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STRATEGIC COASTAL PROCESSES STUDY

Final Report

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CITY OF STIRLING

STRATEGIC COASTAL PROCESSES STUDY

FINAL REPORT

Prepared for

By

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I. ABBREVIATIONS AND GLOSSARY OF TERMS

AHD	Australian Height Datum
CHRMAP	Coastal Hazard Risk Management and Adaptation Planning
CoS	City of Stirling
CD	Chart Datum
CMP	Coastal Management Plan
DSAS	Digital Shoreline Analysis System
DoT	Department of Transport
DPI	Department of Planning and Infrastructure
FAR	First Assessment Report (Climate change)
GIS	Geographical Information Systems
H_s	Significant Wave Height
IPCC	Intergovernmental Panel on Climate Change
LADS	Laser Airborne Depth Sounder
MSL	Mean Sea Level
MSLR	Mean Sea Level Rise
NW	North West
PWD	Public Works Department
SLR	Sea Level Rise
SPP2.6	WA State Coastal Planning Policy
SW	South West
T1	Mean Wave Period
TAR	Third Assessment Report (Climate Change)
WAPC	West Australian Planning Commission
WCD	West Coast Drive
WCH	West Coast Highway

Accretion	the accumulation of sediment
Biogenic	originating from living organisms
Calcarenite	a type of limestone typically composed of more than 50 percent detrital (transported) carbonate sand grains
Cuspate Foreland	accretionary cape or triangular landform extending seaward
Diffraction	the spread of waves around the edges of obstacles resulting in a change of propagation direction
Fluvial	processes associated with rivers and streams and the deposits and landforms created by them
Geomorphology	origin, evolution, form, and distribution of landforms
Holocene	the geological epoch that began after the Pleistocene at approximately 11,700 years ago and continues to the present
Intertidal	the area of the seashore that is above water at low tide and under water at high tide
Lithoclastic	Limestone fragments and grains
Littoral Drift	Longshore transport
Morphodynamic	the adjustment and interaction of landforms with the process acting to change them
Perched Beach	geologically controlled beach characterised by a thin layer of sediment overlying a rock platform
Pleistocene	the geological epoch which lasted from about 2,588,000 to 11,700 years ago, spanning the world's recent period of repeated glaciations
Refraction	the bending of waves because of varying water depths underneath
Seiche	a standing wave in an enclosed or partially enclosed body of water
Terrigeneous	sediments derived from the erosion of rocks on land
Transgression	an event during which sea level rises relative to the land and the shoreline moves toward higher ground, resulting in flooding

II. EXECUTIVE SUMMARY

This report documents work undertaken in response to recommendations from a peer review of the *Watermans Bay & Mettams Pool Coastal Investigations report* by M.P. Rogers and Associates (MRA) in May 2010. The recommendations focused on analysis of a wide range of data including shoreline movement, beach profiles, coastal bathymetry, wave modelling, perched beach dynamics and mapping of rock on beaches. The objective of the study and synthesis of this information was to develop a process-based understanding of the factors affecting the coastal response to sea level rise of the segment of coast between Peasholm Street and Beach Road, within the planning horizons of 2060 and 2110, having predicted increases in mean sea level of 0.3 m and 0.9 m, respectively.

While this report does include preliminary identification of potential "hot spots" along the coast, this assessment is based on a process study alone and does not satisfy the requirements of WA State Coastal Planning Policy 2.6. However, this study is intended to make a key contribution to the future development of the City of Stirling coastal hazard risk management and adaptation planning (CHRMAP). The "hot spots" also indicate the areas along the sandy coast south of Trigg Is. where it is essential for development planning to include outcomes from the CHRMAP.

Review of beach profiles, historic aerial photos and literature indicates that trends of net accretion along beaches from Fremantle to Trigg Beach have been strongly influenced by natural movement of sediment placed nearshore during construction of Fremantle harbour, and that these trends are unlikely to be sustained into the future. Furthermore, significant natural variability in beach width has been observed at Scarborough, being closely linked with variability in the direction of net longshore transport in response to periods of increased northerly weather events.

As a result of increased water depths due to sea level rise, numerical wave modelling indicated an increase in mean wave height up to 6% south of Trigg Is. and up to 30% north of Trigg Is. The increased wave energy penetrating the coast over nearshore reefs is likely to exacerbate the variability in coastal processes.

The dynamics of perched beaches, as are found north of Trigg Is., is not well understood, but available information suggests that the variability associated with erosion and accretion of these features is also likely to increase as a result of sea level rise.

The variation in dune morphology from Cottesloe to Trigg suggests that the high dunes south of the study area may experience direct erosion while north of Scarborough, overwash of waves over the lower foredunes may result in onshore migration of the foredunes and impoundment of some sand onshore leading to a decreasing sediment supply north toward Trigg, and a higher rate of shoreline recession. However, more accurate delineation of rock along this segment of coast is an essential input to the CHRMAP process and will allow more confident assessment of coastal recession.

Areas of shoreline recession north of Trigg Is. will depend largely on the existence of limestone rock. Existing regional scale seismic mapping of the elevation of upper limestone surface indicate this surface is above present sea level throughout the study area. However, the data is too coarse to address planning decisions around the vital access corridors of the West Coast Drive (WCD), which in some places is located less than 10 m from the active littoral zone. Mapping of visual rock outcrops across the study site identified several areas without visible rock in close proximity to the WCD as priority areas for further geotechnical investigation.

Key findings and recommendations include the following:

- Ongoing data collection and monitoring is required to inform future adaptation plan formulation and management including:
  - further LADS data set to detail offshore bathymetry evolution and change;
  - ongoing beach monitoring to identify long term recessionary step jumps as soon as possible affecting the southern sandy beach segments and to further characterise perched beach behaviour at priority “hot spots” in the northern beaches; and
  - prioritised programme of geotechnical investigations to identify rock location and levels.
- First pass coastal assessments of beach recession based on sandy shorelines based on the SPP give conservative allowances in setting how close mainly residential development should approach the coast. Detailed beach modelling response based on locally based qualitative assessments and local geomorphology is required to more accurately determine projected recession of the northern pocket beaches in response to SLR and the increasing wave energy particularly for existing development at the identified pinch points for the critical West Coast Drive. This is required to provide sufficiently detailed CHRMAP response particularly for the rocky coastal segment north of Trigg Is..
- Begin planning for priority CHRMAP assessment of coastal segments impacted by projected shoreline recession with SLR including funding considerations, ongoing monitoring and review work, and communication and consultation strategies to inform risk assessments and prioritising adaptation actions.

1 INTRODUCTION

1.1 Purpose of this Document

In May 2013 BMT JFA Consultants (BMT JFA) was engaged by the City of Stirling (CoS) to undertake a Strategic Coastal Study to develop a sound, process-based understanding of the factors affecting changes to the 6.5 km section of coastline extending from Peasholm St. (Scarborough) in the south to Beach Road (Watermans) in the north, in Perth, Western Australia. The objective of the study was to provide a basis upon which long-term and sustainable management decisions can be made.

This report documents the data collection and assessments undertaken, identifies vulnerable locations and provides recommendations for next steps in coastal hazard risk management and adaptation planning (CHRMAP) in accordance with Western Australian state planning policy.

1.2 Motivation

In 2011 BMT JFA undertook a peer review of a report titled *Watermans Bay & Mettams Pool Coastal Investigations* which was prepared by M.P. Rogers and Associates (MRA) in May 2010 for the CoS. Following this review, five key recommendations were made for collection and analysis of principal data and information sources as a basis for a comprehensive strategic assessment of the coastal processes. These recommendations are summarised below:

(i) Analysis of the Perth coastal waters imagery to identify the possible influences of bathymetry on the nearshore wave climate and shoreline response.
(ii) Collection of shore-normal beach profiles for as many beaches as possible across the entire CoS coastal frontage, with recommendation for at least three profiles collected on each beach to assist in identifying the conditions in which sand is able to be moved onshore as well as offshore.
(iii) 2D wave transformation modelling to evaluate the effects of the nearshore bathymetry on wave focussing and wave shadowing between Trigg Island (Is) and Sorrento.
(iv) Desktop Review of available literature on perched beaches to identify a method relating key parameters to erosion and accretion events.
(v) Seismic profiling to locate bedrock stratum on the beaches at risk.

Assembling these five ‘pillars’ of data was the basis for the timeframe and principal objective for the Strategic Coastal Study.

Since the inception of this study WA State Coastal Planning Policy 2.6 (SPP) was gazetted, requiring local governments to have due regard for the SPP when preparing a local planning scheme.

The specific aim of this Strategic Coastal Study is to distil key information from the analysis of the five data 'pillars' in order to develop an integrated understanding of the physical processes active along the coast, how these processes interact, how changes to sea level rise are expected to modify the action of these processes, and how the coast will respond to these changes. The bathymetry, geomorphology of the coastline and the associated landforms play a fundamental role in how the coastline responds to climate and sea level changes. This study characterises the coastal system and makes a preliminary assessment of areas at risk from erosion or "hot spots" where the potential risk to coastal assets posed by sea level changes predicted for 2060 and 2110 is high.

As such, the Strategic Coastal Study provides vital context for the assessment of coastal vulnerability and the identification of hazards, risk management and adaptation planning (CHRMAP) that will be required in subsequent work to manage these issues in accordance with the SPP. It was not originally scoped however as a CHRMAP assessment.

1.3 Study programme

The Strategic Coastal Study was undertaken as four primary stages of work:

1. Data review and analysis:
   - Data collation and review
   - Review perched beach literature
   - Analysis of beach profile data
   - Analysis of aerial photography to determine historic shoreline movement
2. Wave modelling
   - Modelling of the effects of sea level rise on the nearshore wave field
3. Geomorphological assessment
   - Coastal waters (LiDAR) analysis
   - Identify key sediment controls
4. Coastal risk assessment
   - Identify coastal areas likely to experience significant change due to sea level rise
   - Identify key issues at Mettams Pool and Watermans Bay.

The above study program addressed all of the review recommendations, with the exception of recommendation (v) Seismic profiling. The scope of this task was to be refined based on outcomes from this study and with the view to informing what was required for future hazard identification and management in a future CHRMAP phase. As a result, this assessment was to rely on available information such as that obtained during existing coastal works and visual assessments only.

2 STUDY AREA SETTING

The CoS is one of Perth's largest councils with approximately 6.5 km of the north metropolitan coastline extending from Peasholm Street (Scarborough) in the south to Beach Road (Watermans Bay) in the north (Figure 2-1). West Coast Highway and then West Coast Drive run the full length of the coastline and for the most part separates the residential area to the east from the coastal beach area to the west with notable exception of the Scarborough Beach precinct.

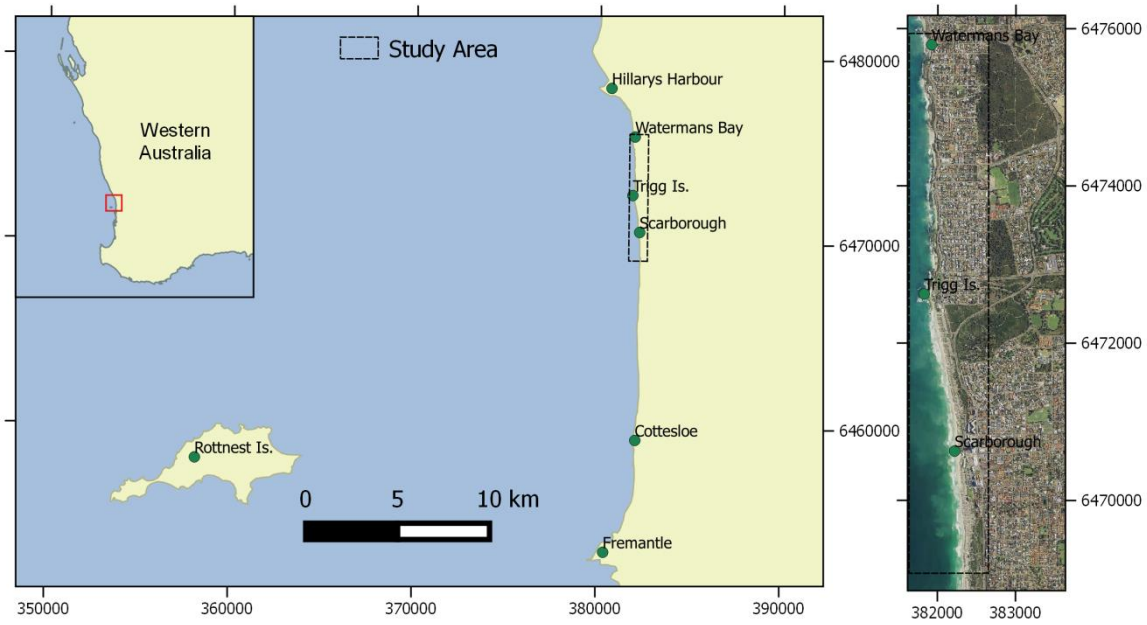


Figure 2-1: Study Area Location

It is important to distinguish between the physical and administrative boundaries of the study area for the Strategic Coastal Study. The administrative boundaries of the study area from the city boundary in the north to Peasholm Street (Scarborough) in the south, is the extent in which coastal vulnerabilities will be assessed and informed recommendations will be made. The physical context of the study area encompasses a much larger extent however, generally aligned with the secondary sediment cells from Pinnaroo Point in the north to Peasholm Street (Scarborough) in the south but more broadly the primary sediment cell which extends further to Fremantle.

This section describes the physical context for the CoS coastline and summarises the geology, bathymetry and coastal ocean climate.

2.1 Geology and Geomorphology

The regional setting of the Perth metropolitan beaches is dominated by the Pleistocene calcarenite ridges and depressions inundated by rising sea level during the last post-glacial transgression to form a chain of reefs and islands including Rottnest and Garden islands which act as a barrier to northward littoral drift. Erosion of the seaward side of the Garden Is ridge and breaching of the ridge crest during the last post-glacial transgression created localised lobes of sediment which, supplemented by biogenic carbonate sediments, have prograded toward the mainland.

The nearshore bathymetry and onshore geomorphology of the CoS coastline is dominated by the Spearwood Ridge of Tamala Limestone which runs from Hillarys to Fremantle. Holocene coastal sedimentation in this region has formed the Quindalup dunes; stabilised and mobile dunes and pocket beaches flanking the seaward side of Spearwood Ridge (Semeniuk and Searle, 1985). There has been significant accretion of Holocene sediment in the coastal submarine depressions between Rottnest Is. and the mainland, forming shallow sand shoals and fringing sand banks primarily where wave energy is transmitted through gaps in the Garden Is. - Rottnest Is. barrier.

The alignment of the shoreline within the study area trends generally north – south. The nearshore reefs in the southern part of the study area trend north-northeast and in the northern part of the study area they trend north-northwest. The 30 m contour line is generally located more than 10 km from the mainland coast; hence the slope of the inner shelf is relatively gentle. The aspect, bathymetry, reefs and islands result in a varying extent of sheltering of the beaches with the study area (Pattiaratchi et al., 1997). The variations in depth of water play a dominant role in spatial variation of wave energy levels along the shore.

The CoS coastline is comprised of two distinct coastal landforms; wide sandy beaches south of Trigg Is. and rocky outcropped limestone reefs, rock platforms and cliffs north of Trigg Is., the rocky shoreline alternating with small bay beaches.

Detailed descriptions of the coastal landforms within the study area have been documented in CoS (1984) and CoS (2006). A brief summary is provided in the sections below.

South of Trigg Island

The coastline south of Trigg Is., a natural barrier to northward sediment movement, is characterised by sandy beach, continuing uninterrupted southward to Cottesloe. The beach between Scarborough and Trigg can be classified as wave-dominated and dissipative, with persistent longshore bar and trough morphology (Pattiaratchi et al., 1997; Short, 2006). South of Scarborough the beach morphology becomes more reflective, with a narrower surf zone and steeper shoreface.

The beach and frontal dunes south of Scarborough Beach are backed by transgressive, shore-parallel dune ridges abutting a high calcarenite ridge extending south to Floreat. Between Scarborough and Trigg the calcarenite ridge is lower and the dunes extend further landward (Figure 2-2).

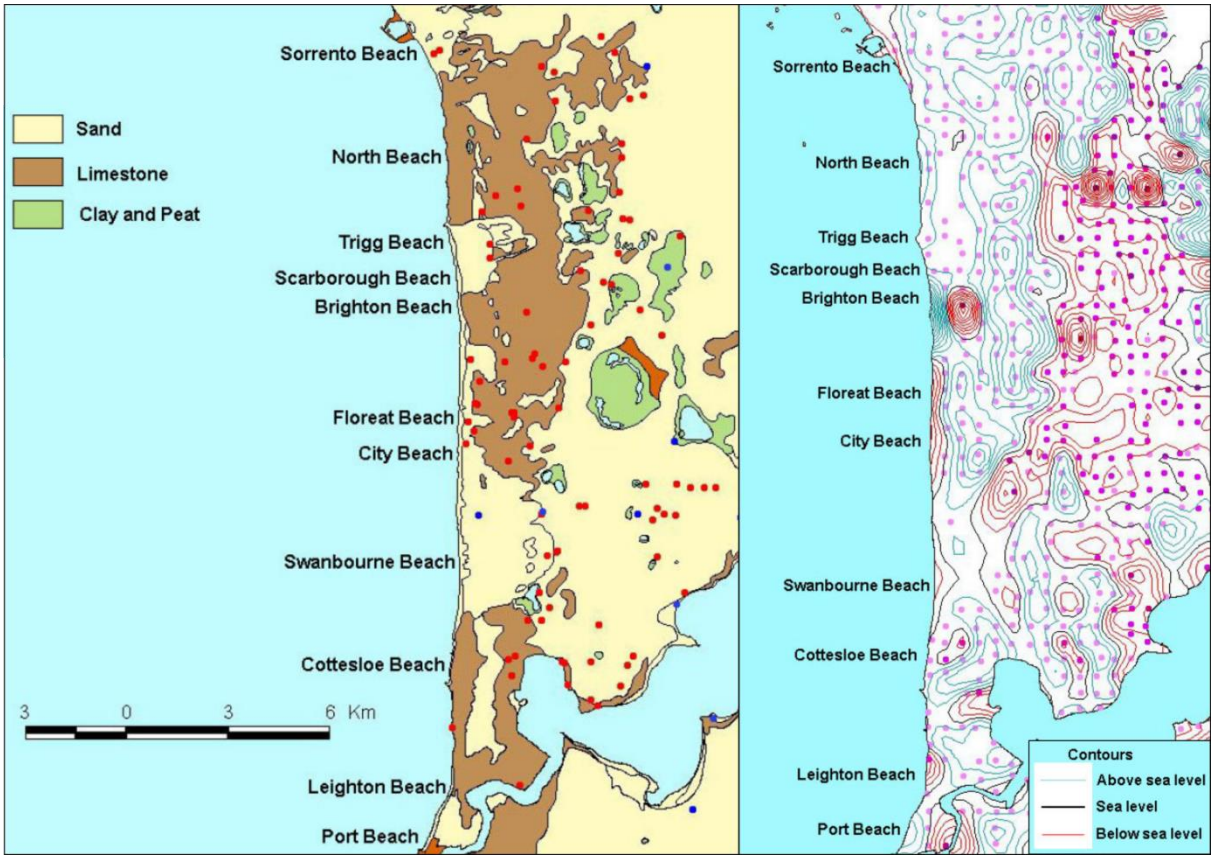


Figure 2-2: (a) Limestone and Sand Extent along Perth Coastline (Gozzard, 1986). (b) Estimated Upper Surface of Tamala Limestone Relative to Sea Level (from Jones, 2005)

North of Trigg Island

From Trigg Is. north to Watermans Beach the coastline is comprised of alternating rocky headlands and embayments. The cliffed headlands range in height from 1 to 8 m. They are comprised of limestone of variable strength and are often deeply incised and undercut, particularly south of Mettams Pool. Between the headlands some of the embayments harbour relatively steep and narrow sandy (perched) beaches occurring as a relatively thin veneer of sand over a limestone platform. Some embayments are backed by low rocky cliffs, others by blowout dunes. Often the head of the embayments is a vegetated sandy bluff and the presence or extent of buried limestone in these areas is unknown.

