affects a relatively small area. For the majority of the coast, existing coastal dunes are above the 500 year ARI inundation scenario for a +1.5m sea level rise (3m AHD total). This produces isolated areas of inundation in locations where the coastal dunes are not high/extensive. Three further areas were identified where inundation will become an issue in the future (in addition to those currently susceptible to inundation). All three areas are in Cells 17 and 18 in the City of Kwinana (Figure 53):

- James Point (+0.5m SLR 100yr ARI);
- BP Australia (+1.5m SLR 100yr ARI); and
- Verve (+1.5m SLR 100yr ARI).

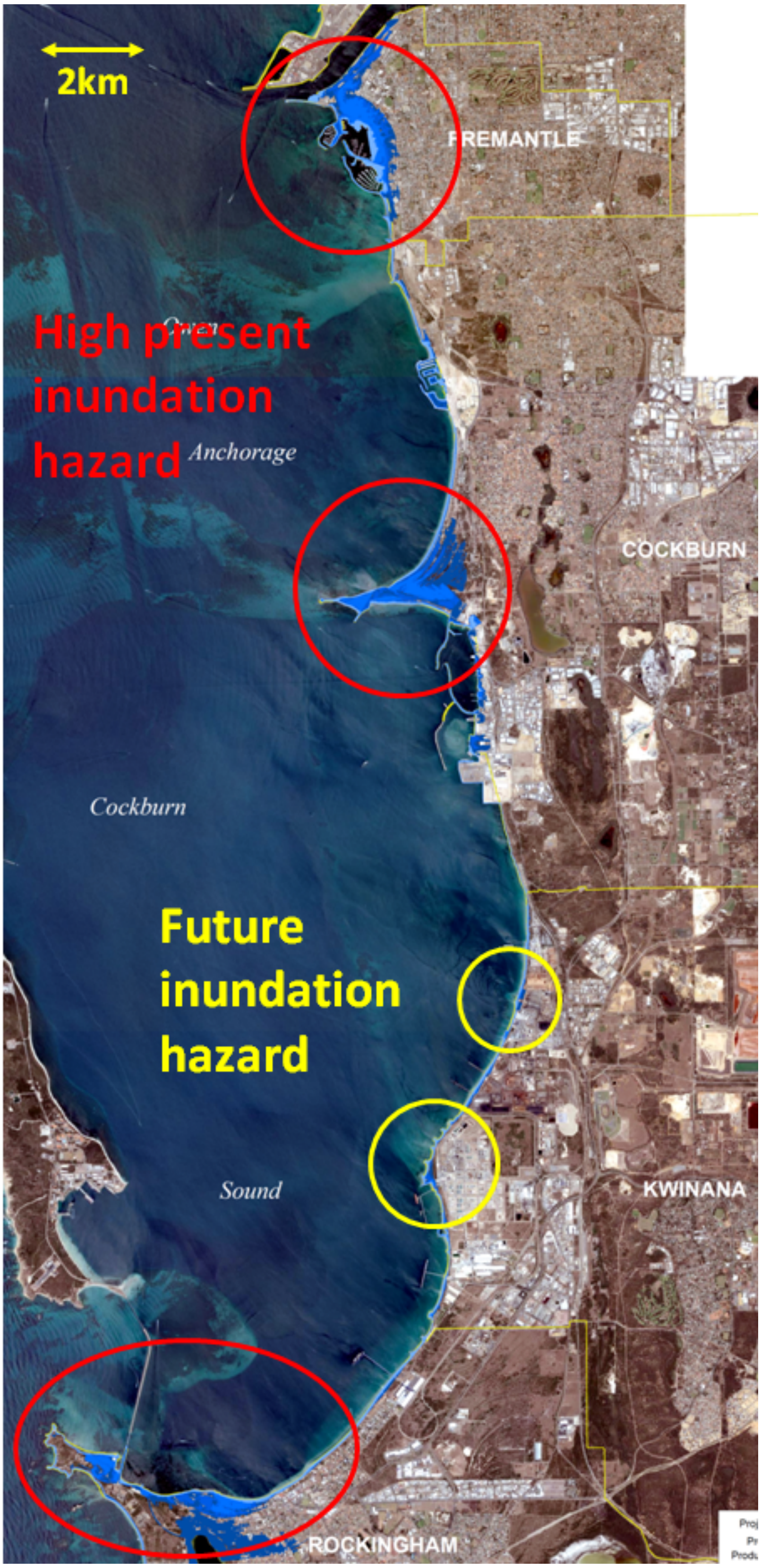


Figure 53: Present and Future High Inundation Hazards

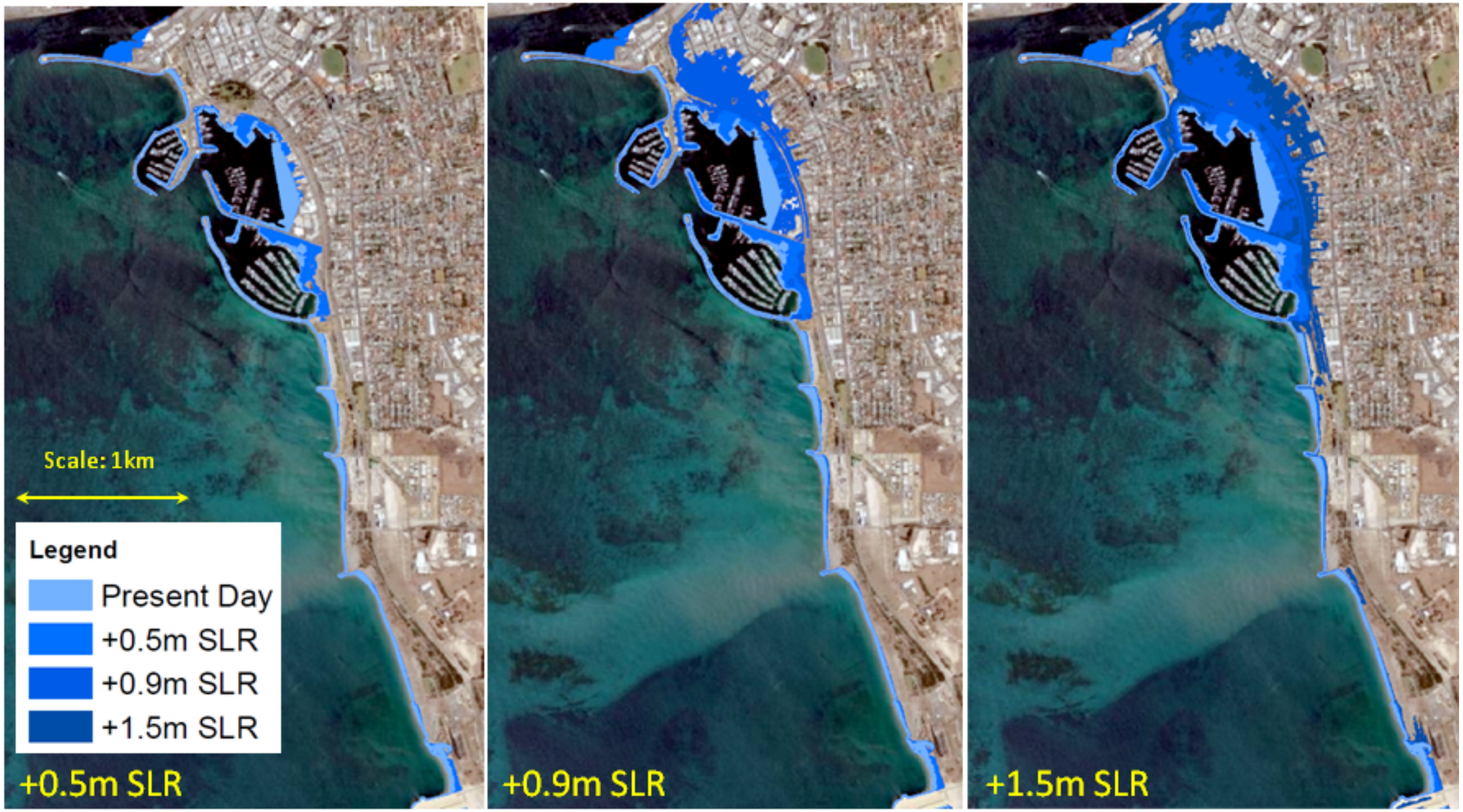


Figure 54: Increased inundation with sea level rise for a 1 year ARI event - Fremantle

Figure 55: Increased inundation with lower event probability for a +0.9m SLR scenario -- Fremantle

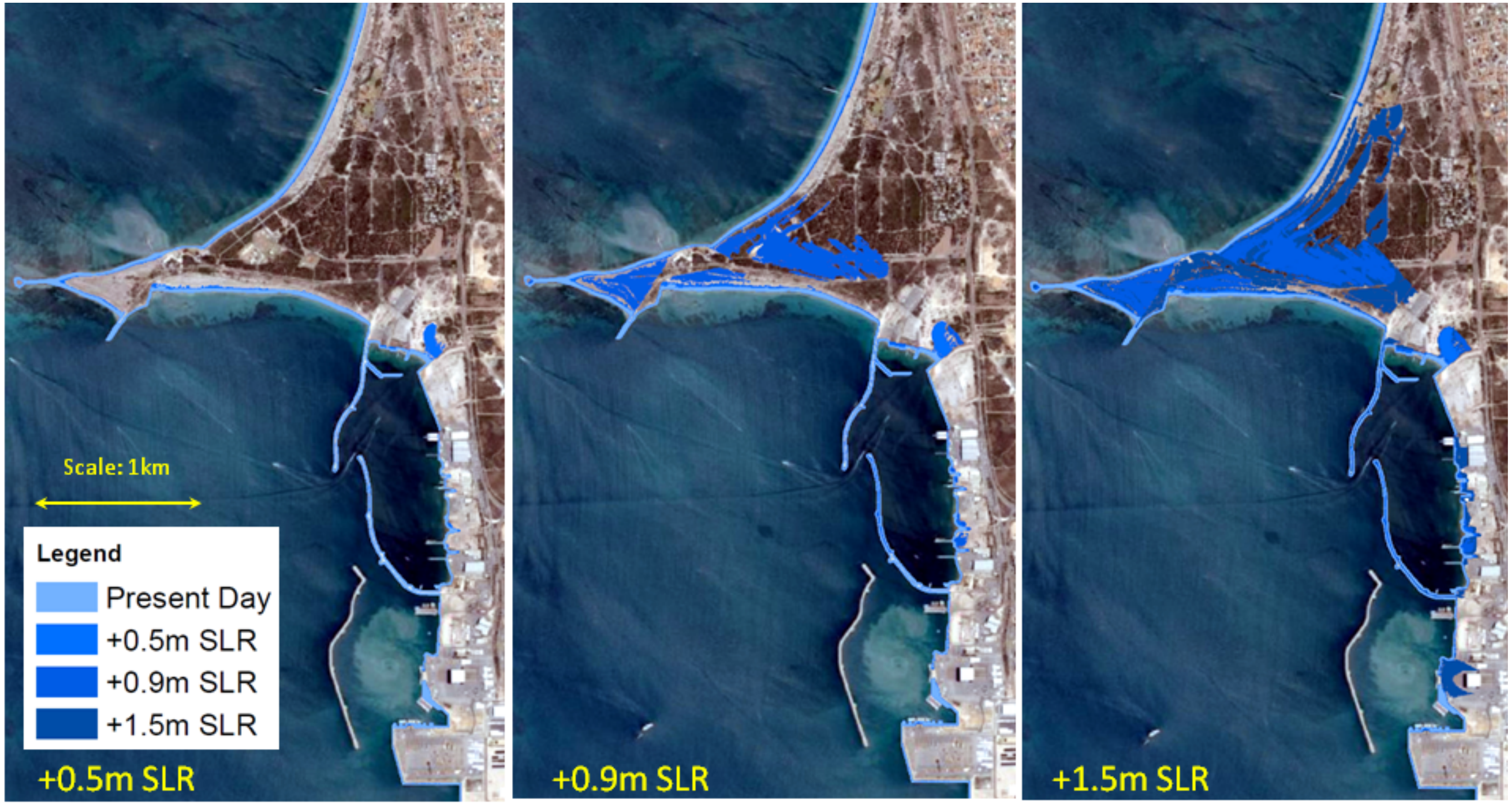


Figure 56: Increased inundation with sea level rise for a 1 year ARI event – Woodman Point

Figure 57: Increased inundation with lower event probability for a +0.9m SLR scenario – Woodman Point

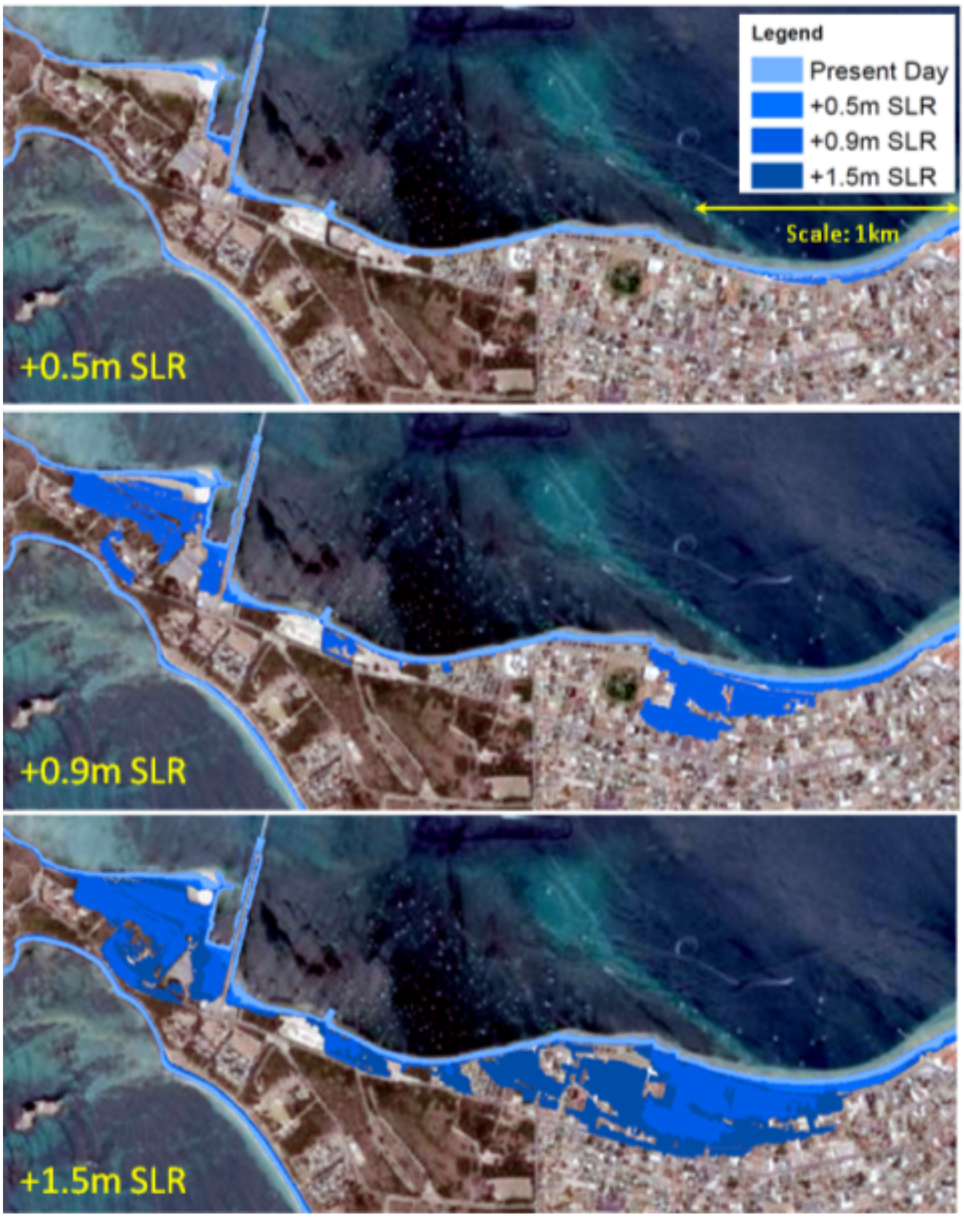


Figure 58: Increased inundation with sea level rise for a 1 year ARI event - Rockingham

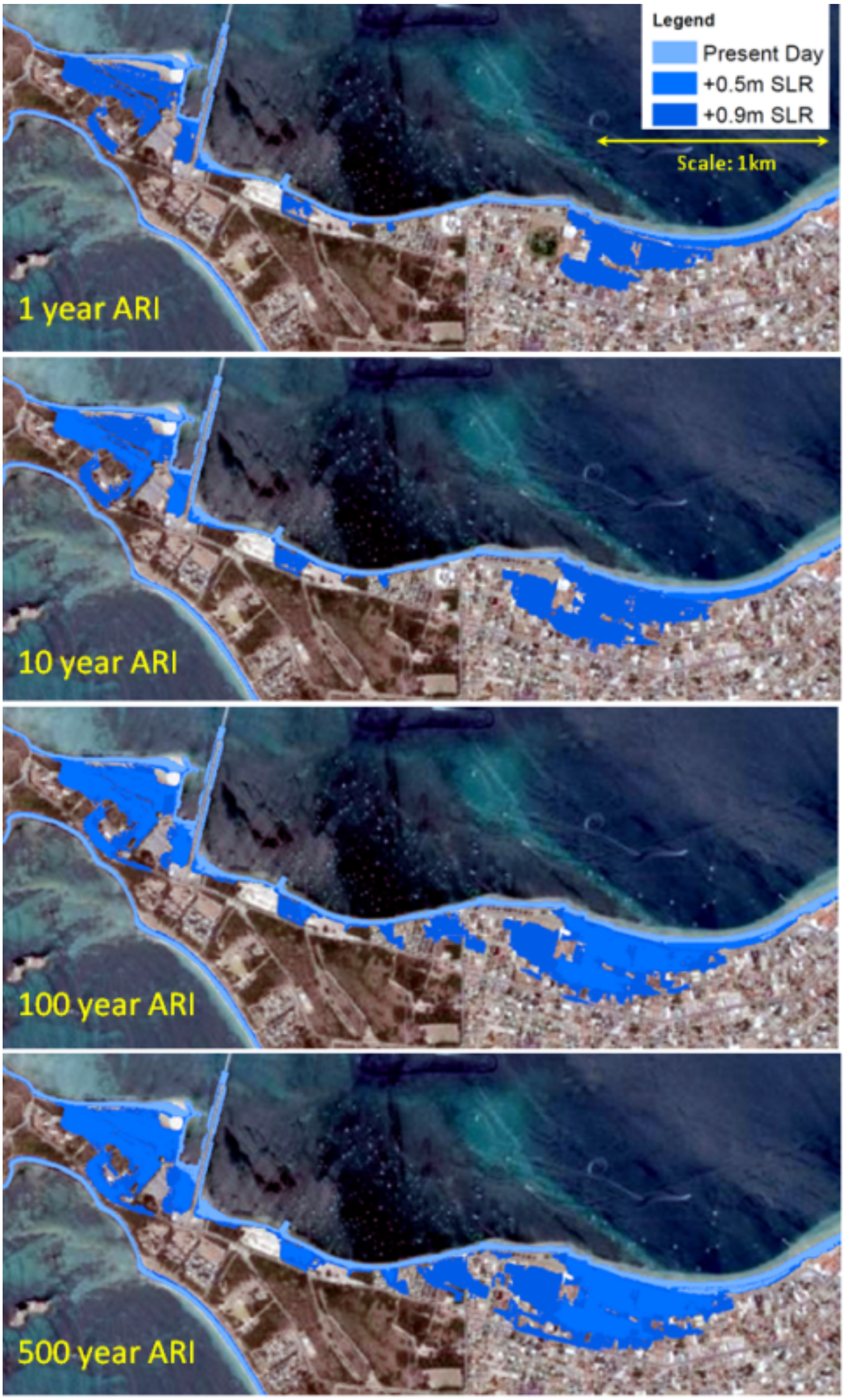


Figure 59: Increased inundation with lower event probability for a +0.9m SLR scenario -- Rockingham

5.2 INUNDATION HAZARD PER CELL

A summary of the present and future inundation hazards for each secondary sediment cell is included in Table 16. Interpretation of the potential increased inundation hazard following the occurrence of erosion is also included. Importantly, the inundation hazard represented relates only to coastal flooding impacts and does not take into account flooding that occurs as a result of issues related to terrestrial runoff. The assessment also neglects wave runup which is significant for local structure design and emergency management as it may contribute to 'erosive flooding'.

Considering these results it is possible to summarise a number of areas where inundation is likely to be an issue at the present time as well as additional areas where inundation is likely to become a problem into the future with elevations in mean sea level.

The three key areas where inundation is likely to be an issue presently are:

- Reclaimed land and the three harbours of Fremantle (Cell 22 in City of Fremantle);
- Woodman Point and small areas of Australian Maritime Complex (Cells 18-21 in City of Cockburn); and
- Southern Cockburn Sound including large areas of Rockingham (Cells 15-16 in Town of Rockingham).

Three further areas where inundation will become an issue in the future are:

- James Point (+0.5m SLR 100yr ARI);
- BP Australia (+1.5m SLR 100yr ARI); and
- Verve (+1.5m SLR 100yr ARI).

The inundation values and maps have been produced solely to inform the coastal asset risk assessment exercise envisaged as Phase 2 of the ongoing Cockburn Coastal Alliance Coastal Vulnerability Project. Inundation mapping represents inundation hazard from sustained high water level events for the topography measured in 2008. It excludes local wave setup and runup which would generate higher short-term water levels. The maps and inundation values should not be used in design of coastal structures, determination of finished floor levels or consideration of overtopping or overwash hazard. Further water level components should be added to the existing inundation values.

Table 16: Inundation Hazards of the 11 Secondary Sediment Cells

Cell	LGA	Present Inundation Hazards	Future Inundation Hazards	Recent Changes since 2008 LiDAR
22: Catherine Point groyne to South Mole Fremantle	City of Fremantle and City of Cockburn	Sections of Fremantle Fishing Boat Harbour and Success Harbour for 10-500 year ARI.	Mews Road breached in a 10 year ARI event for +0.5m SLR scenario through the railway crossing to Marine Terrace. Large areas of Marine Terrace and western Fremantle inundated from a 1 year ARI event for a +0.9m SLR scenario with water breaching a >300m section. Dunes between Duoro Road Groyne and Island Street groyne may be breached by a +1.5m SLR scenario with flooding to landward. Immediately north of Catherine Point groyne may be inundated in the most extreme scenario. The dunes at South Beach provide a reduction in inundation risk between Island Street and Success Harbour. Erosion is likely to be a more significant hazard for the Catherine Point to Success Harbour area.	Works from Island St Groyne to Catherine Point Groyne not incorporated. Inundation hazard should be reviewed with recent design information.
21: Woodman Point (WAPET groyne) to Catherine Point	City of Cockburn	Small areas of the South Fremantle Power Station inlet, Power Station seawall and Port Coogee for >1 year ARI. For the larger inundation events the access to the Cockburn Cement facility, Coogee and Ammunitions jetties may be inundated.	The extent of inundation at SFPS and Port Coogee reclaimed areas increases with SLR. The foredunes south of Catherine Point groyne begin to be breached at a +0.9m SLR scenario, with no inundation of the train line even under the most extreme scenario. Inundation likelihood increases towards Woodman Point with increased sea level rise. A 100 year ARI event with a +0.5m SLR levels water breaches the dunes at low-lying coastal access pathways, inundating the coastal camps. Higher sea level scenarios would result in increased dune breaching and broader inundation areas, with inundation connecting from Jervoise Bay to the south. Inundation hazard of the coastal camps would increase if the single primary dune (3 to 4mAHD) was eroded or coastal access was not managed. A 500 year ARI event with +0.9m SLR would inundate the Cockburn Cement facility.	Port Coogee land levels have raised with further construction. Inundation hazard should be reviewed with recent design information.