A discontinuous intertidal rock platform extends seaward of the shoreline. The platform width is highly variable, extending up to a maximum of 100 m offshore. Gaps or channels in the platform often form topographically controlled seaward currents. In some embayments the sandy beach extends from the vegetation line continuously into deeper water, making it difficult to assess the presence or extent of any underlying rock platform (e.g. between Malcolm and James Streets). In other areas a narrow sandy beach is perched on the rock platform at the head of the embayment (e.g. in front of Clarko Reserve).

The seaward fringes of rock platforms are highly irregular in plan and typically mark a sudden increase in water depth of 1-2 m. In places rock pools are semi enclosed by fringing reef; some have sandy floors such as at Mettams Pool and Watermans Bay.

2.1.1 Bathymetry

The bathymetry of the Perth metropolitan coastline has been mapped at 5 m resolution to approximately 25 m below Mean Sea Level using Laser Airborne Depth Sounder (LADS) and LiDAR (Figure 2-3) in 2009 by the Department of Transport (DoT).

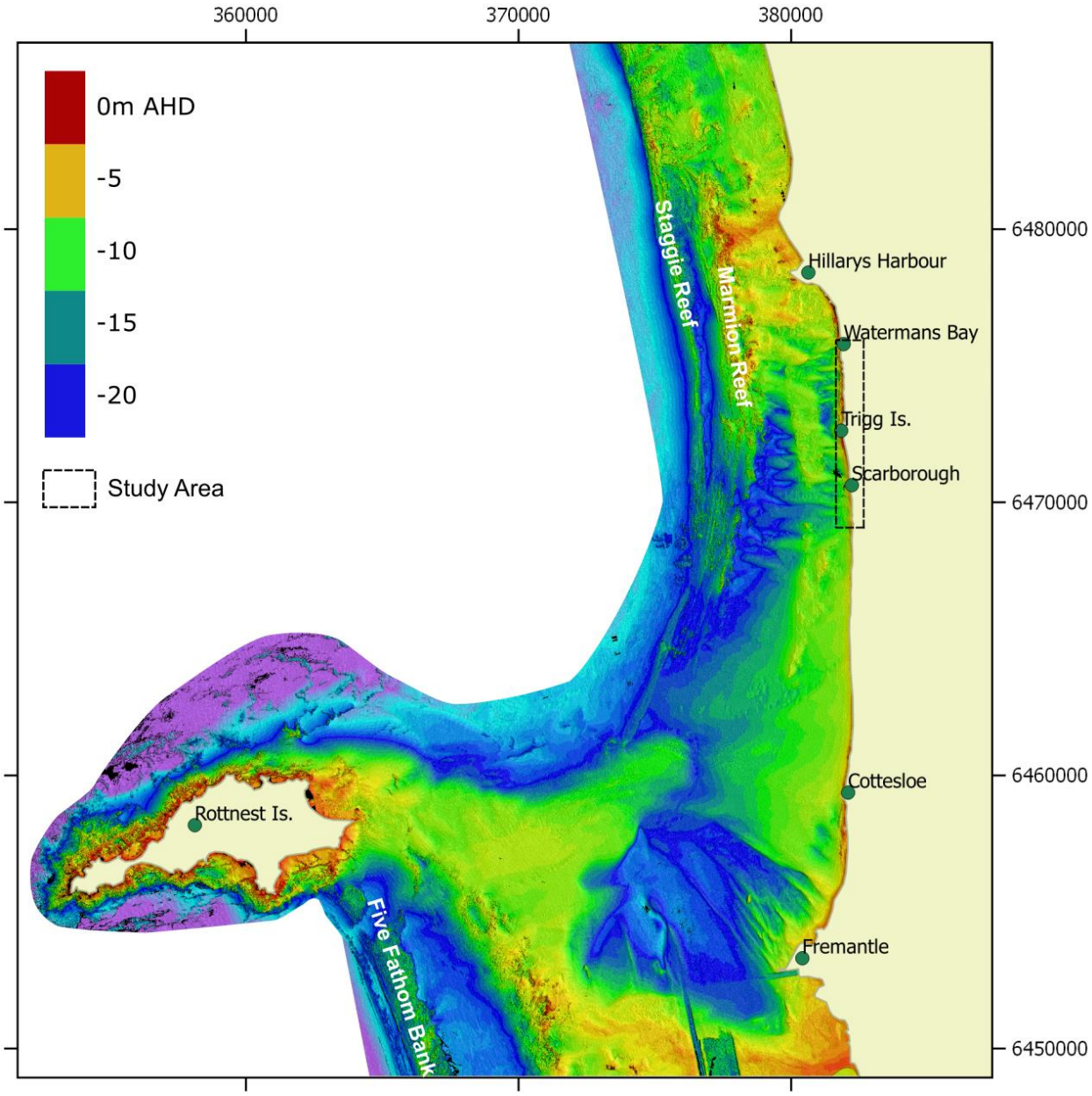


Figure 2-3: Regional Bathymetry (LADS, DoT 2009)

Rottnest Island and South

Rottnest Is. lies approximately 19 km west of Cottesloe on the mainland and 21 km southwest of the southern extent of the study area.

Five Fathom Bank is a linear reef extending 70 km south from Rottnest to Dawesville, with typical minimum depths of 5-7 m below lowest astronomical tide.

A second reef ridge inshore of Five Fathom Bank, extends between Rottnest Is. and Garden Is. with typical minimum depths of 2-5 m below lowest astronomical tide. This ridge includes several islets including Carnac Is. and Straggler Rocks as well as a number of narrow passages through this reef with typical depths of 7 m.

East of the reef between Rottnest and Garden Islands is a sand bank which includes Parmelia and Success Banks; sand ridges extending all the way to the mainland, with typical minimum depths of 3-4 m.

The features from Rottnest Is. to Garden Is. act either as a direct barrier to offshore waves, which predominantly come from the south and southwest, or significantly reduce the height of waves propagating through this gap by dissipating wave energy through wave breaking, bottom friction and diffraction. However, large gaps in the Garden Is. ridge have led to the formation of sand shoals in Cockburn Sound and Owen Anchorage over the Holocene.

The bathymetry offshore from the study area can be generally divided into two areas; south and north of Trigg Is., based on the reef morphology.

South of Trigg Island

Approximately 5 km offshore of the metropolitan coast, there is a 2 km wide band of somewhat discontinuous limestone ridges, extending 6 km south from Trigg Is. to Floreat Beach. This reef complex marks the convergence of Staggie and Marmion ridges that separate as they extend northward. The typical minimum depth of these ridges is 7-8 m. East of this band the depth increases to approximately 18 m.

From about 0.8 km to 1.6 km offshore the Spearwood Ridge is a broad reef platform with nominal depth of 6-7 m extending from North Beach Road to Swanbourne Beach. However, there is a breach in this platform between Brighton Road and Peasholm Street at the southern extent of the study area. In this gap, within approximately 800 m from the shore there are a number of fingers of sand extending east-west. Further south, the sand cover forms a more uniform apron between the shore and the adjacent reef platform, with typical water depths of 5-6 m.

South of Trigg Is. this nearshore sand apron shallows at the shore, with the beaches being characterised as a reflective, low wave-energy form with a wide berm, steep beach face, and an alongshore sandbar (Clarke and Eliot, 1983; Short and Wright, 1981). The beach is backed by a vegetated primary dune 10-12 m above sea level. Anecdotally, isolated rock outcrops are occasionally exposed within the surf zone at points along this stretch of coast, typically during winter.

North of Trigg Island

Approximately 5.5 km offshore the narrow Staggie Ridge is oriented north-northwest. This ridge runs continuously northward from Trigg Is. north beyond Pinnaroo Point. Water depth to the east and west of the ridge is 2 0m decreasing sharply to 9-10 m over the reef.

Marmion Reef is a complex discontinuous barrier reef structure approximately 1 km east-west and located 3 km offshore. Typical minimum depth over the reef is 2-4 m with numerous shallow submerged or subaerial rocks, increasing in size and abundance toward Pinnaroo Point. Depressions along the reef are draped with a layer of sediment. The cuspate foreland at Pinnaroo Point extends offshore at typical depths to 2 m to the east side of Marmion Reef.

From about 1 km to 2 km offshore the broad Spearwood Ridge forms a platform with nominal depth of 8-9 m extending from Trigg Is. to Beach Road. East of this feature water depth increases to about 16 m at the deepest point. North of Beach Road the Marmion and Spearwood ridges converge and inshore water depths reduce to 5-7 m.

One of the most distinct characteristics of the section of coast from Trigg Is. north to Clontarf Street is the sudden transition from sandy beaches south of Trigg Is., to a sequence of rocky headlands and perched beach embayments. These cliffs and embayments are fringed by a relatively flat intertidal rock platform extending offshore from the present shoreline with a width from zero to approximately 100 m.

Seaward of the intertidal rock platform is a second bench, presumed to be rock, running approximately parallel to the shore along the -5 m AHD contour. Seaward of this bench the depth increases suddenly by 3-5 m. The expression of the bench is intermittent alongshore. In several areas the bench is blanketed with sediment, forming a gradual ramp between deep water and the nearshore, rather than a step.

2.1.2 Sediment Cells

The DoT has completed identification of a series of coastal sediment cells between Cape Naturaliste to the south and Moore River, to the north. The area encompasses the inner continental shelf and the coastal land of the southern Swan Coastal Plain as well as Garden Is. and Rottnest Is..

Sediment cells are segments of the coastline within which sediment transport processes are strongly related. The cells have been identified by interpretation of available bathymetric data, coastal geomorphology and metocean processes. Sediment cells may include areas of sediment supply (sources), sediment loss (sinks), and sediment transport processes linking them (pathways).

Sediment cells provide a framework for coastal management by defining 'natural' management units which link the marine and terrestrial environments. This designation comprises a hierarchy of primary, secondary and tertiary cells (Stul et al., 2012) incorporating three space and time scales:

- **Primary cells** relate to large landforms, considering trends of potential change in large landform assemblages or land systems over longer coastal management timescales
- **Secondary cells** describe contemporary sediment movement on the shoreface and potential interdecadal landform response
- **Tertiary cells** are confined to the reworking and movement of sediment in the nearshore and potential seasonal to interannual responses.

The majority of cells are 'leaky' with sediment transport reversal and many tertiary cell boundaries may be migratory. The study area lies within Primary Sediment cell F, and specifically tertiary sub-cell 27a which encompasses Trigg to South Sorrento, as shown in Table 2-1 and Appendix A.

The cuspate foreland at Pinnaroo Point lies approximately 4km to the north of the study area and forms the boundary between primary cells F (Fremantle to Pinnaroo Point) and G (Pinnaroo Point to Yanchep). Secondary cell 27 extends from Trigg Is. to Pinnaroo Point with Marmion Reef marking the offshore boundary.

Table 2-1: Sediment Cells Covering the Study Area

Primary Cell	Secondary Cell	Tertiary Cell
F. South Mole Fremantle to Pinnaroo Point	27. Trigg to Pinnaroo Point	c. Hillarys Marina to Pinnaroo Point
		a. Trigg to South Sorrento
	26. Mudurup Rocks to Trigg	d. Brighton Road to Trigg
		c. Empire Avenue to Brighton Road

2.1.3 Sediment Characteristics

The sediments along Perth metropolitan beaches are generally medium to coarse grained quartzo-feldspathic sands with calcareous lithoclastic and skeletal material (Clarke and Eliot, 1983). Sediments are generally moderately to well-sorted with mean sediments sizes varying between 0.18 and 0.56 mm (Eliot and Clarke 1986; Hegge 1994; Masselink 1996; Masselink and Pattiaratchi 1998b; Tonk 2004), sediments generally coarsen northward of the Swan River (Stul, 2005).

Sediment characteristics of the Perth metropolitan beaches are broadly discussed in Stul (2005); the three parameters considered in characterising the sediments included carbonate content, median grain size and sediment sorting.

The carbonate variation along the Perth metropolitan coastline can be largely attributed to the proximity to local sediment production and the interruption of sediment transport pathways. Within the study area, limited carbonate production is expected south of Trigg Is. due to an absence of nearshore reefs, seagrass beds or eroding limestone cliffs. North of Hamersley Pool carbonate content is observed to increase. This is attributed to the erosion of limestone cliffs and local bio-production.

Whilst the general trend of sediment size increases northward, many of the coarser sediments tend to be found on steeper beaches perched upon underlying rocks or reef. The presence of this coarse fraction is likely due to higher energy waves mobilising coarser sediments during storm events onto beach platforms and are not able to be remobilised until another storm event.

The sediment sampling undertaken by Stul highlighted that sediment sorting generally followed the trend of median grain size, with no incidences of poor sorting. Maximum sorting was observed at Peasholm and Lawley St., considered to be largely attributed to the perched beach at Lawley St. and the narrow beach at Peasholm St. with sediment sourced from the dunes.

2.2 Climate and Meteorology

The climate for Perth metropolitan beaches is dominated by high pressure systems with periodic mid latitude depressions and local seasonal sea-breezes (Eliot and Clarke, 1986). High pressure systems move to the east passing the coast every 3 – 10 days (Gentilli, 1972).

In the summer months, Perth metropolitan beaches experience strong diurnal sea-breezes, also known as the “Fremantle Doctor”. The sea breeze cycle is characterised by offshore winds from an easterly direction in the morning, switching to southerly and southwesterly winds in the afternoon. Perth metropolitan beaches experience a significant sea breeze around 200 days per year, predominately in summer, with an average speed of 5.7 m/s (Masselink and Pattiaratchi, 1998).

In the winter months, mid-latitude depressions dictate the prevailing weather and disrupt the sea breeze cycle, generally with initial northerly winds, shifting to northwesterlies, and then moving rapidly to westerlies and southwesterlies as the system crosses the coast (Masselink and Pattiaratchi, 2001a). The peak occurrence of mid-latitude depressions is in July and the strongest winds in the system are the northwesterlies (Gentilli, 1971). These weather systems generate south-westerly cold fronts (Gentilli, 1971), and the resulting winds are generally initially from the north, increasing in strength while shifting to the northwest (Masselink and Pattiaratchi, 2001).

Steedman (1982) conducted an extreme event analysis using winds from Fremantle from 1962 – 1980, as discussed in Stul 2005. The 50-year return period storm, without including tropical cyclones, has an average duration of 56 hours, average wind speed of 19.5 m/s and a maximum gust of 41.7 m/s. The average wind speed, direction, duration, extremes and event frequency for the main weather systems were tabulated by Stul (2005), and are presented in Table 2-2.

Table 2-2: Winds and Event Frequency of the Main Local Weather Systems (Stul, 2005)

Weather System	Anticyclones	Squalls	Mid Latitude Depression	Dissipated tropic cyclones	Sea breeze
Occurrence	Annual	Dec – April	May – Oct	Oct – Mar	Oct – Mar
Avg. Wind Speed	Light winds	15 – 20 m/s	15 – 29 m/s	15 – 25 m/s	10 m/s
Avg. Duration	Unknown	2 – 4 hours	10 – 55 hours	5 – 15 hours	~7 hours
Avg. Wind Direction	All	All	N →NW→W→SW	Depending on the eye location	180 - 200°
Frequency	3 – 10 days	13 days	Avg. 3 – 8/year	1 in 10 years	>15 days/month
Extreme 30 min Avg	Unknown	25 m/s	20 - 25 m/s	25 - 30 m/s	>20 m/s
References	(Gentilli 1971; 1972)	(Steedman 1982; Eliot and Clarke 1986)	(Gentilli 1971; Silvester1976; Steedman1977; 1982; Lemm et al. 1999)	(Gentilli 1971; Steedman 1977; 1982)	(Gentilli 1971; Masselink 1996; Pattiaratchi et al. 1997)

2.3 Coastal Environment

2.3.1 Astronomical Tides

The astronomical tide experienced at the study area is diurnal, i.e. one high and one low water level per lunar day. Astronomical tide refers to the rise and fall of the ocean surface due to gravitational attraction between Earth, Moon and Sun. Water level variations in coastal areas due to the astronomical tide can be reliably predicted. Tidal plane information for Fremantle are summarised in Table 2-3 below and are considered representative of the study area coastline (MRA, 2010).

Table 2-3: Estimates of Key Tidal Planes for Fremantle (DPI, 2004)

Chart Datum (m)	Existing
Highest Recorded Tide (16/05/2003)	1.98
Highest Astronomical Tide (HAT)	1.36
Mean High Higher Water (MHHW)	1.10
Mean Sea Level (MSL)	0.76
Mean Low Lower Water (MLLW)	0.42
Lowest Astronomical Tide (LAT)	0.21

Perth metropolitan beaches are micro-tidal in nature; however non-tidal fluctuations have a large influence on the rise and fall of the localised water level. These fluctuations are influenced by barometric pressure, wind setup storm surge, continental shelf waves, inshore seiching, sea level change, El Nino events and the influence of the Leeuwin Current. The variations in water level induced by these factors may coincide at times, resulting in a total variation more than twice as large as the range of the tide (Eliot and Clarke, 1986). Further to this, Steedman (1977) reports that inshore seiching produces in a series of smaller amplitude (0.1m) and higher frequency (30 minute) oscillations that become trapped between the shoreline and submerged reef chains.

The influence of non-tidal water level variation can result in significant differences in beach characteristics between the active lower foreshore and the less frequented upper foreshore. Further from this, long periods of non-tidal water level fluctuation can heavily influence net shoreline advance or retreat.

2.3.2 Surge

The term surge refers to the difference between actual water level and predicted astronomical tides. Contributions to surge can be from barometric pressure and setup due to winds and waves, typically during storms. The surge can be of a similar magnitude to the tidal amplitude at Fremantle (Pattiaratchi and Eliot, 2008). Peak surge levels along the Perth coastline caused by mid-latitude storms generally occur between June and July, whereas surge levels associated with tropical cyclones occur between December and March.

The 100-year storm surge amplitude is considered to be 1.0 m above the predicted tide (DPI, 2004) with the potential to be further amplified by local topography. The highest water level recorded at Fremantle to 2005 was 1.28 m above MSL in May 2003 (Stul, 2005). The return period of extreme events is summarised in Table 2-4.

Periods of significant surge are generally short duration but these periods can allow wave energy to reach to higher levels on the shore resulting in erosion and inundation. The level of storminess has been documented to vary significantly over interannual and decadal timescales.