Cell	**LGA**	**Present Inundation Hazards**	**Future Inundation Hazards**	**Recent Changes since 2008 LiDAR**
20: Woodman Point groyne to Woodman Point (WAPET groyne)	City of Cockburn	The two groynes and beaches are inundated.	In a 10 year ARI event for +0.5m SLR scenario the dunes are breached immediately adjacent to Woodman Point groyne in Cell 20 and adjacent to the Woodman Point facility to the north. The dunes are breached in multiple locations and most of the cell is inundated for a 100 year ARI event for a +0.9m SLR scenario. If the dunes were eroded without migrating landward, or more breach points were made due to coastal access, inundation of the landward areas would occur sooner.	
19: Australian Maritime Complex to Woodman Point groyne	City of Cockburn	Beach only.	Minor dune breaching to the west in a 500 year event for a +0.5m SLR scenario with connection to flooding in Cell 19 and Cell 21 by a 500 year event for a +0.9m SLR scenario. The majority of the area is flooded for a +1.5m SLR scenario.	
18. James Point to Australian Maritime Complex	City of Cockburn and City of Kwinana	Access to Kwinana Bulk Terminal facility, Verve southern cooling canal, Aloca Jetty and small sections of AMC may occur for ≥10 year ARI events. The tombolos and BP flume at James Point are also inundated. The BP operations at James Point would be partially inundated in a 500 year ARI event.	Inundation hazard increases with rising sea level at AMC with potential flooding of boat launching facilities and car parks at the Woodman Point boat ramp from +0.5m SLR scenario. The Challenger boat ramp and car park is partially inundated by a +0.9m SLR scenario. Between James Point and Challenger boat ramp there is some breaching and inundation of foredunes for the +0.9m SLR scenario, with increased likelihood of loss of access to loading facilities. For a +1.5m SLR scenario there is inundation hazard for the Verve Power Station for the 100 year and 500 year ARI events. The BP operations on James Point would be partially inundated in a 10 year ARI event in a +0.5m SLR scenario, with increasing inundation extent with increasing SLR.	Present inundation risk to jetty operations should be confirmed with local design information. Construction platform for Desalination Plant is now removed.

Cell	**LGA**	**Present Inundation Hazards**	**Future Inundation Hazards**	**Recent Changes since 2008 LiDAR**
17: Palm Beach Rockingham to James Point	City of Kwinana and City of Rockingham	Access to all jetties, other than BP Jetty are inundated in a 1 year ARI event. The access path at the Rockingham memorial inundates in a 500 year ARI event, without flooding the Esplanade.	In Palm Beach inundation increases with sea level rise, with local breaching of the low foredune plain. For the +0.5m SLR scenario there is a second breach for a 1 year ARI event and multiple breaches for a 10 year ARI event. Flooding to landward occurs for a 100 year ARI event from a breach in Cell 16, with breaching of the Esplanade at Fisher Street for a 500 year ARI event. The area is largely inundated in a +0.9m SLR scenario. Inundation of some coastal carparks is anticipated by a +1.5m SLR scenario. There is increased likelihood of loss of access to jetties, other than BP Jetty, and the Boat wreck at Kwinana Beach with increased sea level rise. The majority of inundation along the remaining coast is focused on the foredune areas, with most land above 4mAHD landward of the initial foredune. The most vulnerable areas to increased inundation with erosion is west of Palm Beach jetty.	Present inundation risk to jetty operations should be confirmed with local design information.
16: Garden Island causeway to Palm Beach Rockingham	City of Rockingham	Minor inundation of boat launching facilities.	A +0.5m sea level rise scenario with a 100 year ARI event causes inundation through a coastal access track west of Bell Street flooding the Esplanade and to landward, with some inundation of the yacht club adjacent to the Cape Peron boat ramp. The extent of inundation and number of breach points increases for a 500 year ARI event. For a +0.9m SLR scenario the 1 year ARI event is a similar extent to the 500 year ARI event for the +0.5m SLR scenario. The 10 year ARI event has multiple breach locations with water extending back to Parkin Street, more of the yacht club inundated and a breach in the west of the caravan park. The 100 year ARI event has a subsequent breach at the east of the caravan park with water extending up Bell Street to inundate Parkin Street. The 500 year ARI event has an extended inundation area. Large sections of the coast between the ocean and Parkin Street and Point Peron Road are inundated in a +1.5m SLR scenario, including sections of the main roads. Water flows up the stormwater channel for Lake Richmond in a 10 year ARI event, with watering entering Lake Richmond in a 100 year ARI event via the stormwater channel and over land. The majority of this cell will have increased vulnerability to inundation with erosion. Access to the Causeway is likely to be restricted in a +1.5m SLR scenario.	Present inundation risk for Causeway should be confirmed with local design information.

Cell	LGA	Present Inundation Hazards	Future Inundation Hazards	Recent Changes since 2008 LiDAR
15: Cape Peron to Garden Island causeway	City of Rockingham	Minor inundation of boat launching facilities and seawall adjacent to the Causeway	A +0.5m sea level rise scenario with a 10 year ARI event causes inundation of the park adjacent to the causeway and a breach of the foredunes adjacent to the oval at the Point Peron campsite. A 100 year ARI event has a broader breach area for inundation and connects with the Causeway jetties, with floodwaters extending to the Woodman Point Wastewater Treatment Plant (WWTP). The extent of inundation increases for a 500 year ARI event. For a +0.9m SLR scenario the 1 year ARI event is a similar extent to the 500 year ARI event for the +0.5m SLR scenario. Significant inundation occurs to the WWTP ponds for a 10 year ARI event. The extent of dune breaching and inundation increases for the +1.5m SLR scenarios. Access to the Causeway is likely to be restricted in a +1.5m SLR scenario.	Present inundation risk for Causeway should be confirmed with local design information.
GI2: Parkin Point to Colpoys Point	Department of Defence	None.	Jetty levels and the road to the Causeway may require further investigation.	Inundation levels provided should be mapped on a Garden Island DEM by Defence in consideration of inundaton management
GI1 : Colpoys Point to Dance Head	Department of Defence	None. Dunes to ~4mAHD.	Armaments jetty levels may require further investigation.	
GI4: Dance Head to Beacon Head	Department of Defence	None. Dunes to ~4mAHD.	Low-lying area from Armaments Jetty to Second Head may require further investigation.	

Note: No high resolution DEM was available in the project timeframes for Garden Island (Figure 34). Inundation hazard is inferred from visual inspection of incomplete coverage of DTM from 2009 Department of Planning LiDAR, consideration of measured profiles (DALSE 2003) and extracted profil

6. EROSION HAZARD REPRESENTATION

Erosion hazard is presented as a series of lines where the anticipated coastal response to present and future erosive pressures has been converted into a horizontal distance of shoreline recession. The horizontal distances provide an indication of the relative sensitivity to erosion without including the impact of coastal management on the anticipated coastal response. Active coastal management has been neglected from the erosion hazard lines because the cumulative impacts of works should be considered across a broad transect of coast and future works cannot be predicted. The erosion hazard information has been presented in a format that allows coastal managers to estimate the cumulative impact of active coastal management for a coastal transect, informing them of the implications of selecting an erosion mitigation option. Any existing shore-parallel, and all future, coastal management will alter the mapped coastal response.

6.1 EROSION MAPPING PRODUCTS

A total of seven erosion scenarios were produced and presented as lines buffered landward of a baseline of the +1m Australian Height Datum (AHD) contour in 2008. This elevation was taken as the present coastal position to provide a link to the inundation hazard lines as the +1m AHD level corresponds to an existing inundation level likely to occur every year. The erosion hazard was calculated at approximately 55-60 locations across the 35 transects to incorporate influence of geological and structural controls, and the alongshore variability in anticipated erosion within a transect. Four layers represent present day acute erosion and long-term response for 2070, 2110 and a high end sensitivity for 2110 (2110+). Three additional layers represent the composite allowance for acute and chronic erosion for 2070, 2110 and 2110+ with the present day allowance added to the three chronic scenarios. The lines are an indication of relative sensitivity to erosion with any management altering the coastal response.

Erosion Hazard lines are provided in GIS format along with the erosion distance values at the points where they were calculated (see Appendix 8 for further information). The lines are also presented as an interactive dataset in one interactive pdf map provided as a separate attachment. The user may view all seven erosion scenarios or turn layers on and off to view the scenario of interest and impact of increased sea level rise. To view layers in interactive pdf in Adobe acrobat software see the description in Section 5 for the Inundation Hazard mapping. An example of the erosion hazard lines is provided in Figure 60 for the Kwinana Industrial Area., demonstrating the increased chronic erosion allowance incorporated for increased sea level rise. Figure 60a shows the increased chronic erosion allowance incorporated for increased sea level rise and gradual response to structures and coastal evolution. Figure 60B incorporates the added allowance for acute erosion for those three scenarios. The chronic 2110 scenario and combined acute and chronic 2110 scenario are compared in Figure 60C demonstrating the addition of between 44 and 73m for acute coastal response at the extents of the cell and only 21-36m for the central section of coast.

6.2 EROSION HAZARD AREAS

The areas of high erosion hazard are separated into areas with existing erosion hazard and areas susceptible to change with sea level rise (see Appendix 8). It is important to note that coastal assets, recreation areas and infrastructure located along the coast were not considered in the assessment of hazard and therefore do not provide a measure of risk. The assessment is based only on consideration of erosion potential.

Three areas with existing acute erosion hazard are:

- Garden Island north of Colpoys Point (Cell GI1b in the jurisdiction of the Department of Defence),
- Palm Beach (Cell 16 in City of Rockingham); and
- Kwinana Bulk Terminal (Transects 18.3 and 18.4 in Cell 18 in the City of Kwinana).

The three areas anticipated to experience the most severe long-term erosion are:

- North of Catherine Point (Cell 22 in the City of Fremantle and City of Cockburn);
- Woodman Point area (Cells 19-21 in the City of Cockburn); and the
- Kwinana Industrial Area to James Point (Cell18 in the City of Kwinana).

Increased erosion is also expected as a result of sea level rise contributing to decrease or cessation of onshore sediment supply, geometric response of the coast due to shifting the hydraulic zone and increased exposure of rock. The supply of sediment onshore may tend to zero between 2070 and 2110. Increased erosion due to the impacts of sea level rise is expected in the following areas:

- South of Catherine Point groyne (Cell 21 in the City of Cockburn);
- James Point and Kwinana Industrial Area (Cells 17 and 18 in the City of Kwinana);
- South end of Garden Island (Cell GI2a in the jurisdiction of the Department of Defence);
- South Beach, potentially enhanced by partitioning of the coast (Cell 22 in the City of Fremantle and City of Cockburn); and

- The cliff line of the Spearwood Ridge will extend south to Challenger Beach as the coast erodes (Cell 18 in the City of Kwinana).

A summary of the present and future erosion hazards for each secondary sediment cell is included in Table 17 along with any site-specific considerations for impacts of coastal management on erosion lines.