Table 2-4: Extreme Water Levels at Fremantle (from DPI Tides and Waves)

Annual Recurrence Interval	Storm Surge (m above predicted tide)	Water Level (m above CD)
1 year	0.55	1.57
5 year	0.68	1.71
100 year	0.95	1.95
Maximum recorded	1.0 (September 1988)	1.98 (May 2003)

2.3.3 Wave Climate

The wave climate is composed of swell and variable local wind waves. A persistent background swell (period 8-18 seconds) is present all year from the Indian and Southern Oceans (Lemm et al., 1999). Swell is predominately from the south to southwest in summer with an increased westerly component in winter (Lemm et al., 1999).

Four years of directional wave data from Rottnest Is. was analysed by the DoT (DoT, 2009) providing a representation of the offshore climate approaching the study area. The DoT's analysis of the wave data found the most frequently occurring swells were from 250°, with a mean significant wave height of 1.5 m. Waves with height greater than 4m are expected to occur less than 1% of the time. The most frequently occurring sea direction was 240°, with significant wave height between 0.5 – 1.0 m.

Up to 90% of deep water swell energy is attenuated as it crosses the continental shelf and reefs (Hegge, 1994, Lemm, 1996). Sea waves (period less than about 6 seconds) experienced within the study area are generated locally by the energetic summer sea breeze and winter squalls. As a result, the wave field is often a superposition of swell and sea, with these wave trains having different directions. This is illustrated in Figure 2-4 where the sea waves, generated by the southwest seabreeze are propagating toward the northeast, while the longer period swell are propagating to the east.

The generation of waves during summer is limited by the duration and the offshore extent of the sea breeze system, with wave heights typically 0.5-1.5 m and periods 3-6 seconds. The direction of these summer sea breeze waves are typically from the south to southwest. In winter, waves driven by storm winds tend to range from the northeast to the southwest.

Looking at a regional scape from Silver Sands (south) to Two Rocks (north), Stull (2005) used a SWAN model to look at the trends in wave characteristics along the metropolitan coast and to aid in defining sediment cell boundaries. Median wave direction was shown to shift from southwest at Two Rocks to northwest at Cockburn, and median significant wave height was shown to generally decrease from Two Rocks to Cockburn. However, within the CoS study area this trend in wave height was reversed with wave height increasing from Hillarys Harbour southward to a local maximum at Trigg Beach, then decreasing again southward to Scarborough.

For the present study BMT JFA used a validated SWAN model to investigate the trends in wave characteristics in more detail along the study area coastline and the effects on these trends due to sea level rise. The wave modelling study is discussed further in Section 4.



Figure 2-4: Superposition of Sea and Swell Waves at Watermans Bay (aerial photo 03/12/2012)

2.3.4 Nearshore Currents

The local currents within the study area are predominately shore parallel driven by local winds. The nearshore current observed during the summer months is far more persistent than during the winter months, with the sea breezes driving the current shore parallel toward the north.

In the winter months, when the wind directions tend to be more variable, a less consistent southerly current is observed punctuated by short periods of much higher southerly movement during northwest storms.

Typical alongshore current speeds driven by the seabreeze are about 1.0 m/s, limited to the surfzone about 35 m wide. Offshore currents rarely exceed 0.2 m/s (Pattiaratchi et al., 1997).

Given the bathymetry along the study coastline, circulating currents are created in the form of gyres due to wind forcing between the reefs and headlands. Also, the breaking, diffraction and refraction of waves across reef platforms and inshore of the reefs can create focussing of wave energy forming zones of flow convergence and divergence and resulting in complex local flow patterns (Semeniuk and Searle, 1985). Small shifts in wave direction can cause migration of these convergence zones alongshore, potentially reversing the local nearshore currents (Clarke and Eliot, 1983).

2.3.5 Sediment Transport

North of the Swan River entrance, Perth metropolitan beaches from Fremantle to Trigg form an almost self-contained sediment compartment with net northward transport, displaying seasonally oscillatory alongshore transport within internal cells (Masselink and Pattiaratchi, 2001).

The supply of terrigeneous sediment in the region is low but a very large quantity of sediment has been retained in coastal barriers over the late Holocene. Sediment production within this region occurs from both erosion of rock features and bioproduction, with a sediment pathway from Rottnest Is. towards Perth's northern beaches (Collins, 1988).

Limited studies including measured data have been undertaken to investigate the sediment transport along Perth metropolitan beaches. The influence of the persistent sea breezes on beach morphology has been explored in Masselink and Pattiaratchi, 1997, Masselink and Pattiaratchi, 1998, Masselink and Pattiaratchi, 2001 and Pattiaratchi, Hegg, Gould, and Eliot, 1997.

Masselink and Pattiaratchi suggest that given the persistent weather systems and sea breeze activity there is a net northward longshore sediment transport in summer driven by persistent sea breeze and net southward longshore sediment transport in winter from the northwest and west-northwesterly swells. The net movement north during summer is considered greater than that observed in winter, resulting in a northward bias (Masselink and Pattiaratchi, 2001). This asymmetry of along shore transport has also been shown to vary significantly over interannual cycles (Eliot and Travers, 2011) resulting in variability in beach width at Scarborough and displacement of up to 50% of the maximum beach width for perched beaches north of Trigg Is. (Elrick, 2005). The net longshore sediment transport rates are greater than the cross-shore, due to the more persistent longshore current (Masselink and Pattiaratchi, 1998).

Northward longshore sediment transport during summer due to the summer seabreeze has been estimated to be in the order of 150,000 m^3 with up to 80,000 m^3 of this being trapped by Trigg Is. (Pattiaratchi et al., 1997). This is offset by southward transport by winter storms, resulting in an estimated net northward transport in the vicinity of Trigg Beach between 10,000 m^3 and 20,000 m^3 per year (Stul and Eliot, 2005; MRA, 2010). Net northward longshore transport past Trigg Is. is estimated to be between 6,000 m^3 and 9,000 m^3 per year. An onshore feed of sediment from offshore sources north of Trigg Is. is inferred to contribute approximately 5,000 m^3 per year to the nearshore budget. This is consistent with the observed increase in calcium carbonate content of sediments from Trigg Is. to Sorrento (Stul and Eliot, 2005).

The alongshore sediment transport flux (north and southward) at Sorrento Beach prior to construction of Hillarys Boat Harbour was estimated at 70,000 m^3 to 90,000 m^3 (PWD, 1984). Since construction of the Sorrento rock groynes in the early 1980's and Hillarys Harbour in 1987, seasonal sediment flux past Sorrento Beach has reduced significantly with Sorrento Beach accreting by approximately 1.3 m per year to 2008 (MRA, 2010).

The seasonal shift in littoral drift direction is understood to be exacerbated in the presence of coastal structures, headlands and rocky outcrops, affecting the beach width in proximity to the obstacle (structure, headland etc.) and also with the size of the obstacle (Masselink and Pattiaratchi, 2001). Hence in the vicinity of coastal structures or natural headlands, the seasonal variation in littoral drift direction induces a seasonal cycle of beach change that is different from the classic transition from summer to winter profile. During summer, a beach located south of an obstacle becomes progressively wider due to accumulation of sediment against the obstacle. At the same time, the beach located north of the obstacle becomes narrower; and the opposite will occur during winter. This pattern is further qualified through the review of historical aerial photographs in Section 3.4 and cross shore beach profiles in Section 3.5.

Stul (2005) computed alongshore component of wave power as an indicator of alongshore sediment transport direction, with reversals in direction indicating sediment cell boundaries. This work indicated that, within the CoS study area the median longshore wave power was directed northward from Scarborough to Trigg Is., southward from Hale Street to Trigg Is., and northward from Hillarys Harbour to Gull Street. The boundary at Trigg Is. is marked by both the geological structure and a convergence point of longshore wave power. The other boundaries are less defined but appear to coincide with changes in shoreline alignment of 5-10 degrees. SWAN modelling by BMT JFA provided greater resolution of wave height and direction within the study area and indicated differences in wave height on the order of 20% over longshore distances of 0.5 km. In reality, such local differences in wave height could be expected to influence longshore current directions to an equal extent or greater than the modelled differences in incident wave direction.

2.4 Structures

Coastal behaviour along the Perth–Fremantle coast is strongly affected by anthropogenic management, including nearshore deposition of enormous quantities of dredged sediment, and active management through installation of coastal protection works.

Manmade structures such as rock groynes can significantly alter the sediment transport alongshore, causing sediment to build up on the updrift side of the structure and depletion of sediment on the downdrift side. Although not within the study area the rock groyne at Cottesloe and the two rock groynes at City Beach, 3 km south of Peasholm Street are considered to cause significant interruption of the alongshore sediment pathway.

A review of the coastal access arrangements and existing coastal protections and defences was undertaken and is documented along with the community assets and amenity infrastructure in Appendix B, a reference map outlining the position of these structures and access arrangements is provided in Appendix B. A condition assessment was not undertaken as part of this assessment.

2.5 Sea Level Rise and Variation

Mean sea level rise is perhaps the most clearly documented impact of climate change. Most global climate models assimilated or validated with recent observations predict MSLR of 0.5 m to 1 m within the next century (IPCC 2007). Whilst sea-level rise is one of the most certain and important impacts of climate change, quantifying the amount of both global-averaged and regional sea-level rise remains one of the important climate change challenges (Church, White et al. 2008). There has been an evolution in global climate models achieved by the Intergovernmental Panel on Climate Change (IPCC) during the last few decades (IPCC 2014). A decrease in the range of sea-level rise projections for 2030 has been observed from First Assessment Report (FAR) to Second Assessment Report (SAR), Third Assessment Report (TAR) and scenarios of B1, A2 and A1B (Warrick and Oerlemans 1990, IPCC 1999, IPCC 2001, Church and White 2011). The sea-level observations from tide gauges and sea-surface altimetry since 1950 were consistent with the estimates of MSLR and probably closer to the higher rates of predictions (Figure 2-5).

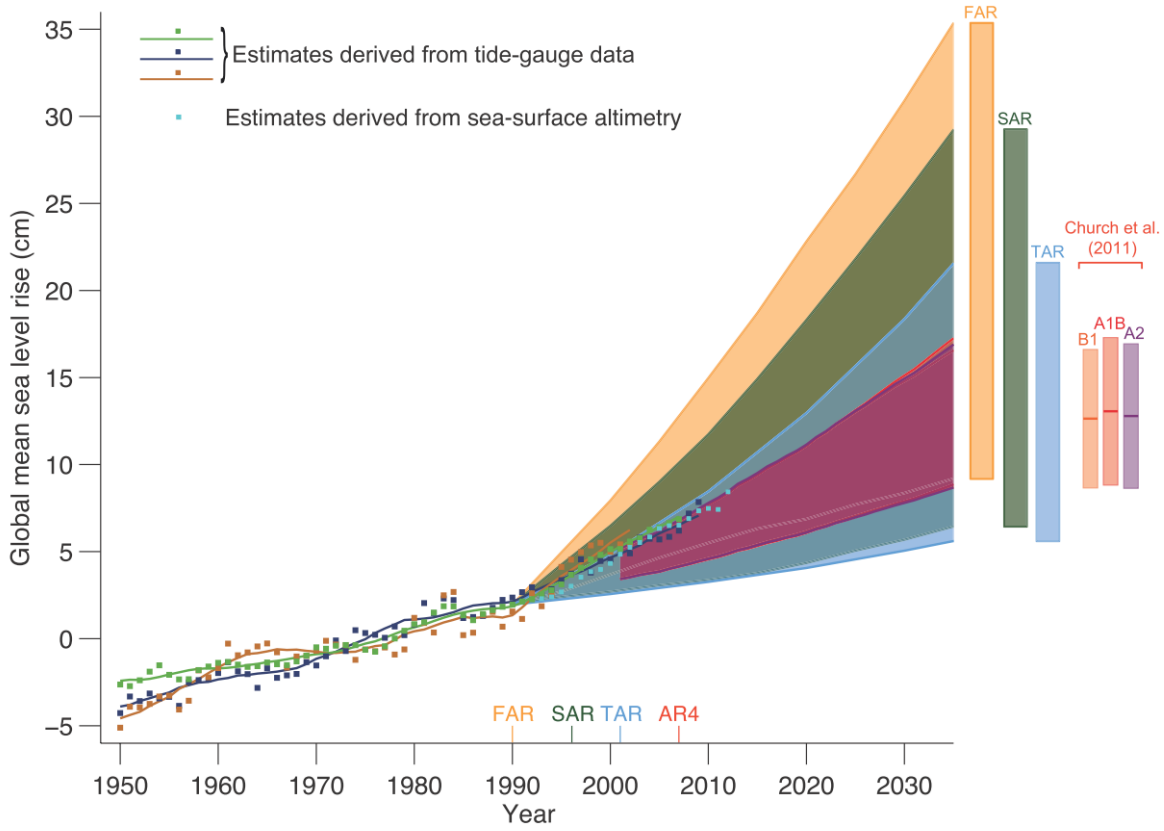


Figure 2-5: Estimated Changes in the Observed Global Annual MSL since 1950 Relative to 1961–1990 (IPCC, 2013)

The altimetry data shown in Figure 2-5 commenced in 1993 and are harmonized to start from the mean 1993 value of the tide gauge data. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR, SAR, TAR and for Church et al. B1, A1B and A2 scenarios.

Department of Transport (DoT, 2010) extrapolated work by Hunt (2009) to provide sea level rise (SLR) values based on the IPCC (2007) A1F1 climate change scenario projections to the year 2110. Based on this, the West Australian Planning Commission (WAPC, 2010) released a position statement indicating that the allowance for sea level rise to 2110 be increased to 0.9 m. Table 2-5 below outlines the expected SLR using the A1F1 scenario for the planning horizons 2060 and 2110.

Table 2-5: Mean Sea Level Rise for Planning Horizons 2060 and 2110

Planning Horizon	2060 (m)	2110 (m)
Mean Sea Level Rise (SLR)	0.3	0.9

Extensive analysis of the variation in regional sea level at Fremantle has being undertaken by the Indian Ocean Climate Initiative – Western Australia. Pattiaratchi and Eliot (2011) provide the following summary:

"*Fremantle tide data have shown that the mean sea level has increased almost 20 cm at a rate of 1.54 mm per annum since 1897. This represents 20% of the maximum tidal range at Fremantle. The rise in sea level has been attributed to thermal expansion of the oceans due to increased warming. Superimposed on this increasing trend, the rate of sea level rise has changed due to inter-annual variability resulting from the El Nino-Southern Oscillation (ENSO) phenomenon. As a result, the mean sea level remained almost constant between 1952 and 1991 and has increased at almost three times the global rate since 1991.*"

The recommended projection by the DoT in Western Australia considers the sea-level rise rates from global models and local tide gages and suggests 0.3 m rise by 2060 and 0.9 m by 2110 in MSL (Bicknell, 2010).

The predicted sea level rise is expected to result in increased water depths over reefs, allowing increased wave energy to penetrate to the shore. This increase in wave energy and higher water levels at the shore has the potential to inundate low-lying coastal land and erode beaches. These potential impacts are discussed in more detail in Sections 4 to 6 of this report.

3 DATA REVIEW AND ANALYSIS

3.1 Data Types and Collation

The following data sources were collated and reviewed in this study:

- Coastal Management Plans
- Academic Papers
- Survey Beach Profiles
- Aerial Photography
- LADS/LiDAR Data
- Coastal Water Imagery.

3.2 Document Review

Some of the principal documents characterising this segment of coast are outlined below.

3.2.1 1984 Coastal Management Plan

In the early 1970s it was recognised by the City that 'piece meal' development of the coast was an unsatisfactory process and there was a need for a comprehensive approach to manage and develop their coastline. The last Coastal Management Plan (CMP) for the CoS was produced in 1984. The CMP largely drew upon reports and research work with the objective of establishing policy guidelines for the future management and development of the coastal area within the City.

The CMP entails a review of the physical environment, urban environment and beach utilisation. The CMP divided The City's coastline into 13 management units, where by a detailed analysis was undertaken for each unit. Major coastal issues where identified for each coastal sector with subsequent policy and management recommendation with the intention of management development action plans to be developed per Management Unit. The following were identified (in order of priority) as major issues that either need further investigation or appropriate plans prepared. It is understood that all of the listed items have been actioned:

- *West Coast Highway realignment: with the intention of re-aligning the northern half of the City's coastline in terms of improving the coastal environment*
- *Special Beach Development Zone – Scarborough: development of the land west of West Coast Highway, specific development guidelines to be prepared for the whole if the commercial area*
- *West Coast Highway: redesign that section of West Coast Highway through the Bay Beaches, keeping with high pedestrian usage and reflecting the need for increased parking and lower volumes of vehicle traffic*
- *Public Car Park: Upgrade existing facilities by redesign of entry exit points*
- *Coastal Facilities: Redesign and upgrade most of the coastal facilities*
- *Stormwater Drainage: Redesign and upgrade drainage outlets onto the beaches to improve appearance and to prevent beach erosion.*

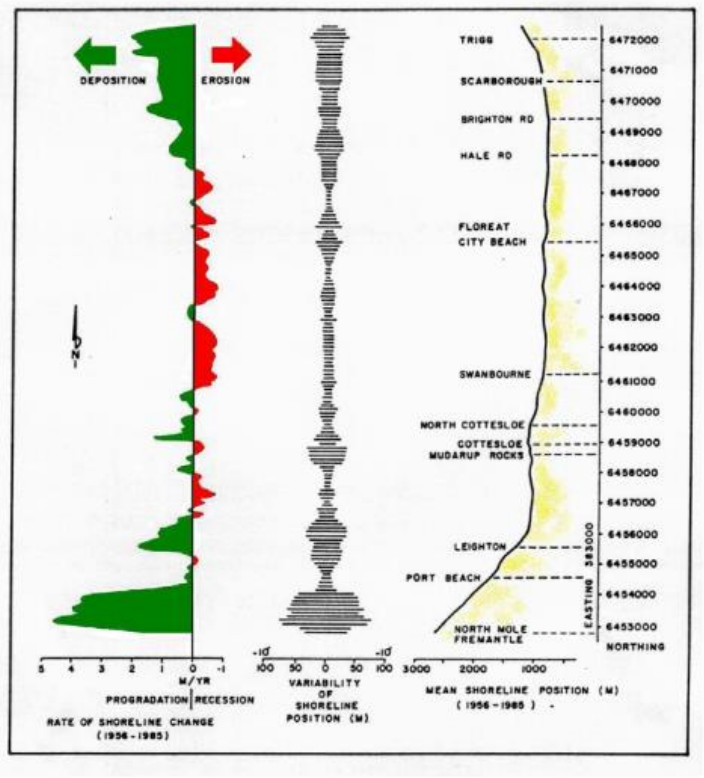
Review of the 1984 CMP by Overman (1996) noted that the CMP omitted the development of risk management strategies, did not adequately account for climate change, needed a more in depth consideration of recreational management, and to link coastal management strategy to a legislatory framework.

3.2.2 2006 CoS Coastal Foreshore Action Plan (CoS, 2010)

The purpose of the 2006 Coastal Foreshore Action Plan (CFAP) prepared by UWA was to develop site specific strategies for management of the coastal foreshore from Trigg Point to Watermans Beach (Beach Road), and to formulate an implementation schedule. The report defined 13 Beach Nodes between Trigg Is. and Watermans Beach (these nodes did not coincide with the 13 Management Units defined in the 1984 CMP). The study identified specific social, environmental, recreational management issues and formulated recommended actions.

The study reviewed the coastal geomorphology including the wave climate and shoreline movements (see Figure 3-1) together with available coastal monitoring and noted that oscillations between a northerly and southerly movement of sediment in the summer and winter respectively are considered responsible for the short term variability in beach morphology and notably width in the study area. It found that it was likely that the supply of sediment to the Open Beaches and Dunes study area through nearshore littoral transport processes is increasingly limited, although citing insufficient data was available subsequent to the work by Bowyer (1987) which importantly reported the trend for accretion in the southern section of the City primary cell, with erosion of beach material between Swanbourne and Hale Road providing the source of sediment accreting in the sink area between Hale Road and Trigg Point.

Figure 2: Shoreline change from Rous Head to Trigg Island 1956-1985



Source: Bowyer (1987)

Figure 3-1: Shoreline Change (CoS, 2010)

Findings of the Northern Perth Metropolitan Coast Coastal Setback Study prepared by MRA for DoT in August 2005 (MRA, 2005) were included in the CFAP assessments of climate, sea level and coastal change. The Northern Perth Metropolitan Coast Coastal Setback Study identified a total of 37 separate shoreline sectors for analysis, based upon physical characteristics and historical trends in shoreline movement. Setback distances were calculated in accordance with the State Coastal Planning Policy in 2003. The CFAP noted that the assessment of the 62 m setback line only encompasses land zoned for parks and recreation within this sector neglects several features and also predates development work within the study area, hence requires careful revision. Additionally, the SPP has been updated with differing allowances required for the calculation of setback distances. The CFAP also questioned the accuracy of the aerial photography interpreted reference datum and the vulnerability of the recreational foreshore development at the Scarborough node. It also recommended the setback approach for the Town of Cottesloe (2008). It is likely that with the increase in sea level rise allowance in the current SPP that the hazard zone developed in this study will increase substantially by in the order of 50 m increasing risk to coastal foreshore assets over the coming decades.

Significantly, the CFAP study found that the absence of regular programmed beach monitoring hampered an essential understanding of the nature of short and long term variations in beach form which have fundamental implications with regard to stability of the natural and built foreshore environment. It noted that these should be located to enable comparison with previous survey data collected by Eliot et al. (1983) whilst also including locations where infrastructure is in close proximity to the beach.

Modelling studies were noted as having been invaluable in revealing the complexity of nearshore sediment transport processes within the study area. However, verification of these is required, particularly given the spatial resolution of these models. It was recommended that the City consider commissioning research to elucidate the nature of nearshore sediment movement which would greatly assist in the strategic planning of works along the coast.

Figure 4b: Location of 8m and 62m setback lines: Scarborough



Figure 3-2: Setback Lines MRA, 2005 (from CoS, 2010)

3.2.3 2013 SEAS Coastal Hazard & Management Plan (Damara, 2013)

This plan was developed to guide the management and potential adaptation of coastal facilities within the Scarborough and Environs Area Strategy Masterplan. The position of infrastructure close to the beach and narrow dune width is noted as making the area sensitive to beach movements and thus requires active coastal management. Challenges to management of the precinct are presented with sea level rise or interference with the alongshore sediment supply and requires adaptive management to address these challenges.

The study area was reviewed in the regional geomorphic context in its setting towards the northern end of the extended coastal sediment cell that stretches from N Fremantle to Trigg. Long term patterns of coastal change were identified associated with accretion towards the northern and southern ends of the sediment cell and erosion at the centre, near City Beach and Floreat attributed to a blend of evolutionary and anthropogenic influences. Historically, a pattern of accretion at the southern end of the present study area was identified associated with the broad beach area at Scarborough. In reviewing the available data and reporting, the study identified that the available spatial information on coastal movement based on aerial imagery alone was insufficient to identify long term trends due to difficulty in interpretation due to the beach form and other factors such as beach use and management. Techniques such as profile surveys are required to identify coastal change in such areas.

Based on previous studies, regional morphology, aerial shoreline data, and beach measurements from various studies and research, the study identified significant variability in the beaches in this area within year variations of beach width (60 m), substantial step changes (30 m), episodic reversals of the overall accretive trend, and a substantial role of dune capture of sediment.

The study noted that the cause of the historic accretion may also become more important to long term future management of this and other sectors of the CoS coastline noting the importance of underlying and nearshore rock and hard stratum to future erosion susceptibility. The study noted DoT findings of rock features 300 m offshore of Scarborough Beach and a ridge offshore from Trigg southern car park that would play a large role in coastline response to future erosion.

The study took a risk based approach identifying possible erosion responses to SLR in the order of 35 to 90 m in medium to high estimates and identified ways in which to manage these for the proposed masterplan concept infrastructure with combinations of progressive and episodic change scenarios to benefit planners.

It is noted for the present study that this precinct has now come under management control of the Metropolitan Redevelopment Authority and will require CHRMAP assessment that will necessarily be cognisant of and refer to wider beach management by the CoS in developing its own CHRMAP response.

3.3 Perched Beach Literature Review

Many of the beaches in the northerly part of the study area are classified as perched beaches. A perched beach is understood to be geologically controlled by a thin layer of sediment overlying a rock platform (Eliot et al., 2005). In the study area the width of the exposed rock platform varies from 0 to 100 m, tends to have a sudden increase in depth of a metre or more at the offshore limit of the platform and is discontinuous alongshore. Perched beaches within the study area are typically within an embayment bounded by protruding rocky headlands. These morphological features have been previously mapped (Green, 2008) and their role in coastal response to sea level rise discussed (Green, 2008). There is often considerable alongshore variation in the topography of these landforms. Some key processes that are likely to be important on perched beaches are summarised in Figure 3-3 and include: obstacles in the nearshore trapping littoral drift; Aeolian sediment transport; development of scour-holes and sediment ramps on the seaward side of hard landforms; dampened offshore sediment flux; wave attenuation; current jets; resonance; and the possibility of a raised groundwater table inhibiting infiltration of water when waves run-up the beach leading to increased erosion (Gallop, Bosserelle et al. 2012).

The response of perched beaches (either natural or engineered) to predicted sea level rises and possible changes in storminess is largely unknown, a number of research papers discussing the behaviour of perched beach morphology for the Perth metropolitan region and other 'hot spots' in the world such as the Mediterranean region were reviewed as part of this assessment (as identified in the database).



Figure 3-3: a) Alongshore Variability of a Perched Beach; and b) Potentially Important Processes (adapted from Gallop, Bosserelle et al. 2012)

The coastline of Perth is characterised by a large seasonal variation in the incident wave height and local beaches exhibit a distinct seasonal change in morphology. However, these morphological changes are better explained by a seasonal reversal in the littoral drift direction than by variations in the incident wave energy conditions (Masselink and Pattiaratchi 2001).

Stul (2005) characterised the metropolitan coast from Two Rocks (~70 km north of Perth) to Silver Sands (~70 km south of Perth) by consistent morphodynamic method by Wright and Short (1984) and Travers (2007). Additional beach types were identified for beaches with inshore reef or beach rock. Perched conditions were observed for over a quarter of the 100 beaches visited in individual field trips (Stul, 2005).

The grouping of the shoreline into sediment cells can be used to group morphology, dynamics, history and function (Searle and Semeniuk 1985). Considering sediment cell boundaries method, five primary, 14 secondary and 52 tertiary cells were identified by Eliot et al. (2005). The results revealed the need to classify perched beaches as these were the beach types that had the most variability in beach width and elevation during the storm due to the limited sand availability (Stul, 2005). A detailed study was undertaken on Yanchep Beach (~60 km north of Perth) to investigate significant processes of a perched beach and the response of the system to metocean driving forces at different time scales using morphological surveys, aerial photographs and numerical models.

3.3.1 Sea Breezes and Storms

The microtidal coast in Perth metropolitan is influenced by one of the strongest and most persistent sea breeze cycles in the world. This, together with offshore limestone reefs attenuating swell means that locally generated sea breeze waves and currents dominate the hydrodynamics for half of the year (Gallop, Bosserelle et al,. 2011). The response of a perched beach in Yanchep to sea breeze was highly variable within just a short distance depending on the immediate local geological formations (Gallop, Bosserelle et al., 2011).

Field investigations during two consecutive winter storms were undertaken on three profiles over sandy beaches of Yanchep lagoon perched on quaternary limestone reefs (Gallop, Bosserelle et al. 2012). An “Exposed Profile” fronted to seaward by a predominantly sandy substrate eroded most with a 2 m-high scarp cut into the dune and accreted almost to the pre-storm volume in a month. A “Reef Profile” was fronted directly seaward by limestone outcrops submerged below mean sea level. It was the most stable overall because erosion was balanced by short periods of accretion during the storm period which was partly due to sediment supplied by longshore transport. A “Bluff Profile” where the dry beachface was perched on a limestone platform with a low bluff along its seaward margin eroded considerably with low recovery after the storm (Gallop, Bosserelle et al., 2012).

The profiles were also most vulnerable at different stages of the storms. The Bluff Profile had the most daily erosion before the peak of the first storm front when significant wave height was still low, and subsequently was not sensitive to a significant increase in sea level and wave height. This contrasted to the Reef and Exposed Profiles which eroded most when significant wave height peaked. This shows that the rocky bluff provided beach protection with the rise in wave energy and sea level and was more vulnerable during lower wave heights. These results highlighted the complexity of the behaviour of beaches that are perched on natural structures. Results suggested that perched beaches could be more vulnerable to erosion that previously thought, due to low rates of recovery after storms (Gallop, Bosserelle et al., 2012).

3.3.2 Seasonal Variability

The effect of coastal reefs on seasonal erosion and accretion was investigated on 2 km of the alongshore zones at the same site and were revealed to alter modes of sediment transport in spring and summer compared to autumn and winter (Gallop, Bosserelle et al., 2013). Seasonal or summer–winter tilting of the profile around different hinge points has been previously observed from 5-year monitoring of a rocky beach and seems to be common in many perched beaches (Muñoz-Perez and Medina, 2010).

In Yanchep, constant sand resuspension and northerly littoral drift due to sea breezes in spring and summer allowed a sand ramp to form in the South Zone so that sand overtopped the reef to infill the lagoon. This blocked the main pathway for sand supply to downdrift zones which subsequently eroded. In autumn and winter, with the dominance of northwesterly storms and reversal in the direction of littoral drift, the South Zone eroded and sand travelled through the lagoon in the current jet to nourish the northern beaches (Gallop, Bosserelle et al,. 2013).

3.3.3 Extreme Wave and Sea Level Events

The impact of a 100-year storm was simulated at the reefed coast of Yanchep lagoon, with present day mean sea level and with an increase of up to 1 m. The 100-year annual recurrence interval levels for waves and sea level were defined using numerical hindcasts of waves, tides and surge for a few decades and applying extreme value distribution on time series of data (Gallop, Bosserelle et al,. 2013).

For the wave model, a 10 m-resolution bathymetry was centred on Yanchep lagoon, extending 5 km alongshore and 10 km offshore. This model was forced with the 100-year annual recurrence interval wave event extracted from Wave Watch III by Tolman (2009) down to ~15 km resolution along the Western Australian coast (Gallop, Bosserelle et al., 2013). Downscaling wave parameters from 15 km grid resolution to 10m grid resolution with a small domain (5 km by 10 km) does not seem to be a smooth transition, especially because of the significant role of offshore reefs in attenuating wave energy.

The morphology model was run on a 2 km by 1 km domain at 5 m grid resolution. The numerical model XBeach was forced with the 100-year extreme sea level and the 100-year extreme wave event and associated wind. Because of the short duration of the extreme storm, it is likely that the simulated beach would not have had enough time to reach the 100-year storm equilibrium profile. Therefore, the boundary conditions were applied 3 times in a row to simulate the maximum erosion that may occur from a 100-year storm (Gallop, Bosserelle et al., 2013).

Qualitative comparisons of sand movement were consistent with measurements made on three profiles during a storm with approximately one year annual recurrence interval of waves. The current speed predicted for the 100-year storm was not be particularly high for this site because although relatively large waves occurring at the peak of the storm could drive faster currents, the high water level during the storm allowed undertow to head seaward out of the lagoon and thus prevented current speeds from getting even higher. Again this shows the need for high-resolution bathymetry and numerical modelling for assessing the impacts (Gallop, Bosserelle et al., 2013). It is not clear if the coincidence of extreme water level (tide and surge) and waves assumed by the authors is based on statistical analysis or historical measurements/hindcast or not.

In scenarios of sea-level rise, wave heights were predicted to increase which increased erosion of the beach face, with 10 m more horizontal erosion on the beach. This increase in erosion may not be extreme because there is less wave dissipation, smaller wave setup over the reef, and weaker longshore lagoonal current at higher mean sea level. This resulted in less sand movement from the beachface and dunes toward outside the lagoon (Gallop, Bosserelle et al., 2013). While there has been a good effort in describing the problem and addressing all processes, the modelling methodology needs a significant improvement for quantitative assessment of the impacts of extreme events on perched beaches.

Field research in southwest Western Australia indicated that natural perched beach behaviour has extreme spatial variation. Beach response to changing hydrodynamics is strongly dependent on the configuration and geometry of local coastal structures, whether natural or anthropogenic (Gallop, 2011).

3.3.4 Conclusions

The results of a number of studies, the Yanchep case study in particular, revealed the vulnerability of a perched beach to hourly/daily scale metocean driving forces e.g. sea breezes and storms. Beach surveys of perched beaches revealed the altering role of adjacent sediment cells as sediment source and sink in different seasons. Literature review of the beach response to decadal forcing mechanisms e.g. wave/surge climate change, extreme waves and mean sea level variability highlighted the need for a comprehensive modelling of hydrodynamic/morphology parameters at appropriate temporal and spatial scale and resolution.

In general the literature has identified that for natural and engineered perched beaches, profiles may recover more slowly from the daily summer sea breeze erosion than exposed profiles. During a storm, perched profiles had less erosion, occurring lower on the beach face than exposed profiles, however did not recover as easily by accretion during low sea level phases of storm activity. Lower rates of recovery for perched profiles could be due to a scour step forming seaward of the rock formations inhibiting cross-shore sediment transport.

While these generalisations can be made regarding the typical responses of perched beaches to storms, it should be recognised that the dynamics of each of the perched beaches along the CoS coastline are likely to vary somewhat due to the variations in the ocean forces, morphology and interaction with adjacent segments of the coast for each site. The assessments on vulnerability in this study and indeed standard setback based future CHRMAP processes can be considered a first-pass assessment of hazards and vulnerability. Within SPP2.6 the guidelines for estimating shoreline recession in response to SLR are necessarily general in nature and have documented limitations (Rollason et al.). Where specific segments of the coast are identified as being at risk, more detailed modelling studies, using one or more numerical models suited to the type of shoreline, are required to better quantify shoreline response and risks, and facilitate development of site-specific adaptation measures.

The ongoing measurement of beach profiles currently being undertaken by the CoS is required to provide observations of beach response at specific CoS sites that will inform management. Assessment of beach profile data from November 2011 to November 2014 is discussed in Section 3.5.

3.4 Analysis of Aerial Photography

As detailed in the 2010 CoS Coastal Foreshore Action Plan (UWA, 2010), the coastline in the study area south of Trigg Point constitutes the northern section of a continuous stretch of wide sandy beaches punctuated by occasional headlands extending approximately 20 km southwards to Fremantle. The characteristics and geomorphological processes of these open sandy beaches and adjacent dunes have been studied by numerous authors, notably Clarke and Eliot (1983), Pattiaratchi et al. (1997), Masselink and Pattiaritchi (2001) and Stul (2005). Additionally, MRA (2005) in the Northern Perth Metropolitan Coast Coastal Setback Study for the DoT has mapped the shorelines of this coastal segment and Damara (2013) SEAS Coastal Hazard Adaptation and Management Plan has assessed coastal movements for the Scarborough precinct.

The studies identify that long term patterns of coastal change have been identified through analysis of the historical imagery, suggesting accretion towards the northern and southern ends of the sediment cell, with erosion towards the centre, near City Beach and Floreat (Damara, 2013). The SEAS study identified significant variability in the beaches in this area within year variations of beach width (60 m), substantial step changes (30 m), episodic reversals of the overall accretive trend, and a substantial role of dune capture of sediment that planning in the southern part of the study area should accommodate.

As part of this study, the earliest reliable coastal data available for the study area is aerial photography. Aerial photos available for this study date back to 1953. In particular, aerial photos allow determination of the historical position of the shoreline by digitisation of scarp, foredunes or vegetation line. The position of the vegetation line can vary naturally over time in a coastal environment, especially in sandy areas. Along Scarborough beach the vegetation line has also varied due to anthropogenic influences (e.g. dune stabilisation and sand placement). In these areas estimated rates of shoreline movement can be less reliable. Nevertheless, it is current practice to estimate shoreline movement trends using position of the vegetation line.

Aerial photos are available for the study area (varying areas) for 1953, 1965, 1974, 1979, 1981, 1985, 1995, 2000, 2004, 2006, 2008, 2010, 2011, 2013, and 2014. The historical aerials were georeferenced in order to undertake an analysis of shoreline movement. For the purpose of this study, the shoreline is defined by the vegetation line.

The coastal mapping tool, Digital Shoreline Analysis System (DSAS) was used to calculate the rates of change of the position of the shoreline over time for each location. DSAS is a freely available software application that is compatible with Environmental Systems Research Institute (ESRI) Geographic Information System (ArcGIS) software. The tool allows for a Net Shoreline Movement to be calculated, the distance between the oldest and youngest vegetation line. The net shoreline movement reports a distance, not a rate. The mapping tool creates transects along a desired length and using the date stamp of each historical vegetation line, calculates a distance of change.

The net shoreline movement was calculated for the compete length of the study area, using the DSAS tool between the years 1965 and 2013, as shown in Figure 3-4. Net accretions are indicated in green and net erosions shown in reds. The mapping tool takes into consideration the degree of accuracy of the vegetation lines (+/- 5 m); therefore all net movements within this range have been highlighted in grey.

The DoT has also published mapped vegetation lines for various years between 1942 and 2001 along the Western Australian coastline (https://mapsengine.google.com/09372590152434720789-17447516222354999649-4/mapview/?authuser=0). Vegetation lines for varying extents of the study areas are mapped for 1942, 1954, 1956, 1965, 1987, 2008, and 2009. The dataset was captured using available imagery and photogrammetric techniques.