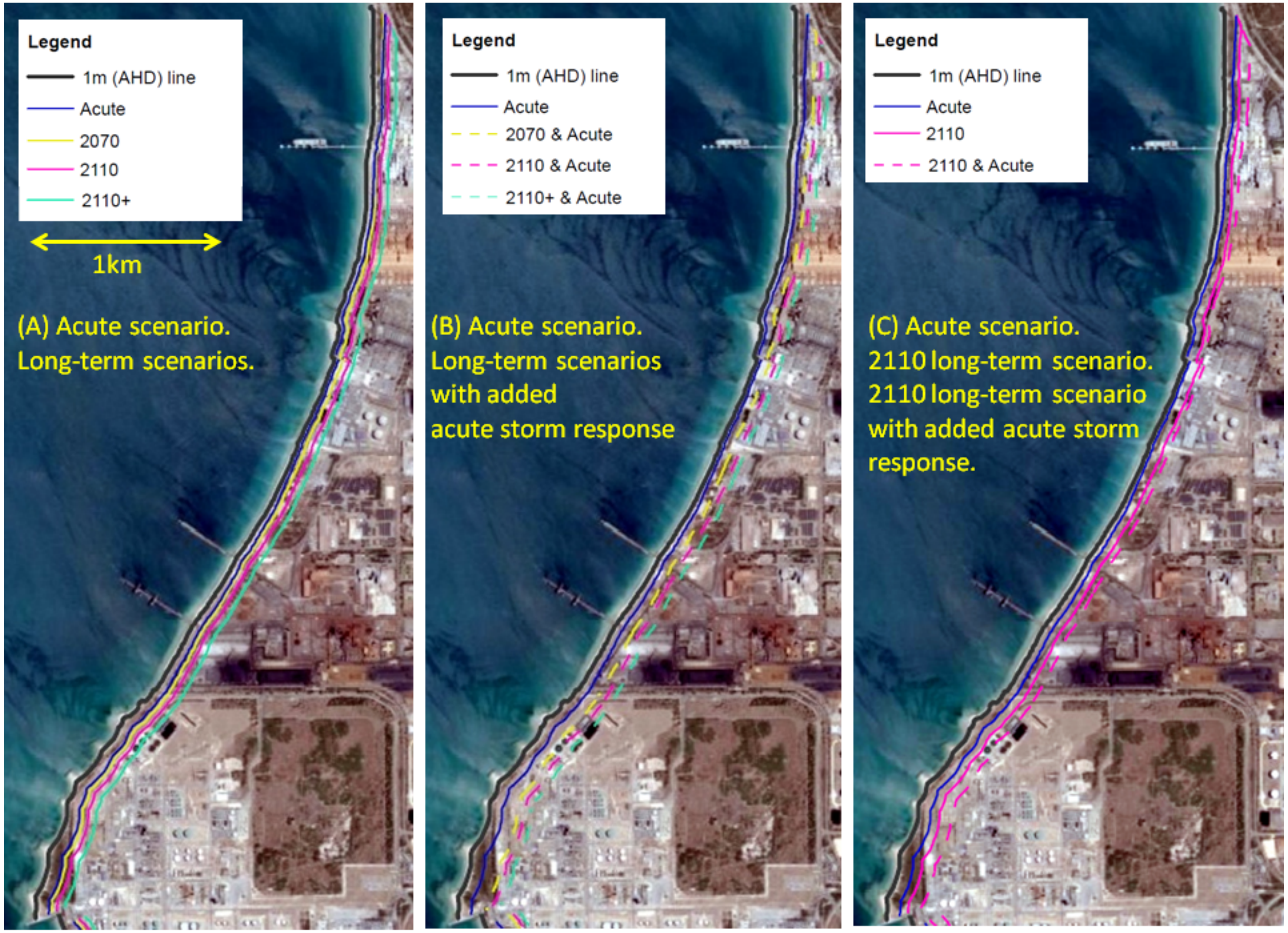


Figure 60: Example of Erosion Hazard Lines for the Kwinana Industrial Area

Table 17: Summary of Erosion Hazards for the 11 Secondary Sediment Cells

Cell	LGA	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
22: Catherine Point groyne to South Mole Fremantle	City of Fremantle and City of Cockburn	Updrift erosion from Catherine Point groyne to Island Street groyne. Erosion of renourished material.	Increased downdrift erosion in the Duoro Road groyne to Success Harbour. Significantly susceptible to increased sea level rise at 2110.	Short-term calculations should be incorporated within the groyne partitions. Adjustments for management should be considered along the cell. Coast location maintained by groynes and renourishment. Insufficient capacity for dunes to migrate landward.
21: Woodman Point (WAPET groyne) to Catherine Point	City of Cockburn	Updraft erosion immediately south of Catherine Point groyne and structure response. Updrift erosion north of Cockburn Cement seawall. Sediment loss offshore south of Port Coogee	Increased erosion immediately downdrift of Catherine Point groyne. Increased downdrift erosion south of Port Coogee. Immediately north of Woodman Point significantly susceptible to increased sea level rise at 2110.	Adjustments for management should be separated at Port Coogee with consideration of any bypassing. Increased exposure of rock control could occur immediately south of Port Coogee
20: Woodman Point groyne to Woodman Point (WAPET groyne)	City of Cockburn	Foredune plain retreat	Increased foredune plain retreat and loss of structural control. Significantly susceptible to increased sea level rise at 2110.	None
19: Australian Maritime Complex to Woodman Point groyne	City of Cockburn	Rotation and loss of material offshore	Increased retreat of foredune plain.	Need to consider offshore losses to dredged areas

Cell	LGA	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
18. James Point to Australian Maritime Complex	City of Cockburn and City of Kwinana	Highest erosion at end points of cell at James Point and Challenger Boat Ramp. Infrastructure impacts on adjacent coasts. Lowering of beach and terrace levels seaward of infrastructure	The whole cell incorporating Kwinana industrial area significantly susceptible to increased sea level rise by 2070. Retreat of the James Point cuspate foreland.	Increased exposure of Spearwood Ridge rock control could occur immediately south of Challenger beach. Cockburn road presented as a hard line in the mapping. Any partitioning of the coast should consider the impact on the whole cell.
17: Palm Beach Rockingham to James Point	City of Kwinana and City of Rockingham	Palm Beach and Kwinana Bulk Terminal to Kwinana Wreck susceptible to acute erosion.	Increased retreat of the foredune plain and reduced structure control. Retreat of the James Point cuspate foreland.	Small rock control immediately south of James Point should be considered. Number of structures would lose functional control with increased sea level rise.
16: Garden Island causeway to Palm Beach Rockingham	City of Rockingham	The whole cell is susceptible to acute erosion.	Increased retreat of the foredune plain and reduced feature control.	Number of structures would lose functional control with increased sea level rise. Insufficient capacity for dunes to migrate landward.
15: Cape Peron to Garden Island causeway	City of Rockingham	The whole cell is susceptible to acute erosion except rock outcrops	Capacity for foredune plain to migrate landward in some areas. Retreat of foredune plain.	Incorporate rock outcrops as controls
GI2: Parkin Point to Colpoys Point	Department of Defence	Retreat of Careening Bay dunes with growth of Parkin Point spit.	Increased susceptibility with sea level rise at 2110.	Interaction with Parkin Point spit and Causeway to be considered.

Cell	LGA	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
GI1 : Colpoys Point to Dance Head	Department of Defence	Limited capacity for storm recovery.	Increased susceptibility with sea level rise at 2110. Focal locations have insufficient capacity for dunes to migrate landward	Incorporate rock outcrops as controls
GI4: Dance Head to Beacon Head	Department of Defence	The cell is the most susceptible to acute erosion on eastern Garden Island, except for rock outcrops.	Increased susceptibility with sea level rise at 2110.	Incorporate rock outcrops as controls

6.3 USING THE EROSION HAZARD LINES

The erosion hazard lines should be adjusted to allow for the coastal response to existing and potential future coastal management, with consideration of the rock and structural controls applicable at the relevant scale. The hazard lines are representative of sediment demand converted to a representative horizontal distance, with any modification to the coast to be balanced within the cell by altering adjacent erosion line distances. For example downdrift erosion distances would increase if the coast was compartmentalised by a groyne or a seawall is installed to maintain the coastal position.

A worked example for how a coastal manager may conduct a simple calculation to estimate the increased erosion demand at the Verve Energy seawall in Cell 18 in the City of Kwinana is provided in Figure 61. The approach is a simple conservation of mass estimated using calculated areas. The following steps are used:

- Estimate distance north and south likely to be impacted by the coastal management. The broader section of coast to the south of the seawall is 1000m with an erosion distance of 21m. The section of coast to the north is 1700m length with erosion distances of 26m and 44m. The total area of coast anticipated to be affected is 2700m.
- Estimate the area likely to be located landward of the erosion line as a result of the management option. Incorporating the existing Verve Energy seawall requires the addition of two sections of seawall located seaward of the erosion line. There is no capacity for erosion landward of the seawall as they are designed to hold the coastal position and the erosion potential will be transferred to the adjacent section of coast. Area 1 is 130m length with a triangular distribution of erosion from 0m at the south to 13m at the north which equates to an area of 850m^2. Area 2 is 180m long and approximately 15m wide which equates to an area of 2,700m^2. This suggests a total adjustment of the erosion lines should equal 3,550m^2 as a result of the existing Verve seawall.
- Estimate altered sediment demand on the adjacent sections of coast. This will be accounted for based on affected distance north and south of the structure, with 1/3 (1,000m) of the length of coast to the south and 2/3 (2,700m) of the length of coast to the north. The area (3,550m^2) is separated into 1/3 (1,200m^2) and 2/3 (2,400m^2) for each section of coast. The areas are divided by the length of coast to determine the amount of the erosion distances should be altered. The southern section is -1.2m (1,200m^2/1,000m) and the northern section is -1.4m (2,400m^2/1,700m).
- Adjust erosion lines. The southern distance of 21m is increased to 22.2m and the northern distances of 26m and 44m are adjusted to 27.4m and 45.4m respectively.

Alongshore variation in adjusted sediment demand may also be incorporated, such as increased erosion distance immediately downdrift of the seawall.

The erosion hazard lines and distances should not be used as setback lines for avoiding coastal hazard, as a sole planning tool to determine if any development or works are appropriate and without consideration of existing coastal management

Management of the OACS coast is likely to experience a significant challenge between 2070 and 2110 (for the projected sea level time series). In this time range, the relative sediment deficit caused by profile adjustment to sea level change balances the historic sediment supply, subsequently with net erosion. As a consequence, structures that hold sediment will preferentially recover from storm erosion, at the expense of unprotected areas, which will be progressively eroded, with limited or no recovery after storms.

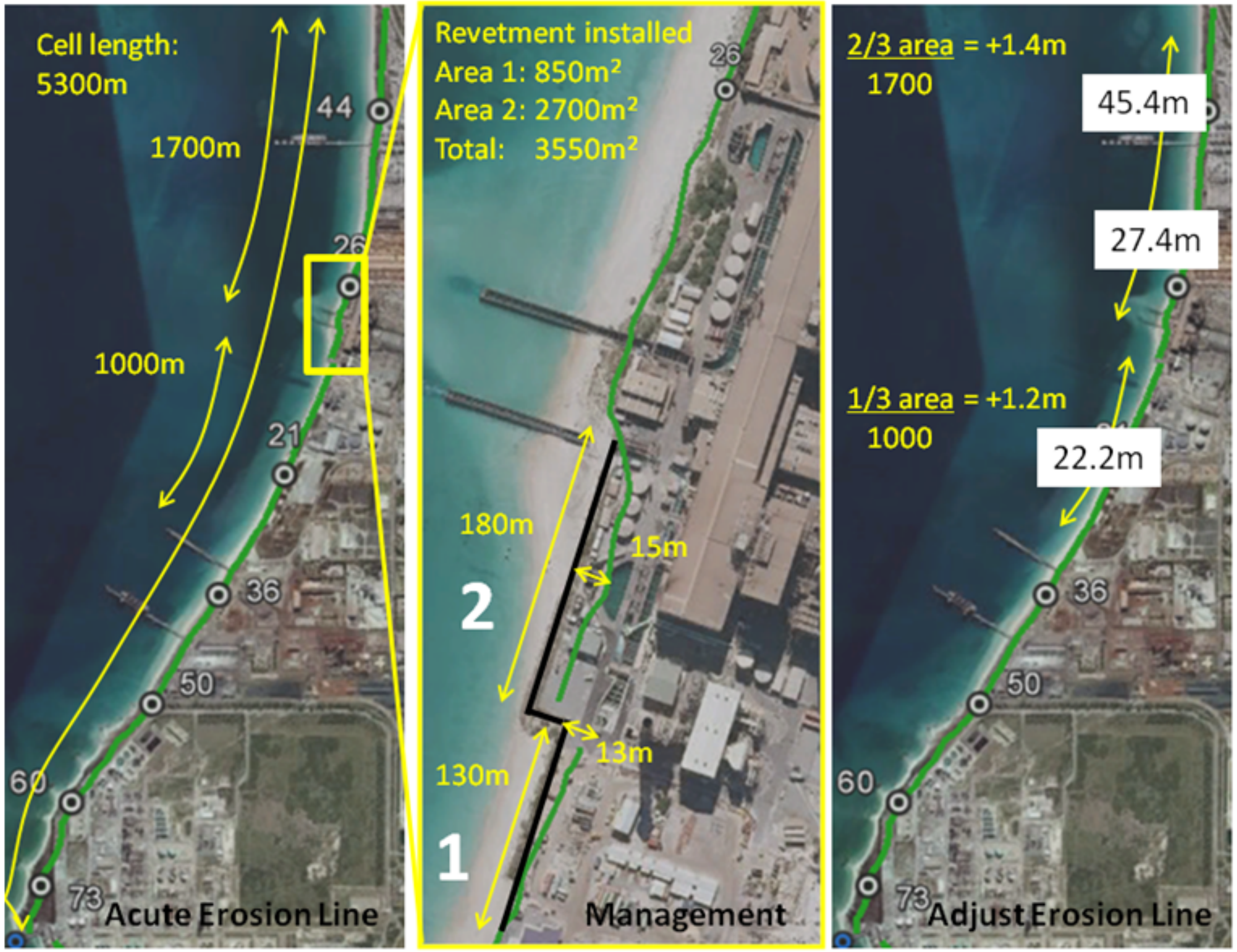


Figure 61: Example of Adjusting 'Acute' Erosion Hazard Line for Management Scenario at Verve Power Station

6.4 EROSION HAZARD SUMMARY

A consideration of the outputs of the erosion hazard assessment allow delineation of the key area of concern throughout the OACS coast (Table 18). The areas of erosion concern are presented without consideration of infrastructure or values at risk or transferral of erosion hazard through coastal management. Several areas are considered to be at risk of erosion under present conditions while others are likely to become more susceptible to erosion as sea levels rise in response to a changing climate. Additionally, some locations along the OACS coast are more susceptible to erosion in response to storm conditions (acute erosion hazard) while others are more likely to exhibit a trend of erosion through time and incorporating a response to sea level rise (chronic erosion hazard). The anticipated response to sea level rise includes increased erosion, decrease or cessation of onshore sediment supplies and increased exposure of rock.