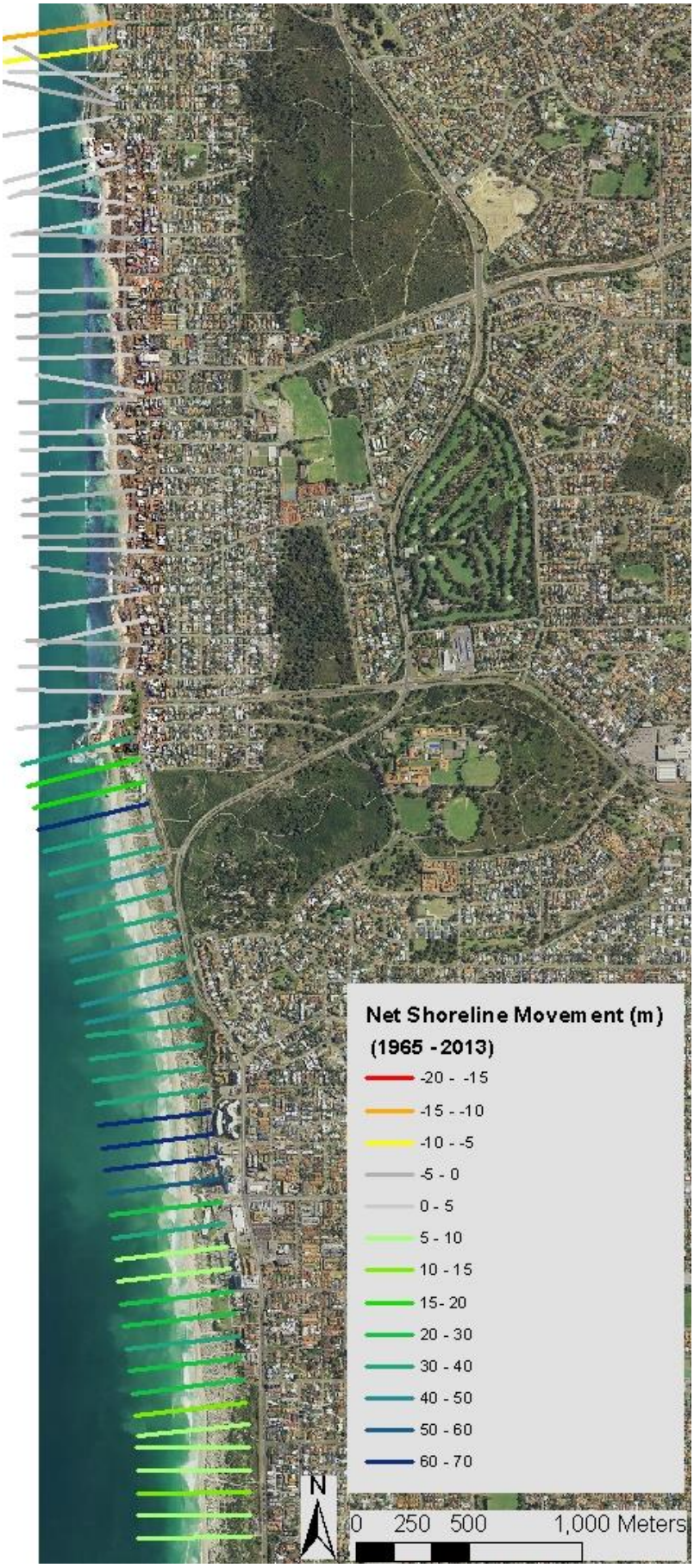


Figure 3-4: Net Shoreline Movement Plot (1965 – 2013)

The review confirmed net accretion in the sandy beach unit south of Trigg found in other studies and the lack of such a trend in the northern unit of the study area with some minor erosive net movement at the northern end. Due note is taken of the variability in beach movement at Scarborough from the literature along with the considerable uncertainty associated with continuing sand supply that has been linked to the historical accretion in this segment, variation in storminess and response to climate change.

During the draft report review period, the recent Scarborough Beach Pool CHRMAP study (MRA, 2015) was received from the CoS which extended the shoreline analyses from Northern Perth Metropolitan Coast Coastal Setback Study (MRA, 2005). The presented time histories from updated aerial photographic record have confirmed the previously noted accretion in the southern sandy beach sector and reported that this accretion all happened prior to 2000 and since this time there has been little change in the shoreline position and further reported that the trend of accretion seen at the site since approximately 1942 has slowed or halted since approximately 2000.

The impact of a reversal of the identified accretion in the record and its impact on coastal vulnerability remains an important signal to monitor into the future. The maintenance of beach profile monitoring in the study area implemented under this study as one of the five pillars has an important role in informing management of coastal change into the future.

Particular areas of interest have been further reviewed in the following sections.

3.4.1 Trigg Point

The CoS has suggested that sand accumulation at Trigg Point has increased significantly in the past decade, in particularly the past 15-20 years, prior to this the beach would be eroded back to the limestone scarp. The following observations could be drawn from the review of the aerial photographs:

- Strong seasonal pattern observed south of Trigg Point, significant build-up of sand during Summer months as shown in Figure 3-5a and Figure 3-5b.
- Increase in sand build up inter-annually, i.e. increased width of beach south of Trigg Point observed in summer months, as shown in Figure 3-5c
- Significant inter-annual build-up of the beach south of Trigg Point in the winter months between 1981 and 2008 (up to 35m), between 2008 and 2013 alignment for the coastline south of Trigg Point has receded back toward the alignment observed in 1981, as shown in Figure 3-5d
- The alignment of the beach directly north of Trigg Point doesn't experience seasonal variation as shown in Figure 3-5a and Figure 3-5b. Inter-annually little change has been observed with the exception of significant build-up of sand (approx. 20m) between March 2010 and March 2011, as shown in Figure 3-5c.

Anecdotal reports indicate that water flowed between Trigg Is and the mainland periodically during the 1970's. The aerial photo from 1974 available for this study did not show such a connection; however, as noted above, this area is very dynamic and it is possible that certain storm events could denude the beach behind Trigg Is, followed by seasonal recovery. The dynamics of sediment flow offshore and inshore of Trigg Is are discussed in more detail in Section 5.3.

Limited change is observed north of Trigg Point towards the southern extent of Mettams Pool (net changes within ±5 m).

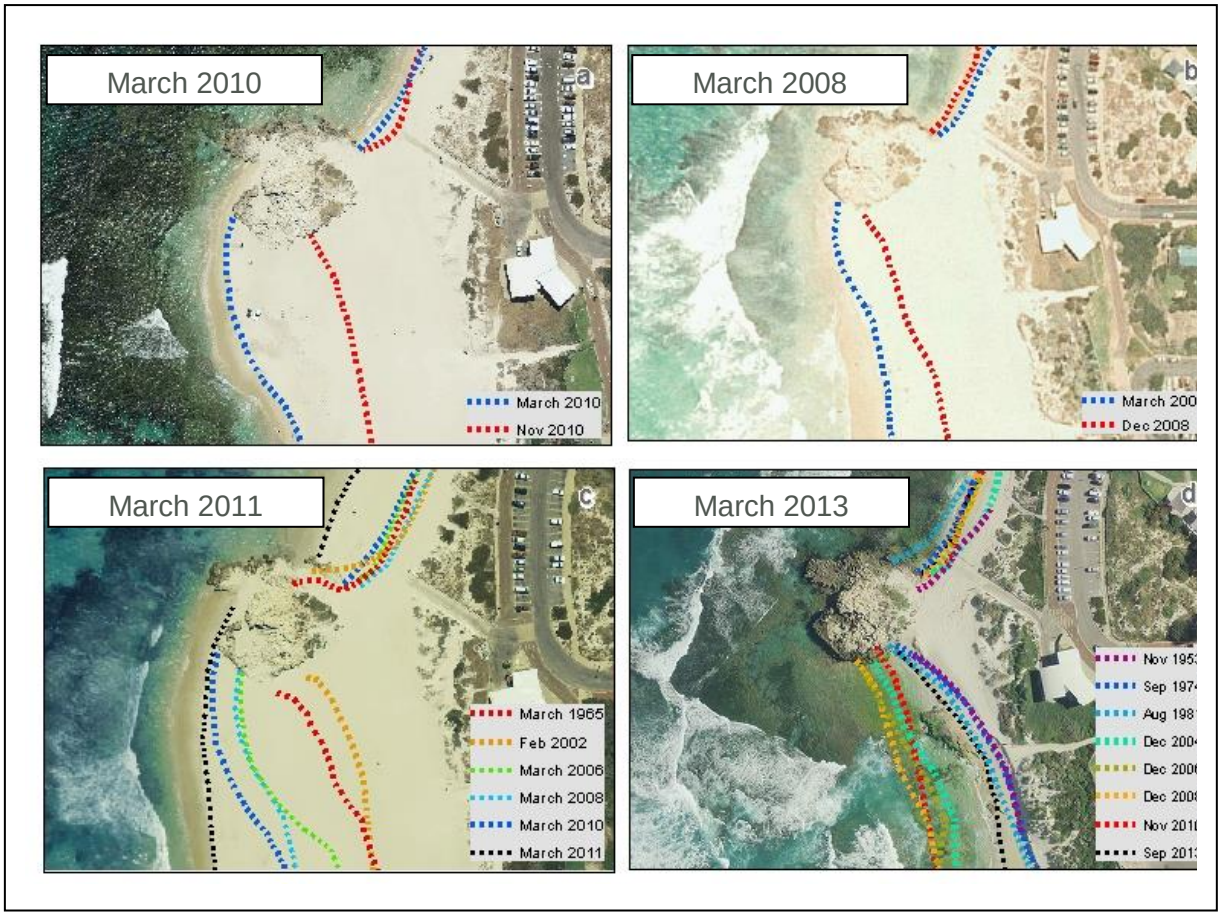


Figure 3-5: Trigg Point Mean Lower Water Mark Mapping

3.4.2 Mettams Pool

Mettams Pool has experienced little change in net movement since 1965. Earlier observations reported a general accretion of 5 m (MRA, 2010) with larger fluctuation on the northern end of Mettams Pool, with a slight erosion trend since 1990. Figure 3-6 shows a net movement of within 5 m for the length of Mettams Pool between 1965 and 2013. There doesn't appear to be a clear trend in erosion or accretion, the net movement is considered to be within the range or the mapping accuracy.

The stretch of coastline along North Beach between Mettams Pool and Watermans Bay shows little change in the vegetation extent observed between 1965 and 2013. The vegetation extent has experienced a net movement within a ±5 m range during with no clear trend in erosion or accretion, this shoreline variation is considered within the vegetation mapping accuracy.



Figure 3-6: Shoreline Movement Plot, Mettams Pool 1965 – 2013

3.4.3 Watermans Bay

The change in vegetation extent at Waterman's Bay is plotted in Figure 3-7. Lines from 1953 and 1965 show variability alongshore with some beach segments accreting and others eroding. Between 1979 and 1995 accretion of up to 10 m is observed followed by a period of recession to 2013 which has coincided with a period marked by a higher frequency of extreme water levels (MRA, 2010). Between 2011 and 2013 the rate of recession reduces to <5m and in some sections no change is observed. This is most likely due to the construction of a temporary geotextile sand container (GSC) seawall along the rear of Watermans Bay in April 2010 to stabilise the beach against further recession.

In general a net retreat has been observed between the period of 1953 and 2013. Up to 12 m recession was noted at the northern extent of Watermans Bay.



Figure 3-7: Shoreline Movement Plot, Watermans Bay 1965 – 2013

3.4.4 Watermans Bay to Hillarys Boat Harbour

The stretch of coastline between Watermans Bay and Marmion has remained relatively unchanged between the period of 1965 and 2014.

The vegetation extent at Sorrento is plotted in Figure 3-8 this section of coastline has experienced net advance since the construction of the groyne field in the early 1980s and the construction of Hillarys Boat Harbour in 1987. Accretion of up to 35 m was observed directly south of Hillarys Boat Harbour between 1965 and 2014.



Figure 3-8: Shoreline Movement Plot, Sorrento 1965 – 2014

3.5 Analysis of Surveyed Beach Profiles

In line with BMT JFA recommendations of the key recommendations of the Watermans Bay peer review, commencing in November 2011 the CoS has collected a series of cross shore beach profiles between North Floreat and Sorrento. The locations of these profiles are shown in Figure 3-9. The 19 profiles were typically spaced between 200 and 300 m alongshore, with the exception of profile location 1 and 2 which are 1.5 km apart. The profile locations were determined by BMT JFA, DoT and CoS during a site visit as part of this study, ensuring all beaches and embayments of particular interest were captured. The cross-shore extents of the profiles are typically 120 – 140 m for sandy beaches and 70 – 100 m for rocky platform beaches.

BMT JFA advised that the offshore extent of the cross shore profiles should be closure depth, however as the survey was undertaken by foot without the aid of a vessel, the offshore extent of the profiles were taken to the greatest depth practicable by foot, typically between -2 and -3 m AHD. Similarly, the onshore extent of the profiles was taken to the extent practicable, typically to the western extent of the Dual Access Pathway or neighbouring infrastructure to the foredune.

The 19 profiles are being re-observed every 1-2 months commencing in November 2011 as part of the ongoing monitoring programme. The dataset length available for this study was 3 years (November 2011 – November 2014).

Plots for each station were created in order to easily interrogate the data inter-seasonally (i.e. compare winter and summer months) and inter-annually (i.e. compare summer and winter profiles each year). These are used to help establish both shoreline position and beach elevations and volumes over time. It should be noted that there are limitations to establishing trends in beach volume and cross shore beach profiling with only three years of data. The intention is for the program to be ongoing to collect a long term robust dataset.

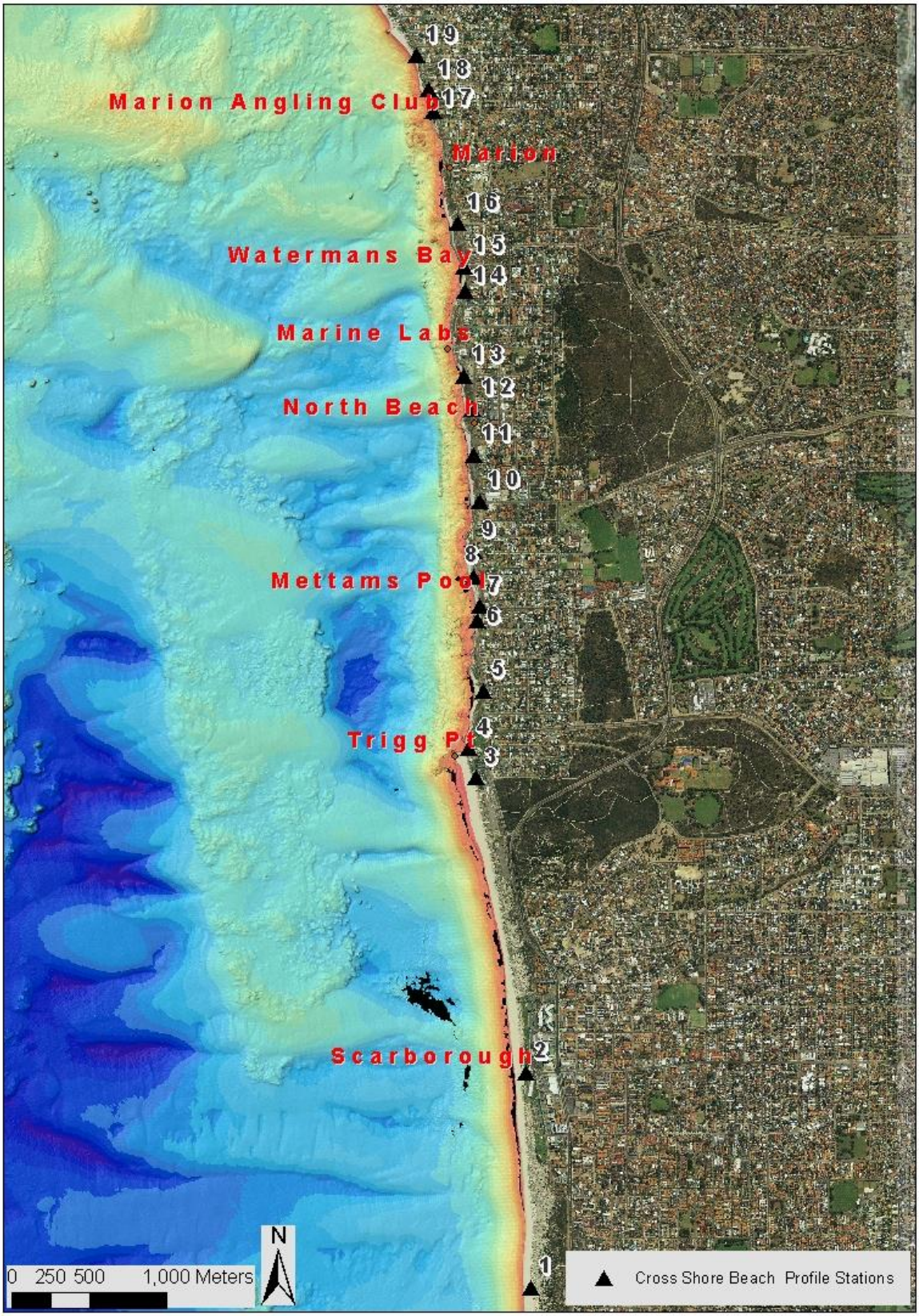


Figure 3-9: Cross-shore Beach Profile Station Locations

The following observation can be drawn from review of the data:

3.5.1 Scarborough Beach (Profile 1 – Profile 2)

A strong seasonal change is observed in the cross shore profiles at Scarborough Beach (Profile 1 and 2). Up to 20-30 m retreat observed over the winter months (May – October), steeping the cross shore profile in the tidal zone. Full recovery of the profile is observed during the summer months (November – April). The trend in shoreline progradation discussed in Section 3.4 is not apparent in the cross-shore profiles, continuing the profiling over a longer period of time would qualify the suggested trend.

3.5.2 Trigg Point and Trigg Beach (Profile 3 - Profile 5)

A strong seasonal pattern is observed south of Trigg Point (Profile 3) with a very dynamic cross shore profile as noted in Section 3.4.1. A typical seasonal cycle is observed, with a very gentle slope observed during summer (1:30), which steepens during the winter months (1:8). The slight advance of the shoreline annually, as shown in Figure 3-5, is also observed in the cross shore profiling. The maximum distance of shoreline advance (100 m) was between November 2012 and March 2013.

Directly north of Trigg Point (Profile 4) a rock platform is exposed at -0.5 m AHD to the seaward extent of the profile. Little change is observed interseasonally or interannually, with a maximum net shoreline change of 6 m. The 20 m advance in shoreline position between March 2010 and March 2011, shown in Figure 3-5c, may be the result of reduced northerly energy during that period.

The rock platform steepens towards Trigg Beach (Profile 5), which is exposed at MSL. The steeper offshore slope allowing for a more dynamic beach profile, a typical seasonal cycle is observed. Up to 12 m retreat during the winter months (April – October) and re-established over the summer months (November – May).

3.5.3 Mettams Pool and Mettams Beach (Profile 6 – 9)

Rock platforms are present at all profiles within Mettams Pool and Mettams Beach. For all profiles the platform is exposed or overlain with a thin layer of sand throughout the survey period. The profile takes the shape of a rock pool at Profile 6, which is not seen at the other profile locations.

The sediment transport process described is Section 2.3.5 is displayed in the lee of Mettams headland (Profile 6), i.e. shoreline advance during winter and retreat during summer. This is driven by northerly transport during the summer building up on the southern side of Mettams headland and starving the northern side.

Comparison of the profiles shows that the steepest gradient at Profile 7 allows for a more dynamic beach profile. The onshore profile dramatically steepens during the winter months, sand moving to the offshore extent of the rocky platform, followed by onshore migration of sediment and restoration of the profile by December 2012, as shown in Figure 3-10.