Table 18: Summary of Key Areas of Erosion Concern

Timeframe	Acute Erosion Hazard	Long Term Erosion Hazard
Areas at Immediate Risk	• Garden Island north of Colpoys • Palm Beach area • Kwinana Bulk Terminal	• North of Catherine Point • Woodman Point area • Kwinana Industrial Area to James Point
Areas likely to be at risk in the future	• Kwinana Industrial Area by 2070 and • South Fremantle (2110) • Woodman Point (2110) • Garden Island (2110)	• Erosion likely to continue on south side of Catherine Point Groyne, unless extreme SLR (>1.0m by 2110) experienced • Extension of cliff line on Challenger Beach • Significant erosion at James Point • Greater erosion possible towards south end of Garden Island • Sediment supplies may 'run out' between 2060 and 2110

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7. Conclusion & Recommendations

This study provides Phase I of a Climate Change Impact and Adaptation Assessment for the Cockburn Sound Coastal Alliance. This Project Phase provides an evaluation of coastal vulnerability, in the context of projected climate change and sea level rise, for the coasts of Cockburn Sound, Owen Anchorage and the east of Garden Island. Mapping of potential erosion and inundation has been developed for scenarios up to +1.5m sea level rise, intended for use in subsequent project phases, which will consider impacts and adaptation pathways.

Inundation hazard was mapped through GIS evaluation of the spatial extent of flooding associated with moderate to extreme storm events, coincident to projected sea level rise. This analysis indicated that inundation for the OACS coast was focused along sections of coast. Locations where existing hazard occurs include Fremantle, Woodman Point and Rockingham, which may expand significantly without suitable adaptation to climate change. Locations that do not presently experience significant inundation hazard, but are anticipated to be threatened due to sea level rise include James Point and parts of Kwinana Industrial Area.

Erosion hazard was evaluated through a combination of models used to describe cross-shore and alongshore change (acute and chronic). Model outputs were interpreted using evidence-based verification, where processes suggested by modelling were compared with the extensive history of change described by coastal monitoring programs along the OACS coast. This technique allowed identification of conditions under which model performance was considered unreliable, allowing improved model interpretation. Coastal response to sea level rise applied refinement, based upon sediment cells, of the Bruun conceptual model, recreating the patterns of focal onshore feed and alongshore distribution that are evident in both historic and stratigraphic behaviour. This use of local geomorphology incorporated evaluation of the *susceptibility* of the coast to sea level rise, in addition to the existing *sensitivity* to variation of metocean conditions, which was captured by the acute response.

Historic patterns of change along the OACS coast have demonstrated the significance of coastal stabilisation works for the redistribution of sediment supply and the transfer of erosion hazard to the adjacent or downdrift coast. Consequently, hazard mapping has been presented in terms of net erosion for coastal segments, with the potential effect of existing or new structures being to exacerbate erosion in otherwise unprotected areas. Sections of coast that are most susceptible to erosion caused by sea level rise are those which are most isolated from sources of sediment, particularly the Kwinana coast.

Table 19 provides a summary of the key findings of the analysis for each of the coastal cells under consideration through this study. This information should be interpreted in conjunction with the erosion and inundation hazard summary tables presented in Section 5 (Table 16 and Table 17) as well as the interactive mapping products (Appendix 7 and 8) that have been supplied as electronic appendices to this document. It will be important for stakeholders to evaluate the information provided from the perspective of their discrete interests within their local government areas but also across cell boundaries. Identification of the areas of greatest concern from both an erosion and inundation hazard perspective through the OACS coast will allow decision makers to prioritise future management efforts and proactively manage in an adaptive manner. This type of adaptive response is an important requirement for the OACs coast due to the diverse characteristics of the coastal system.

Active sediment management within the OACS coast will be an ongoing requirement for stakeholders, with increasing need for focus as the area moves from being in a state of net accretion (at present) to one of net erosion (projected to occur by 2070). In light of this, an overview of coastal management in the OACS coast is provided in Section 7.1 including a discussion on recent and present coastal management pressures (7.1.1), projected changes to coastal management (7.1.2) followed by a brief discussion on monitoring and management triggers (7.1.3).

The final component of this section is a summary of recommendations for future monitoring and studies (7.2).

Table 19: Overview of Key Findings per Coastal Cell

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
22: Catherine Point groyne to South Mole Fremantle	City of Fremantle and City of Cockburn	Supply to the north from Success Bank onshore feed at Catherine Point. Broad shallow nearshore associated with Success Bank. Transport interrupted by Success Harbour.	Sections of Fremantle Fishing Boat Harbour and Success Harbour for 10-500 year ARI.	Mews Road breached in a 10 year ARI event for +0.5m SLR scenario through the railway crossing to Marine Terrace. Large areas of Marine Terrace and western Fremantle inundated from a 1 year ARI event for a +0.9m SLR scenario with water breaching a >300m section. Dunes between Duoro Road Groyne and Island Street groyne may be breached by a +1.5m SLR scenario with flooding to landward.	Updrift erosion from Catherine Point groyne to Island Street groyne. Erosion of renourished material.	Increased downdrift erosion in the Duoro Road groyne to Success Harbour. Significantly susceptible to increased sea level rise at 2110.	Short-term calculations should be incorporated within the groyne partitions. Adjustments for management should be considered along the cell. Coast location maintained by groynes and renourishment. Insufficient capacity for dunes to migrate landward.

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Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
21: Woodman Point (WAPET groyne) to Catherine Point	City of Cockburn	Supplied by material from Success and Parmelia Banks. Material transported south from Success Bank and north from Parmelia Bank. Significant interference by Port Coogee constructed on rock platforms and outcropping of the Spearwood Ridge.	Small areas of the South Fremantle Power Station inlet, Power Station seawall and Port Coogee for >1 year ARI. For the larger inundation events the access to the Cockburn Cement facility, Coogee and Ammunitions jetties may be inundated.	The extent of inundation at SFPS and Port Coogee reclaimed areas increases with SLR. The foredunes south of Catherine Point groyne begin to be breached at a +0.9m SLR scenario, with no inundation of the train line even under the most extreme scenario. Inundation likelihood increases towards Woodman Point with increased sea level rise. A 100 year ARI event with a +0.5m SLR levels water breaches the dunes at low-lying coastal access pathways, inundating the coastal camps. Higher sea level scenarios would result in increased dune breaching and broader inundation areas, with inundation connecting from Jervoise Bay to the south. Inundation hazard of the coastal camps would increase if the single primary dune (3 to 4mAHD) was eroded or coastal access was not managed. A 500 year ARI event with +0.9m SLR would inundate the Cockburn Cement facility.	Updraft erosion immediately south of Catherine Point groyne and structure response. Updrift erosion north of Cockburn Cement seawall. Sediment loss offshore south of Port Coogee	Increased erosion immediately downdrift of Catherine Point groyne. Increased downdrift erosion south of Port Coogee. Immediately north of Woodman Point significantly susceptible to increased sea level rise at 2110.	Adjustments for management should be separated at Port Coogee with consideration of any bypassing. Increased exposure of rock control could occur immediately south of Port Coogee

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
20: Woodman Point groyne to Woodman Point (WAPET groyne)	City of Cockburn	Artificial coast with sediment from Parmelia Bank impounded on structures.	The two groynes and beaches are inundated.	In a 10 year ARI event for +0.5m SLR scenario the dunes are breached immediately adjacent to Woodman Point groyne in Cell 20 and adjacent to the Woodman Point facility to the north. The dunes are breached in multiple locations and most of the cell is inundated for a 100 year ARI event for a +0.9m SLR scenario. If the dunes were eroded without migrating landward, or more breach points were made due to coastal access, inundation of the landward areas would occur sooner.	Foredune plain retreat	Increased foredune plain retreat and loss of structural control. Significantly susceptible to increased sea level rise at 2110.	None
19: Australian Maritime Complex to Woodman Point groyne	City of Cockburn	Compartmentalised coast with no direct sediment supply. Groyne structures extend beyond terrace.	Beach only.	Minor dune breaching to the west in a 500 year event for a +0.5m SLR scenario with connection to flooding in Cell 19 and Cell 21 by a 500 year event for a +0.9m SLR scenario. The majority of the area is flooded for a +1.5m SLR scenario.	Rotation and loss of material offshore	Increased retreat of foredune plain.	Need to consider offshore losses to dredged areas

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
17: Palm Beach Rockingham to James Point	City of Kwinana and City of Rockingham	Low-lying foredune plain coast has a change of aspect with beaches more exposed to the northeast. There is a narrow terrace in Mangles Bay, with a deeper and broader terrace to the east underlying the narrow terrace. James Point lacks contemporary sediment supply and is controlled by a change in aspect and rock features.	Access to all jetties, other than BP Jetty are inundated in a 1 year ARI event. The access path at the Rockingham memorial inundates in a 500 year ARI event, without flooding the Esplanade.	At Palm Beach inundation increases with sea level rise, with local breaching of the low foredune plain. For the +0.5m SLR scenario there is a second breach for a 1 year ARI event and multiple breaches for a 10 year ARI event. Flooding to landward occurs for a 100 year ARI event from a breach in Cell 16, with breaching of the Esplanade at Fisher Street for a 500 year ARI event. The area is largely inundated in a +0.9m SLR scenario. Inundation of some coastal carparks is anticipated by a +1.5m SLR scenario. There is increased likelihood of loss of access to jetties, other than BP Jetty, and the Boat wreck at Kwinana Beach with increased sea level rise. The majority of inundation along the remaining coast is focused on the foredune areas, with most land above 4mAHD landward of the initial foredune. The most vulnerable areas to increased inundation with erosion is west of Palm Beach jetty.	Palm Beach and Kwinana Bulk Terminal to Kwinana Wreck susceptible to acute erosion.	Increased retreat of the foredune plain and reduced structure control. Retreat of the James Point cuspate foreland.	Small rock control immediately south of James Point should be considered. Number of structures would lose functional control with increased sea level rise.