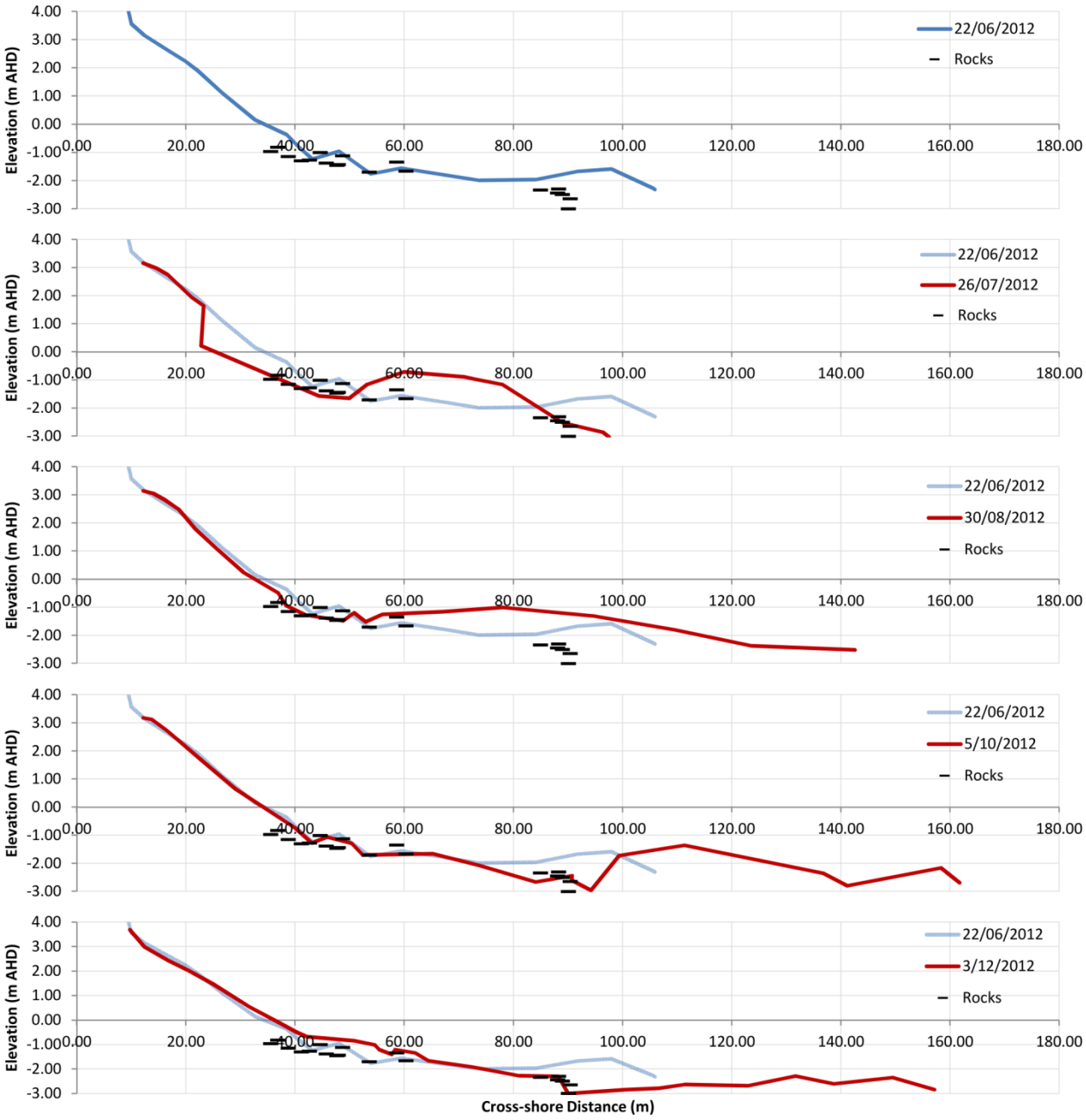


Figure 3-10: Mettams Pool Cross-shore Profile (Profile 7), June – December 2012

3.5.4 Hamersley Pool and North Beach (Profile 10 - 13)

Comparison along this section of coastline demonstrates the sediment transport processes described in Section 3.4.2 and also seem at Mettams Pool. In the lee of Hamersley headland (Profile 10), the nearshore berm is built-up over the winter months and depleted during the summer months. The onshore profile appears to be controlled by the exposed rock at 0.4 m AHD (i.e. profile doesn't advance or retreat).

Profile 11 is located near the southern end of the embayed beach between James and Malcolm Streets. Profile data shows accretion at the foreshore during April-May once the summer seabreeze abates and the wave field becomes dominated by low swell, inducing onshore migration of sediment near the shoreface and also in deeper water. The shore face continues to accrete over winter, likely as a consequence of northerly wave conditions and reorientation of the beach toward the northwest. In December, the onset of the summer seabreeze results in erosion of the foreshore exposing some rock, northward transport and reorientation of the beach toward the northwest. This appears to be accompanied by a build-up of a sediment bank in deeper water around -2 m AHD.

Profile 12 is located in the embayed beach at Castle Street. The sand cover on the foreshore and seaward of rock at about -1 m AHD during December varies by up to 0.5 m between 2012 and 2013, due either to delayed onset of seabreezes and/or variability in sand supply from the south. However, by March the profiles show consistent accretion across the profile out to about -2 m AHD, covering rock near the shore. During winter the upper shoreface is eroded and sand builds up just below mean sea level and offshore.

There is a well-defined rock platform approximately 25 m wide at Profile 13 with an increase in water depth of almost 2 m at the offshore edge. Below 0.5 m AHD this platform is exposed throughout the 18 month survey period. Little sand is moved across the reef resulting in little change in the beach profile. Similar to Profile 12 the foreshore in December 2013 is depleted of sand compared to 2012 but by March the perched beach has accreted to a sand thickness of approximately 0.5 m over the foreshore rock ramp. There is no survey data seaward of the rock platform toe however it is likely that the main pathway for sediment feeding on this beach is on the rock platform around the headland to the south.

3.5.5 Watermans Bay (Profile 14 – 15)

Profile 14 and 15 have a very gentle (1:30) offshore slope which is controlled by a rocky platform in the southern part of Watermans Bay (Profile 14) extending 50 m offshore. The nearshore profile is slightly steeper in Profile 14 than Profile 15. The seasonal pattern at Profiles 14 and 15 support the sediment transport process described in Section 2.3.5, also observed at Mettams Pool and Hamersley Pool, whereby beach profile directly north of headlands and embayments (profile 14) is starved during the summer months and builds up during winter months, vice versa for beaches south of headlands or embayments (Profile 15).

Erosion at the north end of Watermans Bay (Profile 15) during winter 2012 coincides with a delayed and reduced accretion at the south end of the beach (Profile 14). The gently sloping sand bed of Profile 15 out to a depth of about -2 m AHD is dynamic with surveys from June to August 2012 illustrating that a significant portion of winter eroded sediment is transported offshore rather than alongshore southward. Data for December 2012 to April 2013 indicates onshore movement of sediment above a depth of -2 m AHD.

Profile 14 and 15 also support the net erosion trend discussed in Section 3.4.3 where by over the 18 month period a net retreat was observed, slightly more in the northerly extent (Profile 15 – 3.5 m) than in the south (Profile 14 – 2 m).

3.5.6 Marion - Sorrento Beach (Profile 16 – 19)

Profiles 16 - 19 are located north of the City's administrative boundary. Directly north of Watermans Bay (Profile 16) the cross shore profile shows little change during the 18 months survey period, with little seasonal or interannual trend. The cross shore profiles become more dynamic towards the north, with the most active observed at Profile 19. This is considered to be attributed by sheltering in lee of Watermans Bay headland of net northerly transport and the absence of rocky platform towards Sorrento (Profile 19).

3.5.7 Summary of Observations

Key observations from the review of the relevant literature and analysis of the available data include:

- There is a seasonal northward longshore transport in summer due to the persistent sea breeze and southward longshore transport in winter (Masselink and Pattiaratchi, 2001) due to increased wind and wave action from the northwest. This north – south motion of sand occurs on an annual cycle along the study area with a net northerly resultant (Masselink and Pattiaratchi, 2001).
  Analysis of the historical aerial photos and cross shore beach profiles has highlighted a net northerly trend between Peasholm Street. and Trigg Point. Between Trigg Is. and Watermans Bay, the historical aerial photographs show relatively small net shoreline movement. However, these movements are significant given the typically narrow beaches and proximity of infrastructure to embayed beaches. The effect of headlands and rock platforms on the seasonal oscillation of longshore transport is evident north of Trigg Is. Profiles taken at Mettams Pool and Watermans Bay in particular demonstrate accretion of the beach profile on the northern side of the headlands during winter and retreat during the summer months, and vice versa for the profiles directly south of headlands and embayments. However there is significant variability along the study area and also from year to year.
- Review of the literature highlights that less erosion of the lower beachface is expected at perched beaches compared to more exposed profiles. However, perched beaches are not able to recover as easily. The duration of the beach profile surveys is too short to examine the variability in perched beach recovery in detail, but the record does show significant differences in response of perched beaches within the study area within a given year.
- There is currently a very small buffer between the shoreline and infrastructure at Watermans Bay. Historical shoreline movement analysis and profiling has identified a net retreat in vegetation extent and MSL. Given the projected increases in mean sea level and also given that mean sea level has increased at almost three times the global rate since 1991, Watermans Bay is considered a highly vulnerably section of coastline that will require ongoing management. The presence of the GSC seawall at Watermans Bay is also likely to progressively reduce the ability of the beach to recover due to increased wave energy penetrating to the toe of the structure.
- There is a clear trend of accretion between Scarborough and Trigg Point, interannual advances observed directly south of Trigg Point. Insufficient evidence exists to suggest that sand that is held up on the southern side of Trigg Point is resulting in depleted beaches north of Trigg Point; ongoing profile monitoring will be required to further qualify this.

4 WAVE MODELLING

As discussed earlier, the nearshore bathymetry plays a fundamental role in controlling the wave field along the Perth coastline. A nested SWAN model was used to carry out 2D wave transformation modelling to evaluate the effects of bathymetry on the direction and height of waves, to assess how these wave characteristics vary along the study area, and investigate the effects of sea level rise on these patterns.

The following steps were undertaken to achieve these objectives:

- Available metocean and bathymetric data from global models and local observations were collected and analysed
- Relevant quality controlled data were used in setting up the model e.g. grid files, boundary conditions and forcing with reasonable model parameters in two calibration periods
- The model results were calibrated against observations through graphical comparisons and error parameters which showed model skill of 90% or better for wave height at Cottesloe
- The validated wave model was simulated for a period of one year, for the three scenarios of interest; namely 2010 Mean Sea Level (MSL), 2060 (50-years, +0.3 m SLR) and 2110 (100-years, +0.9 m SLR).

Outputs from the model were generally obtained at the 3 m depth contour. The wave modelling study is documented in detail in Appendix C.

4.1 Wave Dynamics

There are a variety of processes that transform waves as they propagate from deep water to the nearshore.

Wave **refraction** is the bathymetric steering of waves. Wave celerity (speed) is faster in deeper water causing the direction of wave propagation to bend toward shallower water. Refraction typically causes convergence of waves and increase of wave height on headlands, shoals and reefs, and divergence of waves with decreased wave height in embayments.

Wave **diffraction** is the spreading of wave crests into the shadow of barriers encountered by the waves. Longer wavelengths diffract more readily than short wavelengths. Although there are few areas within Marmion reef acting as complete barriers to wave passage, the shallow depths result in dissipation of a significant portion of the incident wave energy. Waves passing between these shoals diffract into areas of reduced wave height.

Wave **scattering** from very shallow rocks and islets results in waves propagating from directions deviating significantly from their direction in deeper water; even after refraction and diffraction effects. Scattered waves typically have reduced height and period. Several subaerial outcrops along Marmion reef appear to be effective in scattering waves, resulting in waves propagating toward the southeast, despite sheltering by Marmion reef.

Wave **breaking** occurs as waves approach shallow water, either over a reef or at the shoreline. With decreasing water depth waves shoal resulting in increased wave height and steepness. When the wave height approaches or exceeds about 75% of the local water depth wave breaking will take place, dissipating wave energy.

Waves south of Trigg Is. typically break as plunging or collapsing breakers with swash run-up onto the sandy shore. North of Trigg point waves break on the relatively gentle sloped sandy beaches at the head of some embayments, on the edge of fringing rock platforms, or against near vertical rock cliffs. Where the shore is relatively steep, waves may reflect, being redirected offshore.

Together, refraction, diffraction and scattering of waves as they approach the shore of the study area results in complex wave patterns as illustrated in Figure 4-1.

The SWAN model accounts for wave generation, dissipation and propagation processes. As such refraction effects are fully represented. Diffraction effects are approximated and have been shown to perform reasonably where these effects are not extreme. However, scattering effects are not accounted for in SWAN.

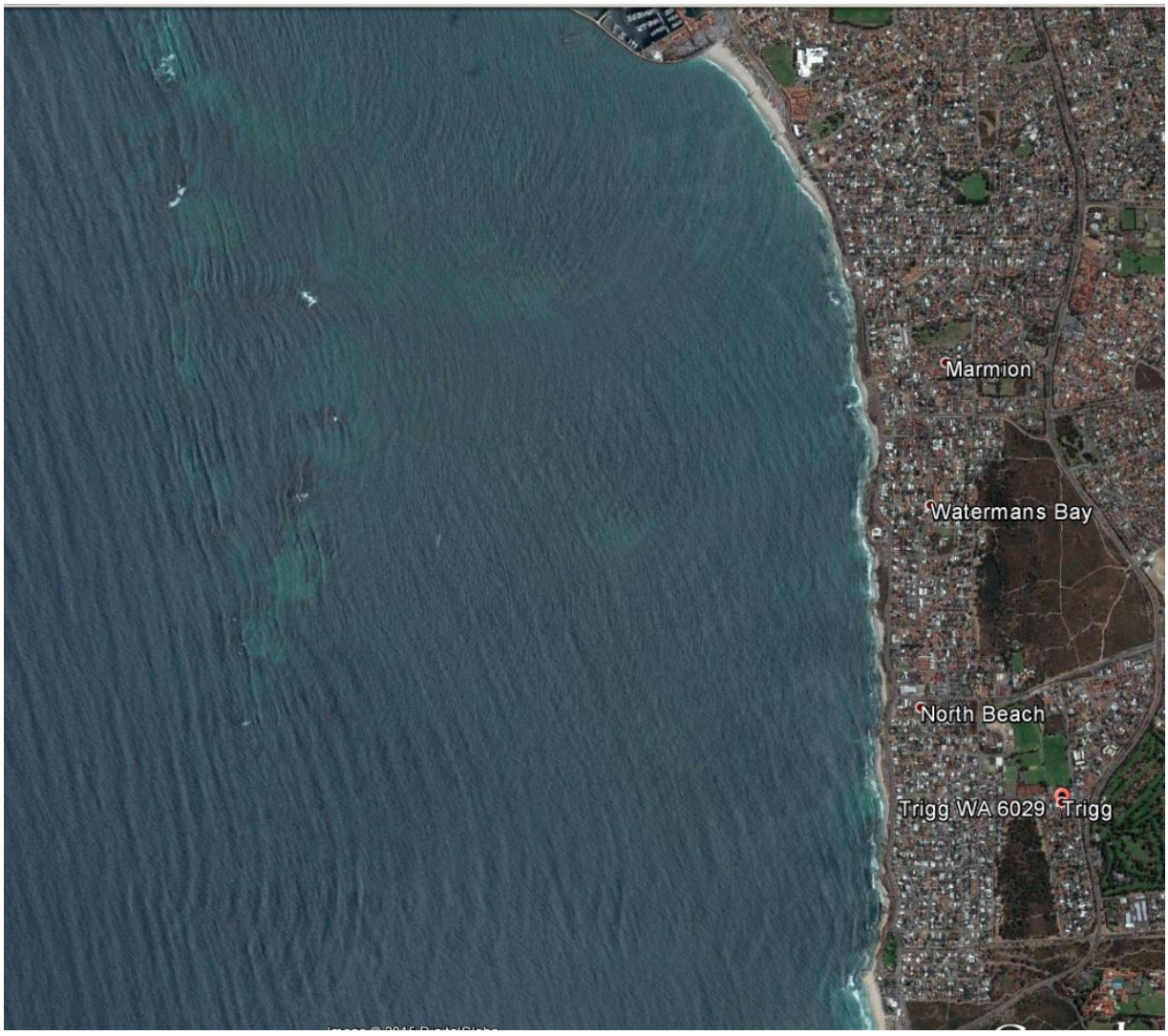


Figure 4-1: Example of Complex Wave Field North of Trigg Is. due to Wave Refraction, Diffraction and Scattering

As the offshore waves travel towards the shore, they are strongly influenced by the reefs, islands, bathymetric variation and headlands. The degree of wave focussing or sheltering at the shore depends on the path of waves as they approach the shore. The waves experienced at the coast depend heavily on the direction of waves and the nature of the bathymetry they pass over as they approach the shore. As a result, the wave condition experienced at the coast can vary significantly across the study area.

4.2 Key Outcomes from Wave Modelling

Table 4-1 provides a summary of the results from the numerical modelling results and Figure 4-2 shows the change in wave height along the study area coast for SLR of 0.3 m (year 2060) and 0.9 m (year 2110).

Table 4-1: Summary of Numerical Wave Modelling Results (BMT JFA, 2015)

Coastal Area	Mean Significant Wave Height[1] (m)			Percent change in Mean Wave Height		Percent change in Mean Wave Energy	
Sea Level Rise	0.0m	+0.3m	+0.9m	+0.3m	+0.9m	+0.3m	+0.9m
South of Trigg Is.	0.93	0.95	0.99	2%	6%	5%	14%
North of Trigg Is.	0.7	0.76	0.9	10%	29%	20%	67%

[1] Significant wave height at the 3 m depth contour

4.2.1 Wave Height Trend

The SWAN modelling indicates that there is a general trend of wave height increasing from Peasholm Street north to Trigg Is., then decreasing from Trigg Is. north to Hillarys Harbour. However, north of Trigg Is. there is significant variability with several points where wave height is notably higher than the adjacent segments of shoreline (Figure 4-2). Specifically, there is a local wave height increase at the north end of Trigg Beach, with a rapid decrease in wave height north of Trigg Is. There are also local peaks in wave height at North Beach Road and Hale Street (South of the Marine Lab). These peaks coincide with points of converging wave directions as the result of refraction and penetration of waves through gaps in the Marmion reef. Variation in the direction of offshore waves is expected to result in these convergence points shifting northward and southward to some extent.

From Scarborough the mean wave height increases north to Trigg Is. However, this trend is much less significant for the highest 1% of waves.

In general, the increased water levels due to predicted sea level rise can be expected to result in reduced dissipation of wave energy by bottom friction and breaking over reefs. Intertidal reef presently acting as an intermittent barrier to waves will be expected to allow the transmission of more wave energy from the deep water to the coastline. This will result in larger wave heights on the lee side of reefs and dissipation of more wave energy at the shoreline. This trend is reflected in results from numerical wave modelling (BMT JFA, 2015) which indicates an increase in mean significant wave height (50% exceedance) of 2% and 6% for sea level rise of 0.3 m and 0.9 m, respectively for the study area south of Trigg Is, compared to increases of 10% and 29%, respectively for the study area north of Trigg Is.