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
17: Palm Beach Rockingham to James Point	Town of Kwinana and City of Rockingham	Low-lying foredune plain coast has a change of aspect with beaches more exposed to the northeast. There is a narrow terrace in Mangles Bay, with a deeper and broader terrace to the east underlying the narrow terrace. James Point lacks contemporary sediment supply and is controlled by a change in aspect and rock features.	Access to all jetties, other than BP Jetty are inundated in a 1 year ARI event. The access path at the Rockingham memorial inundates in a 500 year ARI event, without flooding the Esplanade.	At Palm Beach inundation increases with sea level rise, with local breaching of the low foredune plain. For the +0.5m SLR scenario there is a second breach for a 1 year ARI event and multiple breaches for a 10 year ARI event. Flooding to landward occurs for a 100 year ARI event from a breach in Cell 16, with breaching of the Esplanade at Fisher Street for a 500 year ARI event. The area is largely inundated in a +0.9m SLR scenario. Inundation of some coastal carparks is anticipated by a +1.5m SLR scenario. There is increased likelihood of loss of access to jetties, other than BP Jetty, and the Boat wreck at Kwinana Beach with increased sea level rise. The majority of inundation along the remaining coast is focused on the foredune areas, with most land above 4mAHD landward of the initial foredune. The most vulnerable areas to increased inundation with erosion is west of Palm Beach jetty.	Palm Beach and Kwinana Bulk Terminal to Kwinana Wreck susceptible to acute erosion.	Increased retreat of the foredune plain and reduced structure control. Retreat of the James Point cuspate foreland.	Small rock control immediately south of James Point should be considered. Number of structures would lose functional control with increased sea level rise.

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
16: Garden Island causeway to Palm Beach Rockingham	**City of Rockingham**	Low-lying foredune plain coast with behaviour influenced by marine features, exposure to the north and the Causeway. Broad terrace width increases to the west of the cell.	Minor inundation of boat launching facilities.	A +0.5m sea level rise scenario with a 100 year ARI event causes inundation through a coastal access track west of Bell Street flooding the Esplanade and to landward, with some inundation of the yacht club adjacent to the Cape Peron boat ramp. The extent of inundation and number of breach points increases for a 500 year ARI event. For a +0.9m SLR scenario the 10 year ARI event has multiple breach locations with water extending back to Parkin Street, more of the yacht club inundated and a breach in the west of the caravan park. The 100 year ARI event has a subsequent breach at the east of the caravan park with water extending up Bell Street to inundate Parkin Street. Extensive inundation occurs for a +1.5m SLR scenario, including main roads and water flowing into Lake Richmond (200 year ARI). The majority of this cell will have increased vulnerability to inundation with erosion. Access to the Causeway is likely to be restricted in a +1.5m SLR scenario.	The whole cell is susceptible to acute erosion.	Increased retreat of the foredune plain and reduced feature control.	Number of structures would lose functional control with increased sea level rise. Insufficient capacity for dunes to migrate landward.

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
15: Cape Peron to Garden Island causeway	**City of Rockingham**	Foredune plain located between large rock outcrops as part of the Garden Island Ridge. Recent foredune plain growth associated with the Causeway. Influenced by pulses of sediment supply through the Garden Island Ridge. Causeway has modified local wave climate.	Minor inundation of boat launching facilities and seawall adjacent to the Causeway	A +0.5m sea level rise scenario with a 10 year ARI event causes inundation of the park adjacent to the causeway and a breach of the foredunes adjacent to the oval at the Point Peron campsite. A 100 year ARI event has a broader breach area for inundation and connects with the Causeway jetties, with floodwaters extending to the Woodman Point Wastewater Treatment Plant (WWTP). The extent of inundation increases for a 500 year ARI event. Access to the Causeway is likely to be restricted in a +1.5m SLR scenario.	The whole cell is susceptible to acute erosion except rock outcrops	Capacity for foredune plain to migrate landward in some areas. Retreat of foredune plain.	Incorporate rock outcrops as controls

Cell	LGA	Attributes	Present Inundation Hazards	Future Inundation Hazards	Present Erosion Hazard	Future Erosion Hazards	Considerations for Impacts of Management on Erosion Lines
GI2: Parkin Point to Colpoys Point	Department of Defence	Careening Bay is altered by the Causeway, facilities and dredging. Loss of material from the coast is partially transferred to Parkin Point spit. No significant supply to the beaches and limited capacity of recovery.	None.	Jetty levels and the road to the Causeway may require further investigation.	Retreat of Careening Bay dunes with growth of Parkin Point spit.	Increased susceptibility with sea level rise at 2110.	Interaction with Parkin Point spit and Causeway to be considered.
GI1 : Colpoys Point to Dance Head		Coast is sheltered from most extreme events with shallow embayments controlled by rock outcrops from the Garden Island Ridge and marine features of variable extent and depths. Limited capacity for storm recovery.	None. Dunes to ~4mAHD.	Armaments jetty levels may require further investigation.	Limited capacity for storm recovery.	Increased susceptibility with sea level rise at 2110. Focal locations have insufficient capacity for dunes to migrate landward	Incorporate rock outcrops as controls
GI4: Dance Head to Beacon Head		Some sediment supply transported around Garden Island south past Beacon Head with reworking. Coast controlled by rock outcrops and marine features.	None. Dunes to ~4mAHD.	Low-lying area from Armaments Jetty to Second Head may require further investigation.	The cell is the most susceptible to acute erosion on eastern Garden Island, except for rock outcrops.	Increased susceptibility with sea level rise at 2110.	Incorporate rock outcrops as controls

7.1 OACS COASTAL MANAGEMENT

An early focus for management of the Owen Anchorage coast was provided by coastal development of Fremantle including the popular Hydrodrome near South Beach and the historic Fremantle to Armadale train line (now remnant). Intermittent erosion was managed by walling for individual facilities, with later installation of a large groyne at Catherine Point, further supported by an extended sand feed from sidecast dredge material from Success Channel. The groyne provided enhanced coastal stability to the north, including a large seaward reconfiguration of the coast, but also reduced sediment supply to the south, where the South Fremantle Power Station had experienced sedimentation issues.

Industrial development of the Cockburn Sound area prompted significant development of landing facilities and seawater intake / outlets for cooling plants. The consequent desire for high coastal stability prompted installation of various works, including the series of detached headlands around James Point. Construction of Garden Island Causeway has also had implications for coastal management further south, with interruption of the sand supply around Point Peron creating a sedimentation issue to the west of the Causeway and an extended period of coastal adjustment on the Rockingham foreshore to the east.

The use of coastal stabilisation techniques along the OACS coast has generally been effective. This is due to both a net sediment supply and capacity for only mild storm erosion because of wave shelter. Partitioning provides a means of redistributing erosive pressures, by capturing the sediment supply updrift (Figure 62).

This shifts the nature of erosion pressures from sand supply variation (occurring updrift in a sediment cell) towards recovery lag effects (occurring downdrift). The relative behaviour of a coast is a balance of the two scenarios, determined by the effectiveness of coastal protection structures to limit alongshore transport. Consequently, short coastal protection works such as Island St rock groyne, Palm Beach timber groynes, or structures on the broad subtidal terraces in Cockburn Sound, generally demonstrate less tendency to cause downdrift volatility than larger structures such as Catherine Point groyne.

Since partitioning of the OACS coast with stabilisation works, coastal management pressures have been largely related to the difficulty of distributing the available sand supply via structures, whilst accommodating variability caused by storm erosion and longer-term (seasonal and inter-annual) variations in prevailing conditions.

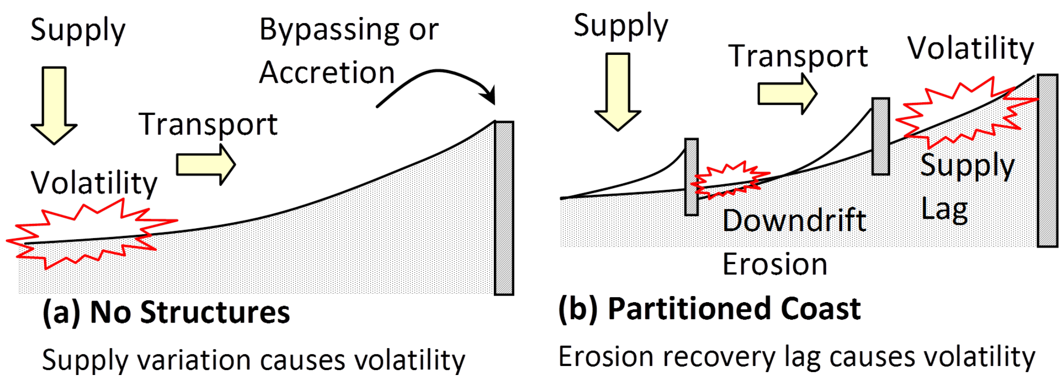


Figure 62: Transfer of Coastal Volatility Using Structures

7.1.1 Recent and Present Coastal Management Pressures

The situation of net coastal accretion along the OACS coast means that historic and active erosion pressures have largely been related to the difficulty of distributing this supply via structures, whilst accommodating variability caused by storm erosion and longer-term variations in prevailing conditions. Although coastal structures have been generally effective at redistributing erosive stress in the desired fashion, the effect of partitioning increases the susceptibility of different areas to erosion-recovery cycles. This effect has been exacerbated in locations where infrastructure has been built too close to the coast to accommodate variability.

Existing coastal management along the OACS coast operates within the legacy of the previous works, many of which have been developed through consideration of isolated sections of coast, based upon jurisdiction rather than geomorphic connectivity. Despite this potential limitation, there have been relatively few areas experiencing regular erosion pressures. Interpretation of available coastal profile monitoring suggests that possible mechanisms for erosion are development of sediment sinks caused by installation of new structures (e.g. Port Coogee); alongshore transfer of storm erosion (including seawall effects along Kwinana, with schematic diagram Figure 63); and downdrift recovery lag (e.g. South Fremantle).

Existing coastal management pressures include:

- Documented recent erosion has occurred along the South Fremantle foreshore and Kwinana Beach which are isolated from sediment supply and have previously been supported by renourishment works. Without amended management, these stresses are likely to worsen progressively;

- Coastal response to construction of Port Coogee is still underway and it is likely to take a number of years before a relatively 'stable' configuration, including the effects of bypassing, to be established;
- The coastal response to lengthening Catherine Point groyne is anticipated to be increased stability to the north and greater coastal variability to the south;
- Steepening of the sub-tidal parts of the profiles from Coogee Beach to Woodman Point represents a 'priming' of the coast for potential rapid erosion under stormy conditions with reduced capacity for recovery.

These pressures have been relatively mild and managed effectively with limited reactive works, such as sand nourishment.

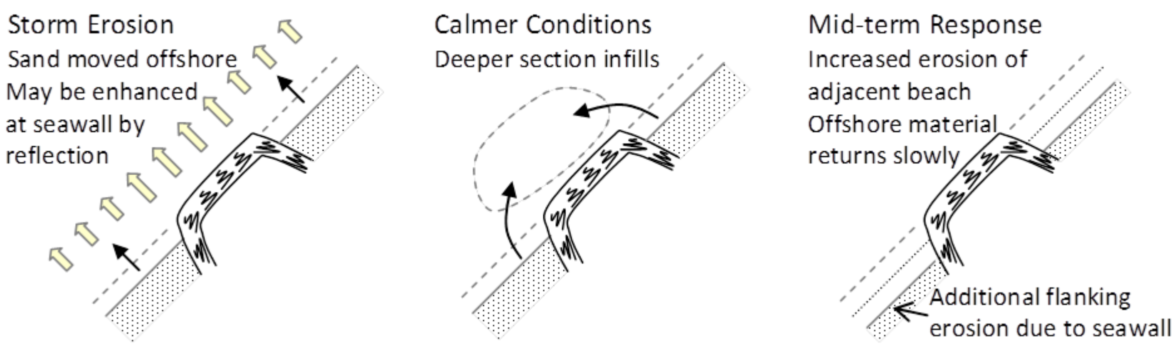


Figure 63: Alongshore Transfer of Storm Erosion. Example Showing Flanking Erosion

7.1.2 Projected Changes to Coastal Management

Coastal management in the OACS coast is likely to experience a significant change from present day conditions through to 2110. The change is suggested schematically by Figure 64 which indicates a net change in the balance of coast that is retained (high stability), supported by sand feed (dynamically stable) or has restricted supply (prone to progressive erosion). The overall coastal behaviour is projected to change from a situation of net accretion through to net erosion by around 2070 (Figure 65). This is anticipated to cause a change from the existing management focus, which involves redistribution of the available sediment supply, to one where selective retention is required, with erosion of unprotected areas amplified by additional coastal protection structures.

The overall shift in behaviour will not be precisely mirrored at a local scale, with the effects of retention (involving structural control and proximity to sand supply) and beach volatility (balance of exposure to storm erosion and potential for beach recovery) potentially creating significant variation to the time frame at which any particular coastal segment comes under stress. This will produce a progressive increase in the proportion of coast experiencing erosive stress, which is strongly linked to the retentive capacity, responsiveness to storm erosion and proximity to sand supplies. A simple interpretation of how these factors vary along the OACS coast is provided in Table 20 with a relative indication of the timing of a shift from generally stable to eroding conditions.

An interpretation of the likely sequence of coastal management pressures for the OACS coast, based upon sea level rise response is suggested by Figure 65. This analysis assumes that present-day sediment supply from feeds at Catherine and Woodman Points experiences only moderate decline over the next 100 years.

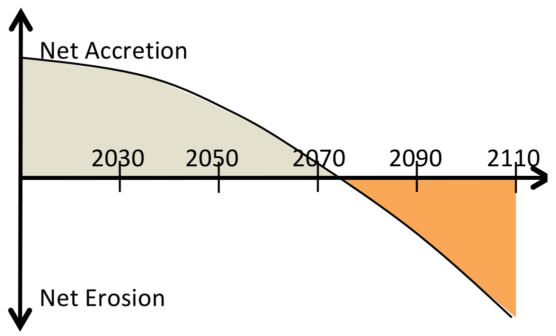
Table 20: Relative Effect of Retention, Storm Response and Supply Proximity (excluding Garden Island)

Cell	Transect	Coastal Segment	Retention	Storm Response	Supply Proximity	Relative Effect
22: Catherine Point groyne to South Mole Fremantle	22.1	Fremantle Sailing Club to Duoro Rd groyne	Low	Moderate	Low	-25 to +5yrs
	22.2	Duoro Rd to Island St groyne	Moderate	Moderate	Moderate	-15 to +15yrs
		Island St groyne to Catherine Point	Moderate	Moderate	High	-10 to +20yrs
21: Woodman Point (WAPET groyne) to Catherine Point	21.1 & 21.2	Catherine Point to Power Station	Moderate	High	High	-15 to +15yrs
	21.3	Power Station to Port Coogee	High	Moderate	Low (end-point)	-15 to +15yrs
	21.4 & 21.5	Port Coogee to Armament Jetty	Low	Moderate	Low (end point)	-25 to +5yrs
	21.6	Armament Jetty to Woodman Point	Low	Moderate	High	-15 to +15yrs
20: Woodman Point groyne to Woodman Point (WAPET groyne)	20.1	Woodman Point Beach	High	Moderate	High	-5 to +25yrs
19: Australian Maritime Complex to Woodman Point groyne	19.1 & 19.2	Woodman Point Beach to Jervoise Bay Harbour (West Beach)	High	Low	Moderate	-5 to +25yrs
18. James Point to Australian Maritime Complex	18.1	AMC to Sutton Road	High (rocky)	None	Low	n/a
	18.2 to 18.4	Sutton Rd to Mason Rd	Moderate	Low	Low	-15 to +15yrs
	18.5 & 18.6	Mason Rd to BP Flume	High	Moderate	Low	-15 to +15yrs
17: Palm Beach Rockingham to James Point	17.1	BP Flume to Service Harbour	High	Low	Low	-10 to +20yrs
	17.2	Service Harbour to SS Kwinana	Moderate	Low	Low	-15 to +15yrs
	17.3	SS Kwinana to CBH Jetty	Low	Moderate	Low	-25 to+5yrs

Cell	Transect	Coastal Segment	Retention	Storm Response	Supply Proximity	Relative Effect
	17.4b & 17.4a	CBH Jetty to Patterson Rd	Low	Moderate	Low	-25 to +5yrs
16: Garden Island causeway to Palm Beach Rockingham	17.5 & 16.1	Patterson Rd to Hymus St	Low	Moderate	Low	-25 to +5yrs
	16.2	Hymus St to GI Causeway	Low	Low	Moderate	-15 to +15yrs
15: Cape Peron to Garden Island causeway	15.2 east	Point Peron Launching	High	Low	High	0 to +30 yrs
	15.1 & 15.2 west	Point Peron Launching Ramp to Point Peron	Low	Moderate	High	-15 to +15yrs

Table 21: Likely Sequence of Coastal Management Pressures Based on Sea Level Rise Response

Timeframe	Likely Coastal Management Pressures
Present to 2025	Largely status quo. Erosive pressures with recovery following storm events or fluctuations in sediment supply from Catherine Point to South Beach, northern side of Woodman Point and Kwinana Beach. Potential for erosion south of Port Coogee. *Smaller structures allowing sand transport remain effective.*
2025 to 2050	Increased pressure on existing sites likely to shift towards gradual progressive erosion due to reduced recovery. Stress on Kwinana Beach likely to extend towards Rockingham. Erosion near Sutton Street is likely to become apparent. *Dune management largely ineffective to sustain buffers.*
2050 to 2070	Impact of sea level rise upon sediment supply noticeable. Sections towards the downdrift ends of compartments will experience progressive erosion with very limited recovery after storm erosion. *Linear coastal defences likely to require strengthening. Increased call for larger structures.*
2070 to 2090	The relative pattern of sediment deficit will be broadly apparent, with only locations close to sand feeds (i.e. Catherine and Woodman Points) experiencing fair recovery after storm erosion. *Alongshore structures (groynes) largely ineffective due to lack of supply.*
2090 to 2110	Sediment supply unable to balance sediment deficit, causing erosion to extend to Catherine & Woodman Points. Progressive erosion widespread, exacerbated by extensive retaining structures. *Multiple calls for erosion protection works and renourishment programs are likely.*



Overall behaviour of the OACS coast is projected to shift from a position of net accretion through to one of net erosion by around 2070.
This shift is locally highly modulated by characteristics of smaller beach segments, including retentive capacity (e.g. controlled coast, proximity to supply) and beach volatility (combining exposure to storm erosion and potential for beach recovery).

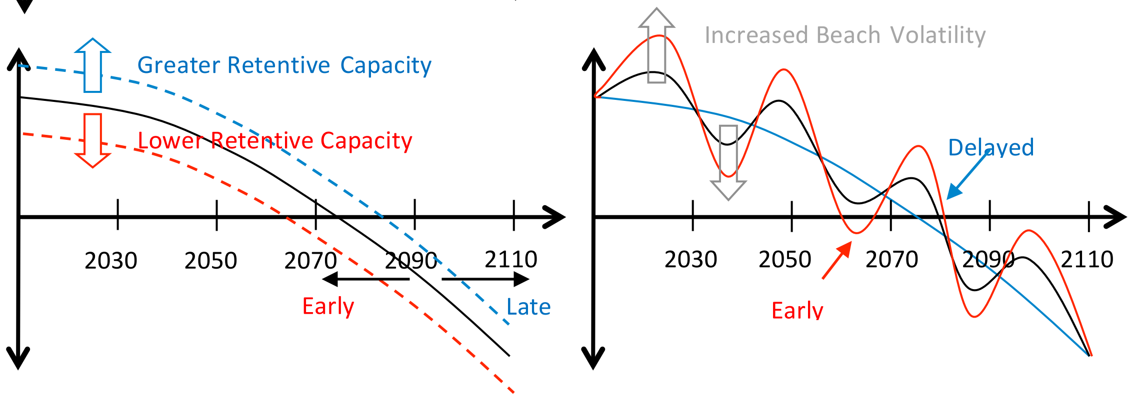
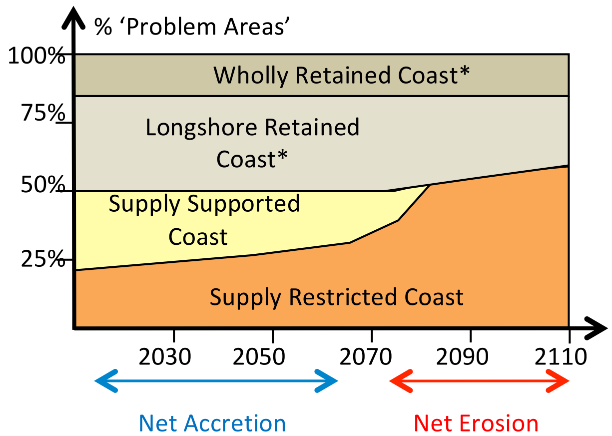


Figure 64: Change in Coastal Behaviour from Net Accretion to Net Erosion



* The use of retaining systems to provide stability requires an increasing commitment to the maintenance and adaptation of structures, through seabed deepening and consequent higher wave stresses

Figure 65: Significant Change in Coastal Management Required with Sea Level Rise

7.1.3 Monitoring and Triggers

The study undertaken has focused upon the potential impacts of coastal change associated with sea level rise. However, deliberate use of existing monitoring information to verify model performance has also provided insight regarding possible limitations of the publically available monitoring framework to identify change and facilitate decision-making. Importantly, as suggested by Appendix 4, there exist a number of privately-managed instruments that if made available to supplement the public data sets, would provide a more effective monitoring framework.

The use of any monitoring system for decision-making requires further consideration of the values potentially impacted by coastal hazards. Identification of values forms a later phase of the Cockburn Sound Coastal Vulnerability and Adaptation Pathways Program.

Water Level Monitoring

Water levels within the OACS coast are monitored through isolated tide gauge stations, with two primary stations at Fremantle and Mangles Bay (discontinued 2011). Previous analyses, particularly through the spectral signature of the Fremantle record, have identified a range of inundation processes, including seiching. Monitoring using only two gauges in the OACS coast allows limitation identification of seiching, which could be improved through an additional gauge (located off the Fremantle-Mangles axis to avoid node-antinode positions) or flow measurements. The Mangles Bay tide gauge should be reinstated to provide a second longer-term dataset. Integration of a high frequency radar system which measures waves and surface currents, such as part of the WA Integrated Marine Observing System, should be evaluated as an effective tool to cover the OACS waters.

Recommended planning for sea level rise (Department of Transport 2010) suggests adopting conservative high mean sea level scenarios in the assessment of design flood levels. However, considerable uncertainty associated with estimation of extreme water level occurrence is superimposed upon the uncertainty of projected mean sea levels. This provides scope for both under and over estimation of extreme water level likelihood, obscuring the value of any flood estimate for decision making. This suggests the need for design approaches that evaluate threshold exceedance and facilitate adaptation to change. Whilst these represent good engineering practice, they are rarely incorporated in decision-making assessment.

Wave Monitoring

Wave monitoring relevant to the OACS coast is publically available from Rottnest offshore waverider buoy (directional) and Owen Anchorage wave buoy (non-directional). These provide an indication of offshore-inshore transformation, but the complex bathymetric structure and lack of inshore directional information limits the relevance of information derived directly from observations. Whilst numerical modelling may be used to provide spatial extrapolation, the single buoy inside Owen Anchorage gives limited capacity for model calibration or verification, and is particularly constrained for evaluation of swell-diffraction and wind-wave generation in Cockburn Sound

Improved capacity for model verification or calibration could be achieved through installation of additional directional wave monitoring devices inside Cockburn Sound. To this end, the capacity for high frequency radar to be used should be investigated. However, the existing set of privately-held wave data (Appendix 4) has a broad spatial range, which could be used more effectively than it has been previously (for single point calibration) if data-sharing agreements were established.

Wave conditions are not generally used to define decision-making thresholds, except in the more general senses for marine structure design, mooring and navigation (a component of underkeel clearance). Inaccuracy of wave estimates can commonly be addressed through adaptation of structures or practices.

Erosion Monitoring

The OACS coast is generally well-monitored through established programs of coastal profile monitoring (Appendices 4 and 5), which is supported through the analysis of aerial imagery to capture vegetation lines. Review of available monitoring has prompted the following recommendations:

- Profiles should continue to be monitored on a regular basis. The frequency of monitoring may need to vary according to the perceived threat to coastal values. The last comprehensive profile monitoring of Cockburn Sound was in 2003;
- Because vegetation lines provide a proxy for coastal change, any discrepancies between the profiles and vegetation lines should be deferred to the profiles;
- The capacity for change to occur towards the outer edge of the terrace is potentially significant for long-term erosion due to sea level rise. As these changes occur slowly, extended profiles that cover the offshore limit of beach terraces should be measured on roughly a five yearly basis.