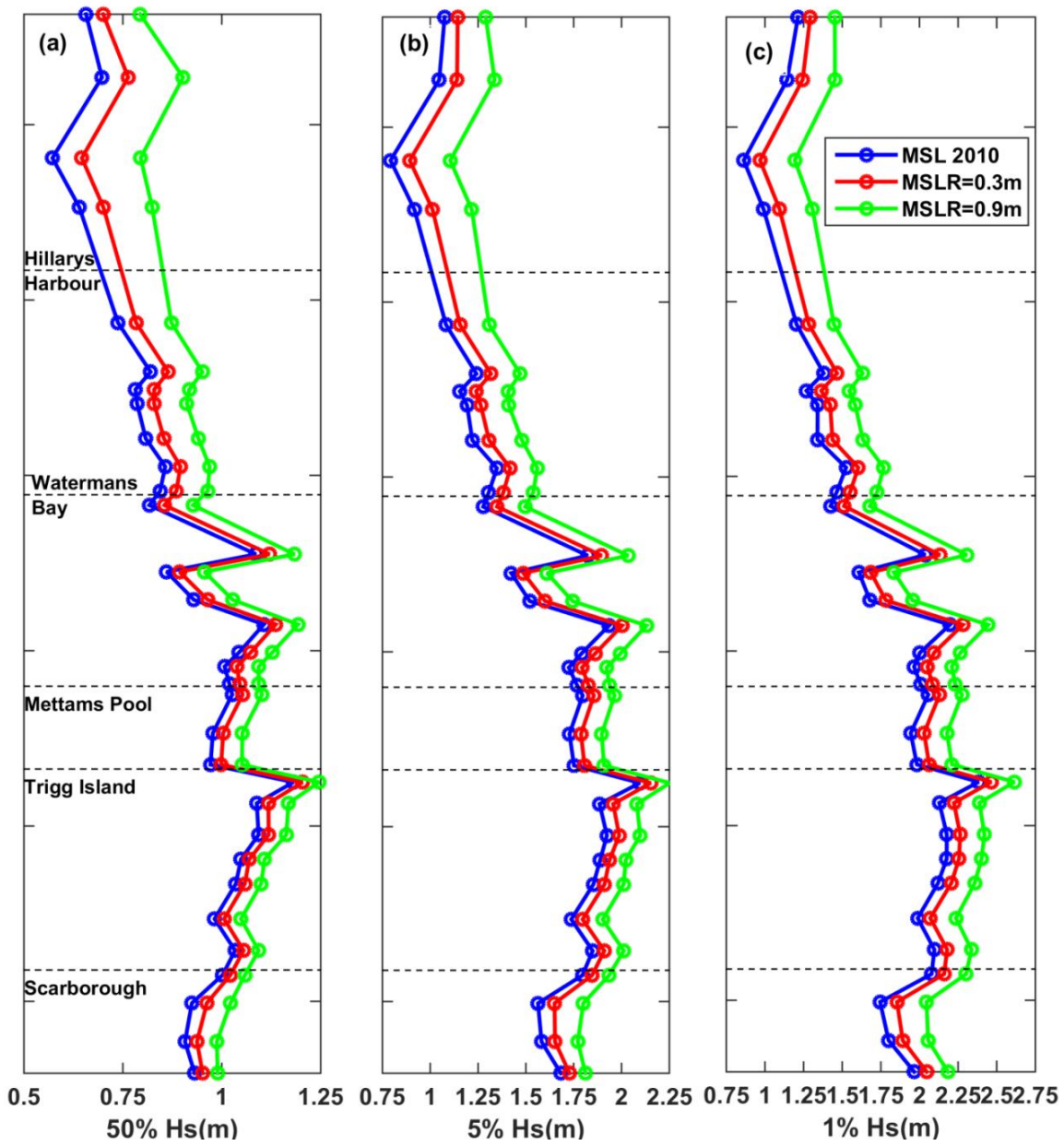


Figure 4-2: Modelled Significant Wave Height (Hs) for Fixed Exceedance Probabilities, for Present MSL, and Sea Level Rise of +0.3 m and +0.9 m. Hs for Exceedance Level of (a) 50% (mean wave height), (b) 5%, and c) 1%

4.2.2 Wave Period Trend

The mean wave period was influenced by both swell and sea waves.

Mean wave period across the study area is generally 6 seconds or less indicating the dominance of locally generated sea waves. Mean period for the largest waves is clearly swell dominated with periods typically between 9 and 13 seconds (Figure 4-3). Penetration of swell waves appears to diminish somewhat north of Watermans Bay. In the sea level rise scenarios the mean wave period decreased about 0.5 seconds in the southern area and increased by a similar magnitude in the northern area. For the largest 1% of waves, the mean wave period decreased about 0.5 seconds across the whole study area as a result of a greater proportion of short period wave energy being transmitted over Marmion Reef due to increased water depth.

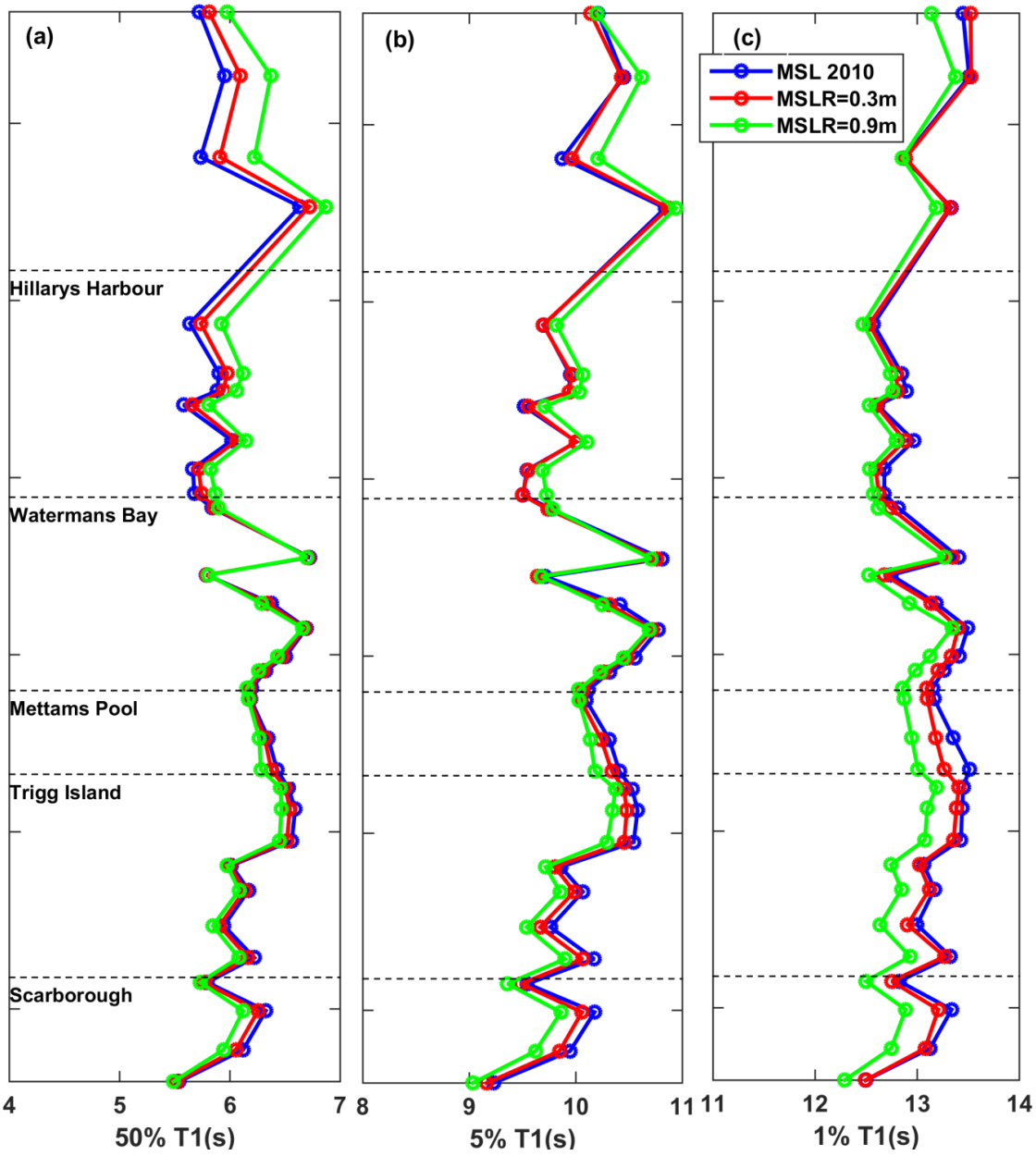


Figure 4-3: Modelled Mean Wave Period (T1) for Fixed Exceedance Probabilities, for Present MSL, and Sea Level Rise of +0.3 m and +0.9 m. T1 for Exceedance Level of (a) 50% (mean wave period), (b) 5%, and c) 1%

4.2.3 Wave Direction Trend

Transformation of swell waves across reef bathymetry results in a general reduction of wave height north of Watermans Bay and also a turning of wave direction toward the north between Trigg Is. and Hillarys Boat Harbour. This variation in swell wave height and direction is evident in numerical wave modelling results and also aerial photos as shown in Figure 4-4. The effect of Marmion reef on variation of wave height and direction within the study area is most notable for swell waves and sea waves from the west and northwest (during storms). The effect of Marmion reef on direction and height of waves driven by local winds becomes progressively less as the wind direction becomes increasingly southerly.

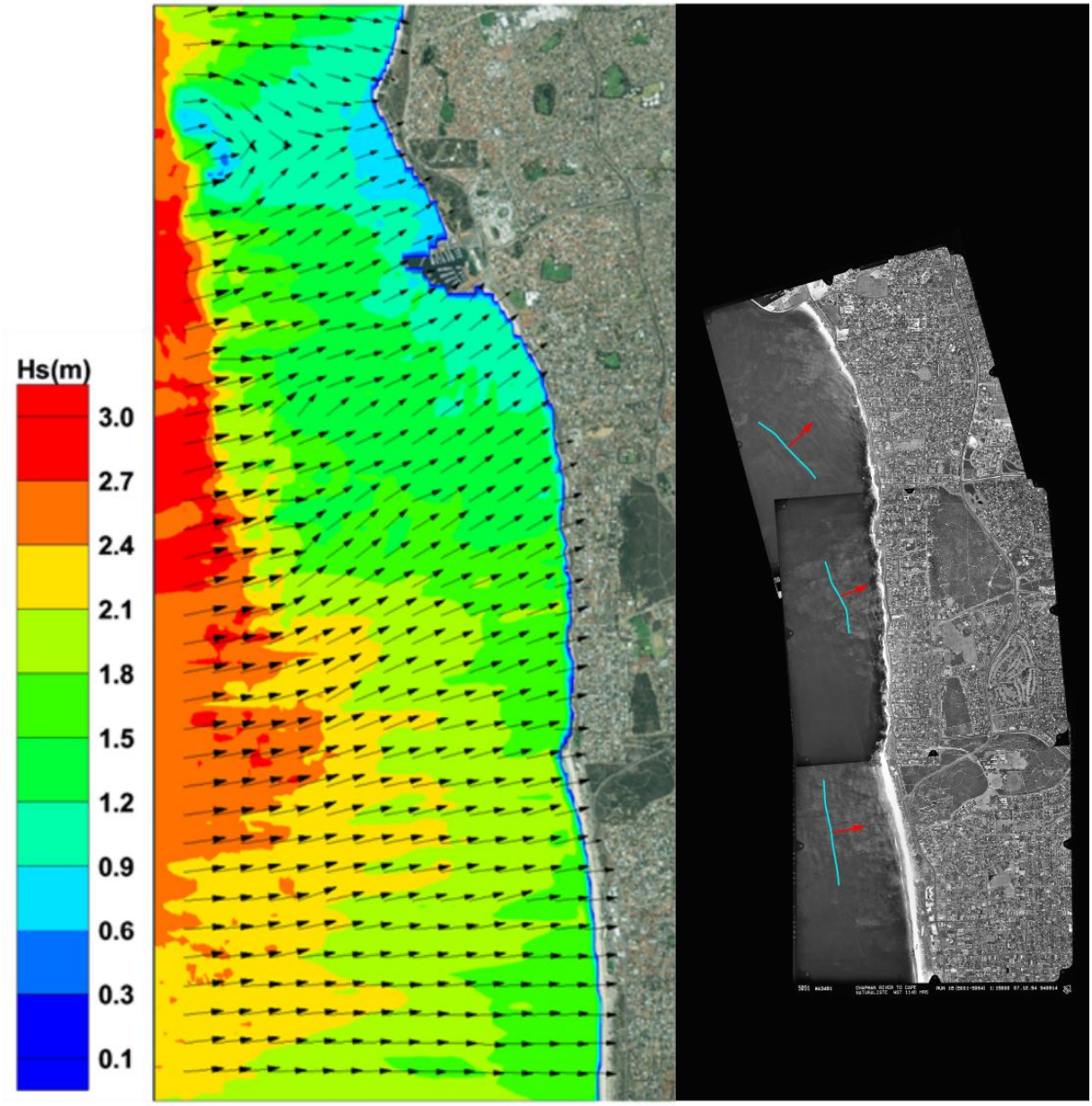


Figure 4-4: Variation in Wave Height and Direction Due to Refraction/Diffraction over Marmion Reef. Left: Example of Modelled Significant Wave Height and Direction on 23/07/2013. Right: Wave Crests and Propagation Direction Digitised from Aerial Photos (7/12/1994)

Since longer period waves are refracted more than short period waves, increased water depths over reefs due to sea level rise will reduce the refraction of swell waves somewhat. However, the change in water depth due to sea level rise is small in comparison to typical wave lengths so changes to refraction are not expected to be significant.

Increase in sea level may also reduce the wave scattering effect of some intertidal reef areas.

Where bottom friction, wave breaking or direct barriers to wave propagation give rise to wave diffraction, the increase in sea level is expected to see increased transmission of waves across these areas leading to reduced wave diffraction.

Overall, the primary effect of sea level rise in relation to refraction, scattering and diffraction is that the inshore wave field north of Trigg Is. may see some reduction in the spatial variability of wave direction.

The above discussion on effects of sea level rise on refraction, diffraction and scattering is consistent with the results from wave modelling with a general increase in wave heights but based on the wave modelling there was no observable change in the alongshore trends in wave heights or positions of wave height maxima for the +0.3 m and +0.9 m sea level rise scenarios.

As a result of sea level rise the increased water depth over reefs is expected to result in reduced attenuation of waves and reduced wave breaking. This may see a reduction in wave pumping, the amplitude of seiching and generation of long period waves as more wave energy in the gravity band is dissipated directly at the shoreline.

5 GEOMORPHIC FRAMEWORK

This section discusses in general terms the processes considered to govern the shaping of the CoS coast based on the available data analysed, reviews this in the context of the detailed offshore bathymetry and changes, and interprets how these processes may be affected by sea level rise using a conceptual framework of the coastal system.

5.1 Sediment Cell Hierarchy

The sediment cell hierarchy developed for the Vlamingh coast (Stul et al. 2007; Stul et al. 2015) has been used as a reference framework for description of both observed historic behaviour, and in response to projected changes. The hierarchy was developed to support decision-making at relatively large temporal and spatial scales, and was built through identification of coherent coastal behaviour, as evidenced by coastal landforms. Sediment cell definition considers that there are strong relationships between coastal landforms, the materials that comprise them and the environmental forcings that shape them, with a hierarchical structure developed to support interpretation at multiple spatial and temporal scales.

The applicability of a hierarchical geomorphic framework to assessing coastal response to sea level rise has been presented for the southwest region of Western Australia and the Pilbara (Eliot, 2013). Such a framework is intended to provide a more robust approach to projecting coastal change than the widely used approaches of assuming either (i) uniform coastal response; or (ii) establishment of a new equilibrium cross-shore profile based upon ambient wave conditions.

The Stirling coast bridges two secondary sediment cells within the larger Fremantle to Pinnaroo Point primary sediment cell, and effectively contains four tertiary sediment cells. The coastal dynamics of each tertiary cell differ due to the geomorphic structure within each cell, although sediment exchange occurs over cell boundaries, albeit providing varied impedance. Mudurup Rocks and Trigg Is. reef system provide substantially greater transitions of sediment transport behaviour than the more subtle boundaries at Empire Avenue, Brighton Road and South Sorrento (refer Section 2.1.2 and Appendix A).

Table 5-1: Sediment Cells Framework Relevant to Stirling Coast

Primary Cell	Secondary Cell	Tertiary Cell
F. South Mole Fremantle to Pinnaroo Point	27. Trigg to Pinnaroo Point	c. Hillarys Marina to Pinnaroo Point
		b. South Sorrento to Hillarys Marina
		a. Trigg to South Sorrento
	26. Mudurup Rocks to Trigg	d. Brighton Road to Trigg
		c. Empire Avenue to Brighton Road
		b. North Swanbourne Pipe to Empire Avenue
		a. Mudurup Rocks to north Swanbourne pipe
	25. South Mole Fremantle to Mudurup Rocks	b. Leighton salient to Mudurup Rocks
		a. Rous Head to Leighton salient

With the aim of identifying the predominant coastal landforms susceptible to sea-level rise and any restrictions to sediment transport, the various geological, metocean and landform characteristics described earlier in this report were analysed in relation to the following key characteristics, from regional to local scales:

- Metocean processes driving coastal landform development (coupling between landform and seabed)
- The capacity of geological structures to retain sediment
- Sediment supply from marine or terrestrial sources.

The results of this analysis at regional and sediment cell-scales are illustrated in Figure 5-1. The following subsections discuss interpreted changes to these processes and landforms in response to sea level rise.

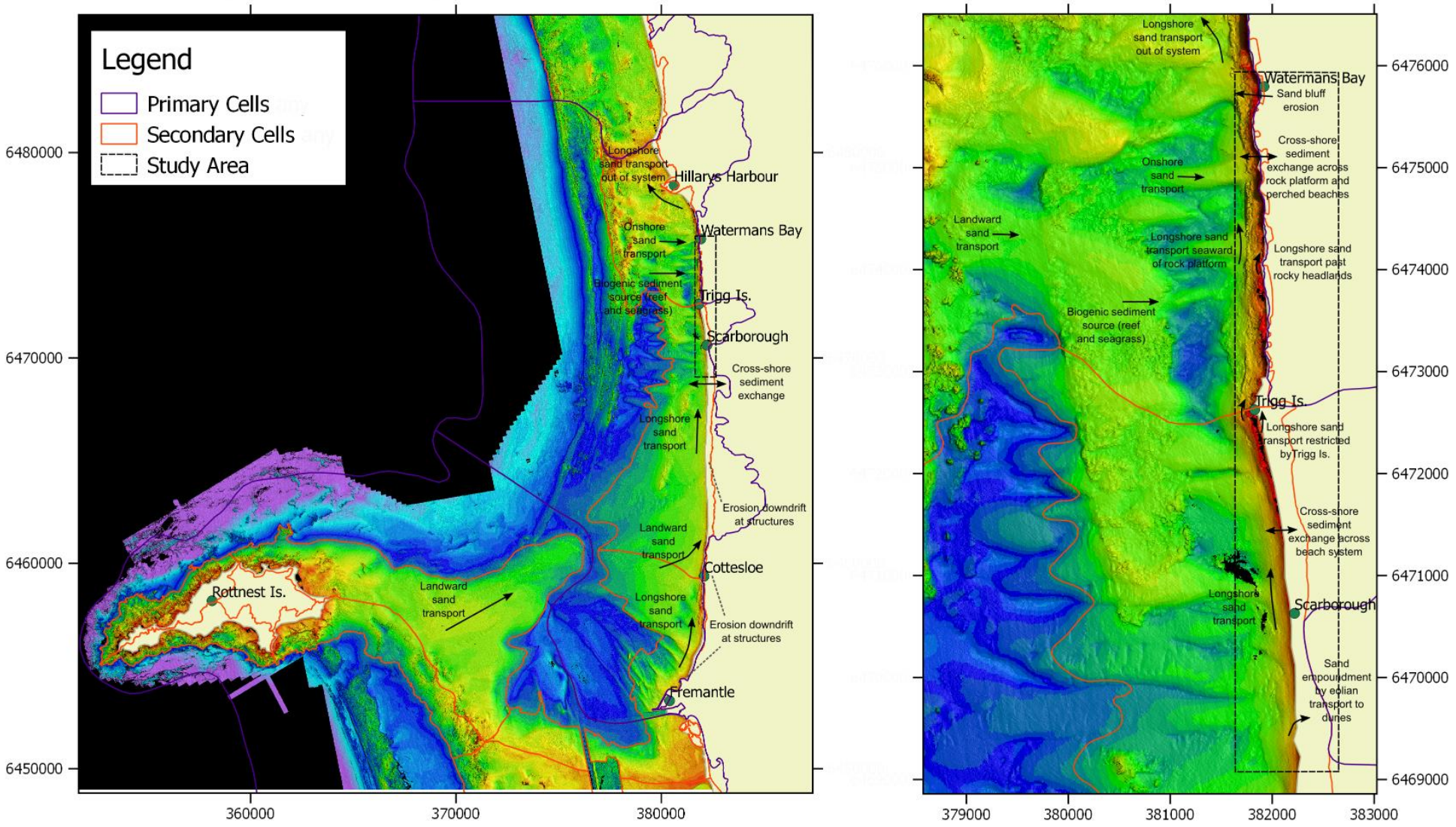


Figure 5-1: Interpretation of LADS Bathymetry between Fremantle and Hillarys Harbour

5.1.1 Primary Sediment Cell Influences

As discussed in Section 2.1.1 the presence of multiple reef systems is a critical factor influencing the coastal evolution over millennial time scales. Regional behaviour suggests that sediment availability was originally much higher, with relict features in the lee of nearshore reef chains.