Monitored profiles, along with a coast parallel line, provide a suitable means of estimating volumetric changes along the OACS coast. This facilitates improved quantification of sand feeds, bypassing and alongshore transport rates, whilst also enabling the use of holistic decision-making for coastal management.

The use of profiles to provide management triggers provides an improvement over vegetation lines, which are only a proxy for coastal change. However, when used as a trigger, the profiles also require consideration of potential for acute change, aliasing due to seasonal variation and sensitivity of the object or amenity being managed.

The possibility of using coastal profile monitoring to support decision-making on a holistic basis may be challenged by data ownership. Data and cost sharing agreements would need to be well established to avoid vested interests disrupting the monitoring program.

Monitoring for Geomorphic Tipping Points

The potential for dramatic change to coastal behaviour associated with geomorphic tipping points (Section 4.2.7) suggests that there is a need to clearly identify whether a critical threshold is being approached. In most cases, identification requires analysis that is supplementary to existing monitoring, and the need should be determined subject to other indicators.

Dune mobilisation is indicated by scarping, blowouts and overwash features. The relative incidence and extent of these features can be assessed by photographic monitoring, including aerial photography, but should be considered in the context of relative storminess. Where indications suggest dune mobility is occurring, closely spaced survey information is required to quantify profile movement. The results should be interpreted using known renourishment and dune stabilisation projects.

Terrace mobilisation can only be identified effectively by hydrographic survey and therefore should be evaluated as part of the coastal profile monitoring. However, rapid onshore flux of sediment usually is an early indication of terrace mobility. This should be distinguished from the flux associated with post-storm recovery, which usually corresponds to a portion of the eroded distance.

Infilling of coastal depressions and expansions of tidal channels generally occur at a scale that is not apparent from monitoring surveys. Indicators of infilling including deposition ribbons or fans; whilst channel cutting may be marked by scour or vegetation stress if there is increased saline water influx. The extent and incidence of these features is appropriately assessed by photographic monitoring, with simple monitoring (e.g. channel depth relative to a fixed structure) being developed where appropriate.

Broader brush geomorphic tipping points, including the transition from net accretion to net erosion, or the activation of a structural sediment sink (causing local net erosion for the adjoining coast) may be difficult to distinguish from natural variability. However, the approach of applying holistic coastal management to the OACS coast is a primary means of determining whether there is a significant change in behaviour.

7.2 MONITORING RECOMMENDATIONS

Management of the OACS coast would benefit from ongoing monitoring and interpretation. Recommendations for future monitoring and studies include:

- Installation of improved hydrodynamic instrumentation to enable calibration and validation of any modelling undertaken.
- Continued monitoring of profiles is important given the lack of change above the vegetation line. Once changes is observed in the dunes it may be too late to instigate a proactive, adaptive response. Evaluation of coastal change should be based on a consideration of volumetric change as opposed to change along a shoreline alone, with a combination of profile and plaform change. The last comprehensive marine profile surveys for Cockburn Sound were completed in 2003 and it is strongly recommended that this be repeated with extension beyond the toe of the terrace. Dataset access for Owen Anchorage would need to be provided by Cockburn Cement Limited.
- Photo monitoring conducted for WACoast (Gozzard 2011) should be repeated and extended for the OACS coast as per the approach recommended by Department of Transport (2012). Visual comparison of site photos provides context for interpretation of the measured profile, vegetation line and bathymetric changes.
- A comparison of available historic bathymetric information to further understanding of terrace behaviour that has been outlined through the present work. Areas of interest include around Port Coogee where the beach and lower edge of the terrace appear to be steepening towards Parmelia Bank. The adjustment of the system is potentially leading to loss of sediment offshore from Port Coogee, potentially due to intensification of currents). Historic terrace response in Cockburn Sound could be extracted from a bathymetric comparison of the recent LiDAR and the 1944 bathymetry, which would require digitising.
- If and when LIDAR is repeated it should be compared with the existing dataset. The potential change in rock control points over time should be considered in relation to the delineation of tipping points.
- Disseminating relevant water level data to the members of the Cockburn Sound Coastal Alliance. This should include storm water level extremes and monthly mean sea level, to help interpret coastal management pressures, along with annual means (and exceedance levels) to help track requirements for adaptation. It should be noted that tracking of a single station against sea level rise projections is not meaningful due to the significant influence of inter-annual mean sea level variations, mainly attributable to El Nina-La Nina climate fluctuations.

- Investigating projected loss of beach width. Loss of beach width was not explicitly considered as a component of the present Project brief. That is, hazard has been assessed in terms of changes to the vegetation line and dune movement only with no consideration of the likely changes to the beachface. This may be important given the amenity value of the beach and the likely need to consider this attribute in subsequent phases of the assessment proposed by the Cockburn Sound Coastal Alliance. It is recommended that information in this report is interpreted to provide an assessment of the capacity of discrete sections of the coast to retain beach amenity under scenarios for sea level rise. The output of this assessment would be hotspots for beach loss superimposed on the assessment of erosion and inundation hazard.

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GLOSSARY

Aggregation (Spatial)	Representation of a large spatial data set (of units) by a smaller set (unit groups). Characteristics of the smaller set are derived from the larger set by gathering units together into groups that behave in a similar way. Spatial aggregation requires that groups are developed from units with geographic proximity.
Average recurrence interval (ARI)	The average time interval between occurrences of an event of a particular magnitude. Events of a given recurrence interval may, and often do, occur in far more rapid succession over the short-term, when influenced by extrinsic (background) environmental conditions.
Bathymetry	The vertical level of the sea floor in ocean, seas and lakes; by common convention described as water depth below a nominated vertical datum, which typically corresponds to lowest astronomic tide.
'Bath-tub' inundation	Representation of inundation model results using a single vertical level. This typically obscures spatial variation in elevation associated with a flood event.
'Best-estimate' models	Models for which each process is simulated by a technique selected to provide a best estimate of reality.
Coastal adaptation	Modification of behaviour, through construction of infrastructure or change in land-use practices, that prevents or reduces the risk associated with coastal hazards.
Coastal compartment	An area of coast bounded alongshore by large geologic structures, changes in geology or geomorphic features exerting structural control on the plan form of the coast.
Coastal hazard	The interaction of coastal processes with human use, property or infrastructure, the action of which adversely affects or may adversely affect human life, property or assets.
Coastal hazard lines	Spatial representations of a particular coastal hazard scenario. Typically this will be a particular event, or associated with a defined likelihood of occurring.
Coastal inundation	When ocean water levels and waves are high enough to cause flooding of normally dry land.
Coastal recession	A continuing landward movement of the shoreline OR a net landward movement of the shoreline within a specified time.
Coastal sediment cell	A length of coast and adjacent areas within which the movement of sediment is apparent through identification of land features which function as sediment sources, transport pathways and sediment sinks. Typically sediment exchange to adjacent cells is restricted, although cells are rarely isolated completely.
Coastal vulnerability (to climate change)	The threat to coastal landforms, associated infrastructure or land-use that may be caused by a sustained shift in environmental conditions.

Continental shelf waves	A water level signal that travels parallel to the coast (southwards on PNP coast), with characteristics that are determined by the continental shelf structure. The wave has maximum amplitude at the coast and decreases offshore. Continental shelf waves are generated by synoptic weather systems, particularly those causing winds parallel to the shore, and have been observed to travel extensive distances along the Western Australian coast.
Cuspate forelands	Accretions of sand extending seawards that develop in the lee of a shoal or offshore feature due to wave refraction or diffraction around both sides of the offshore feature. Cuspate forelands principally develop in response to variation of longshore sediment movement and are highly susceptible to changes in metocean processes
Depth of Closure	The water depth beyond which repetitive profile or topographic surveys (collected over several years) do not detect vertical sea bed changes, generally considered the seaward limit of littoral transport. Note that this does not imply the lack of sediment motion beyond this depth.
Downdrift	The direction of predominant movement of sediment close to the coast.
Downscaling	The process of combining information collected at a coarse resolution with an additional source of information to describe behaviour at a fine resolution.
Estuarine flood damping	Reduction of vertical flood levels from the ocean to an estuary caused by friction through the estuary channel and dispersion of incoming floodwaters across the estuary basin.
Estuary sequestration	The process of gradual accumulation of marine sediments within estuarine basins, particularly that which has occurred in the recent millenia over which sea levels have been largely stable.
Geomorphic assessments	Using measurement and knowledge of landforms to identify or extrapolate processes or active pathways of change.
Heuristic-based approach	A scientific technique where a potential range (lower to upper limits) of a parameter are evaluated, commonly used where it is not possible to define a single precise value for that parameter.
Holocene	An epoch of the quaternary period, from the end of the Pleistocene, about 8,000 years ago to the present time.
LADS (Laser Airborne Depth Sounding)	Laser bathymetric survey tool that has applicability in clear coastal waters down to approximately 70 m depth
LiDAR (Light Detection and Ranging)	A type of aircraft-based remote sensing, using laser-driven pulses of light and multispectral cameras to scan and process digital information about a landscape.
Landform	A naturally shaped feature of the Earth's surface. Landforms range in size from small features apparent at a local scale to large structures apparent at a land system or regional scales.
Landform mapping	Identification, classification and definition of spatial coordinates for landforms within an area of interest.

Lowest Astronomic Tide (LAT)	The combination of astronomic tidal components which would produce the lowest total water level. LAT is normally defined within a 19-year tidal cycle.
Mean sea level (MSL)	The average level of the surface of the sea, over a nominated period of time. A range of different periods are commonly used, including monthly, annual and the 19-year tidal cycle.
Meteotsunami	Sea level oscillations, with periods of the order of minutes to several hours, generated by the movement of atmospheric pressure jumps. They are distinct from but related to seiches and storm surges. Meteotsunami can be locally generated by squalls, tornadoes, thunderstorms or frontal passages.
Polylines	In computer graphics, a continuous line composed of one or more line segments. You can create a polyline by specifying the endpoints of each segment. In draw programs, you can treat a polyline as a single object, or divide it into its component segments
Probabilistic models	Modelling of some type (e.g. numerical or analytic) with a statistical element attributing the likelihood of particular outcomes. Distinction may be made between typical event (ambient) modelling which is represented by percentage occurrence, and extreme event modelling which only identifies the likelihood of exceptional conditions.
Seiche	A standing wave oscillation of a waterbody that continues, pendulum fashion, after the cessation of a disturbing force (seismic or atmospheric) that has the same frequency as the natural frequency of the water body system.
Shoreline	A discrete line representing the landward limit of the sea at some point in time. Methods to define shoreline vary and may be based upon a fixed vertical level, or by the apparent interface of water and land using a particular means of detection, such as aerial photography.
Still water level	The vertical level that the water surface would be in the absence of wave action. This is commonly estimated by averaging the water level over a period of time, such as five or fifteen minutes.
Storm surge	A rise in water levels that may be attributed to atmospheric influences including pressure, wind and waves during a storm or tropical cyclone.
Stratigraphy	The study of geologic strata or layers of sediment.
Tides	The periodic rising and falling of the water surface resulting from gravitational attraction of the moon and sun and other astronomical bodies acting upon the rotating earth.
Tidal modulations	Tidal modulations are slow variations of the amplitude of the diurnal (~24-hour) or semidiurnal (~12-hr) tide associated with longer period relative motions of the Earth, Moon, and Sun.
Transgressive (coastal) barrier	Along-coast landform developed through the landward movement of sediment due to marine processes, including aeolian (wind), wave and sea level rise.

Appendix 1 - See Accompanying PDF – PROJECT INITIATION DOCUMENT

Appendix 2 - See Accompanying PDF – SET THE CONTEXT REPORT

Appendix 3 - See Accompanying PDF – PHYSICAL PROCESS ASSESSMENT SUMMARY REPORT

Appendix 4 – See Accompanying PDF - ADDITIONAL DATASETS

Appendix 5 - See Accompanying PDF - COORDINATES, PROFILES & WAVE MODEL OUTPUT LOCATIONS

Appendix 6 - See Accompanying PDF - COMBINED PROFILES AND MODEL OUTPUTS PER PROFILE

Appendix 7 - See Accompanying PDF - INUNDATION HAZARD MAPS

Appendix 8 - See Accompanying PDF - EROSION HAZARD MAPS