The main inputs into the primary cell include sediments from the Garden Is. reef chain (alongshore) and Rottnest Is., including limestone erosion and biogenic productivity. It is unclear what the proportions are for relict and modern sediment supplies.

The Swan River is the main fluvial inlet for the region but provides little sediment input into the coastal system (Searle and Semeniuk, 1985). The long-term net northward sediment transport reflects the dominance of persistent southwest seabreezes is occasionally punctuated by short-term reversals during periods of more energetic northerly winds. Between Fremantle and Hillarys Harbour the longshore transport is interrupted at several points; the natural and man-made structures at Mudurup Rocks, Cottesloe and the two rock groynes at City Beach.

The whole primary cell coast is subject to stresses which provide a tendency for net northerly sediment transport, comprised of mainly northward transport during summer and variable conditions during winter.

5.1.2 Secondary Sediment Cell Influences

The secondary cells can largely be considered to be discrete.

Seasonal forcing effectively results in beach ‘rotation’ over the whole cell, although it occurs as a set of smaller rotations largely corresponding to the tertiary sediment cells (Masselink and Pattiaratchi, 2001).

Historical analysis has demonstrated significant accretion on the southern side of the south cell and significant accretion on the northern side of the north cell, with a smaller volume of erosion focused on the City Beach area (Kempin, 1953; Bowyer, 1987).

Behaviour of the southern cell is strongly related to the landward movement of dredge spoil, which resulted in substantial accretion on Port and Leighton Beaches. This supply has subsequently been isolated through construction of the Rous Head facilities.

Transfer from the south cell to the north cell is impeded by Mudurup Rocks, which allow only a small portion of the seasonal rotation to result in sand bypassing.

The northern cell has exhibited a progressive increase in the total volume of beach sediment, although this has not been evenly distributed, with large accretion along Scarborough and Trigg, but mild erosion along Floreat and City Beach.

Features characteristic of cross-shore sediment transport occur between Hale Road and Scarborough. These are considered likely to be active over long-time frames and may potentially contribute a small volume of sediment supply to this section of coast.

5.2 Long Term Bathymetry Change

On the timescale of decades, sediment feeds onshore from deeper sand banks migrating slowly shoreward, and from biogenic sources (reefs and seagrass beds). This movement of large benthic sand features is demonstrated by a comparison of bathymetric data along the metropolitan coast spanning 30-years. Hydrographic soundings compiled to characterise the bathymetry circa1978 were compared to LADS bathymetry data from 2009 (Figure 5-2). It is important to note that the differences in bathymetric depth rely on both data sets having a reliable and common vertical datum. The earlier data set is compiled from numerous independent hydrographic surveys with varying datums. As such the data is generally considered to be less accurate and reliable than the 2009 LADS data. Nevertheless, within approximately 2.5 km from the shore of the study area, the differences show spatially coherent changes in depth considered to be real. Typical differences over the 30-year period are between 0.4 m to 1 m, corresponding to a rate of change between 1mm/yr and 3mm/yr. This synoptic view of the bathymetric change over three decades show some complexity which is subject to interpretation.

5.2.1 South of Trigg Island

The presence and magnitude of movement for sand banks appears to increase progressively from south to north along the study area. South of Trigg Is. there are three main banks. Movement of this sediment in deeper water (offshore) is likely to be primarily due to wave orbital motions associated with longer period swell and larger storm waves rather than near-bed mean currents. Closer to shore in shallower depths sediment motion will become increasing influenced by shore-parallel mean currents driven by wind and waves. Consequently, migration direction in deeper water is expected to be dominated by drift in the direction of wave propagation, whereas closer to shore sediment movement becomes progressively more energetic as a combination of cross-shore wave motion and longshore current motion.

Approximately 1 km north and south of Scarborough Beach there are broad areas within 500 m from shore indicating a deepening of the seabed by 0.5 m to 1 m. The difference plot indicates onshore migration of a sand bank extending shoreward from the gap in the Spearwood Ridge toward Scarborough Beach. These observations are consistent with a trend of accretion at Scarborough described further in Section 0. However, they point toward the gradual depletion of onshore sediment feed between Peasholm Street and Scarborough Beach.

South of Peasholm Street there is no indication of accretion trends within about 1.5 km of the shore. Rather there is a narrow band of deepening extending about 250 m offshore. This band is continuous south to the rock groynes at City Beach.

In the 1 km south of Trigg Is. there are two fingers of sand extending from the Spearwood Ridge toward the shore with indications they are migrating onshore (and possibly toward the southeast). The nearshore area between these fingers shows a longshore band of accretion widening toward Trigg Is.

Between Scarborough Beach and Trigg Is. the apparent continuity of the sand banks between the Spearwood Ridge and the mainland suggests a continuous pathway for onshore feed of sediment. The offshore end of the northern finger shows a deepening trend however the longevity of this feed is likely to be supported by biogenic sediment production along the reefs.

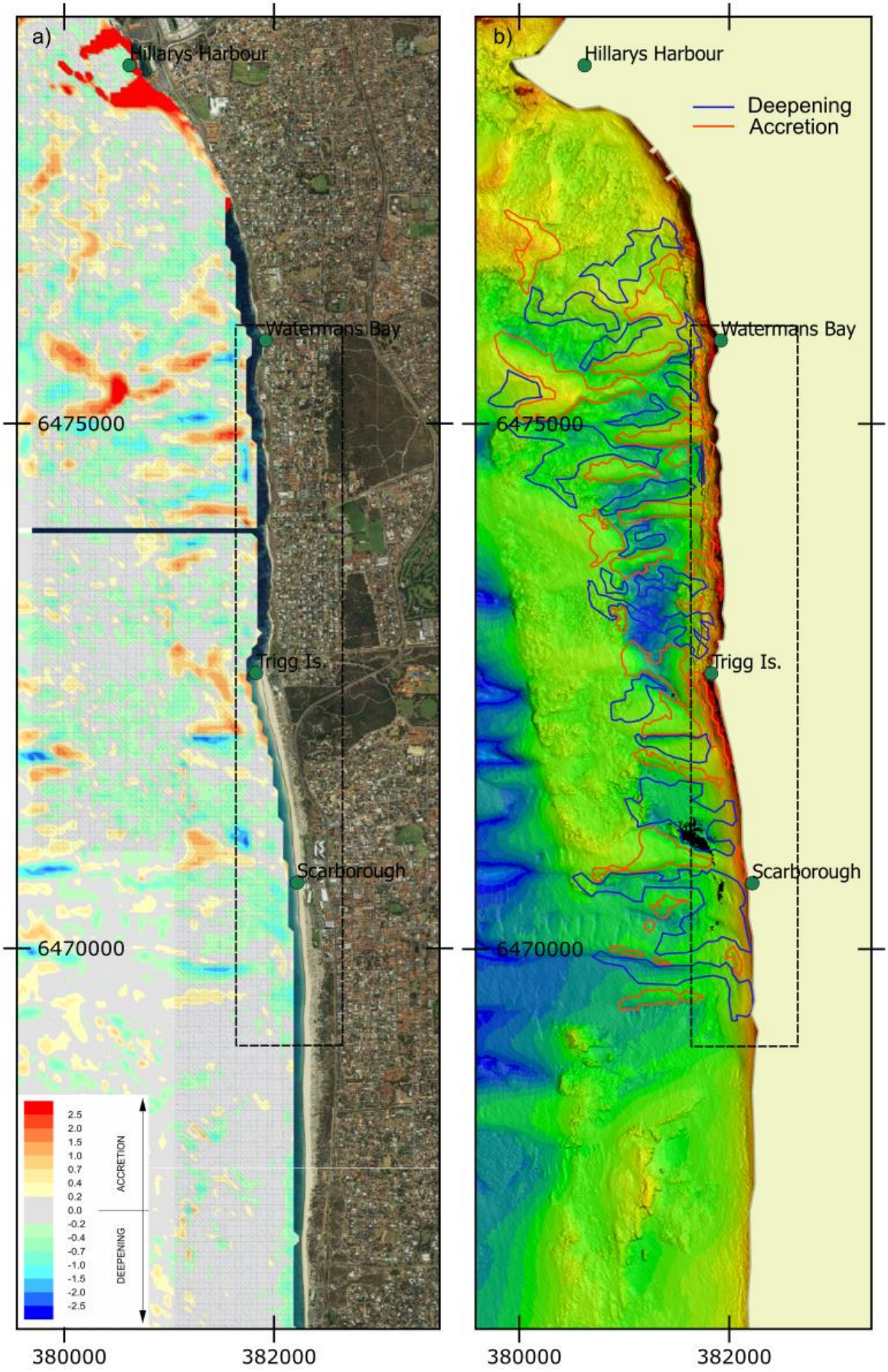


Figure 5-2: Bathymetry Change from 1978 to 2009 (30-years), Hillarys Harbour to City Beach

5.2.2 North of Trigg Island

The northward supply of sediment appears to have led to gradual accretion of a lobe of sediment seaward and northward of Trigg Is. Within about 800 m of the shore between Kathleen and Giles Streets lies a deep depression (-17 m AHD) with a deepening trend. From Saunders Street to Troy Ave several sand banks extend east-west. Connection of these fingers to either the mainland or Spearwood Ridge appears to alternate, with bands welding to the shore approximately at Beachton Street, Lawley Street, and between Mary Street and Beach Road. In these areas the rock bench at -5 m AHD appears buried forming a more or less gradual ramp from deep water to the toe of the intertidal rock platform (Figure 5-3). With the exception of Watermans Bay between Mary Street and Beach Road, these sand ramps from deep water indicate an accreting trend. Generally the seabed shows an accreting trend shoreward of the -5m AHD bench and deepening trend seaward. However, adjacent to Watermans Bay there is a deepening trend in the area between the sand banks and the nearshore zone.

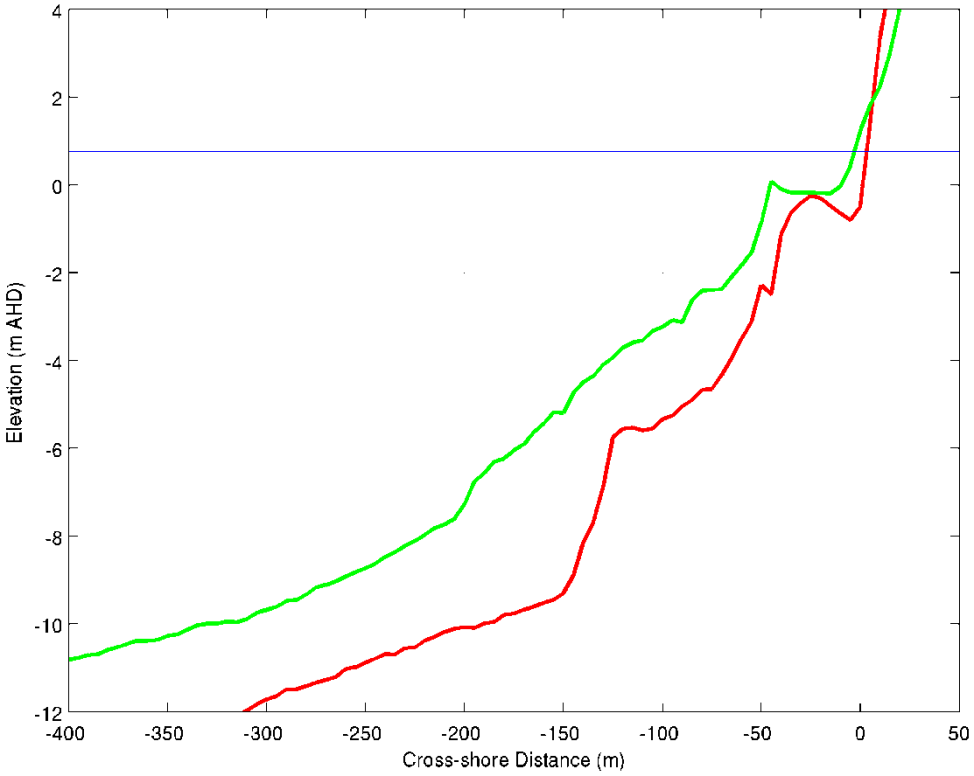


Figure 5-3: Bathymetry (LADS) Cross-shore Sections Showing the Intertidal Rock Platform and -5 m AHD Rock Bench at Margaret Street (red) and North Beach Road (green)

The patterns in deepening and accretion indicate that many of these large features are mobile. Between Hillarys Harbour and Trigg Is. the sand banks generally show a deepening trend on the west and northwest sides, while there is generally an accreting trend on the east and southeast sides, suggesting migration toward the southeast. The slopes on the south side of sand banks are generally up twice the steepness of the northern slopes, which also indicates net southward migration. Migration to the southwest suggests that the penetration of persistent long period swell over the reefs may be the primary driver, despite typically small wave height. With sea level rise the increase in penetration of ambient swell over offshore reefs may result in some increase in migration of deep sand banks and net shoreward deep sediment transport.

Limitations of the bathymetric comparison over the 30-years from 1978 to 2009 include:

- Relatively high level of noise/uncertainty for 1978 data compared to 2009 LADS
- Limited to no data within about 150 m from shore.

A second LADS data campaign would be required to allow a high resolution and accurate comparison to confirm trends and inform direction of feature migration and assist in interpreting future impacts on study area beaches.

Coastal Response South of Trigg Is.

The CoS coast south of Trigg Is. is part of the continuous sandy beach that extends from Cottesloe to Trigg Is. From 1.5 to 2.0 km offshore is a discontinuous section of the Spearwood Reef chain, with a break between Ventnor Avenue and Brighton Road. Local knowledge indicates there is a small number of rock features occurring as nearshore reefs or are occasionally exposed following severe storm erosion.

With sea level rise, the expected increase in wave energy reaching the shore in the study area south of Trigg Is. is 5% to 14%. This can be expected to contribute to an increase in the wave-driven component of storm surge which, when combined with predicted long-term rise in water level will expose the upper beach face and back beach dunes to increased wave action and dune erosion.

Sediment pathways influencing the southern study area beach include:

- The net northward longshore transport under the action of locally generated seas
- Sand mobilised into the nearshore transport system by gradual erosion of the back beach dunes
- Onshore transport from coastal sand banks.

5.2.3 Northward Alongshore Transport

From 1893 through to the 1920s over 6 million cubic metres of sand and rock were dredged during construction and deepening of the Fremantle Inner Harbour. This material was placed offshore and along the shoreline up to 1,500 m north of the harbour (DPI, 2004). Further dredged material was discharged in the area during the 1950s and 1960s. As a result of these sand sources, from 1901 to 1983 the Port beach shoreline accreted almost 200 m as a result of onshore sand migration, but since 1993 Port Beach has eroded. Studies following severe erosion at Port Beach in 1996 and 2003 conclude that this erosional trend is due to the long-term net northward transport and depletion of the onshore feed of historical dredged material. This is supported by almost continuous accretion of 1 m/year at Leighton Beach (north of Port Beach) from 1945 to 2000 (DPI, 2004).

Approximately 15 km north of Port Beach, Clarke and Eliot (1983) used a 16-year survey record (1965-1981) to confirm observations by Kempin (1953) that the 600 m length of Scarborough Beach from Scarborough Beach Road to Reserve Street was accreting at an average rate of 3.0 m/year. As noted in Section 3.4 analysis of data from 1942 to 2009 for the same beach showed that most of the net accretion occurred primarily in the period 1965-1980, with a relatively static beach width from 1994 to 2009 (Eliot and Travers, 2011).

Despite general agreement on the net-northward transport of sand along the Perth metropolitan coastline, it is unclear to what extent the history of beach accretion at Scarborough Beach is related to that at Port Beach. Also, there are several hindrances to northward alongshore transport to the City of Stirling coastline; specifically, the rock groynes at Mudurup Rocks (Cottesloe) and City Beach. Mudurup Rocks is also the southern boundary for secondary sediment cell 26 which extends to Trigg Is.

5.2.4 Variation in Beach Width

Eliot & Travers (2011) noted that more northerly wave energy resulted in recession at Scarborough beach width. Over the period 1942-2009 there were three episodes of mild beach recession at Scarborough characterised by more northerly winds. Sea level rise may not necessarily be accompanied by more frequent or energetic northerly winds but the rise in sea level is expected to reduce the attenuation of waves propagating across the reefs from the north during such events. With alongshore sediment transport being proportional to breaking wave height with exponent of 2 or more (Kamphius, 1991, CERC, 1984) the incidence of larger waves from the northwest has the potential to increase the annual southward component of alongshore transport, increasing the likelihood of periods of beach recession. This effect can be expected to become more significant with increase in sea level rise. However, the extent to which this effect will dominate northward transport, resulting in net annual recession of beaches south of Trigg Is. is unknown, but it is likely that this area will experience an increase in variability of beach width in response to individual storms, and in the subsequent recovery time.

Earlier studies on the variability of width of Scarborough Beach reported an 8.5 m beach retreat for each 0.1 m rise in mean sea level (Clarke and Eliot, 1983, Eliot and Travers, 2011). This empirical finding suggests shoreline retreat on the order of 25 m and 80 m for 0.3 m and 0.9 m sea level rise, respectively. Importantly, periods of mild beach recession were associated with periods of higher than normal northerly wind.

5.2.5 Dune Erosion

The sandy beaches from Hale Road north to Trigg Is. are typically backed by a sparsely vegetated foredune 4-5 m above present sea level abutting a larger vegetated dune standing 10-15 m above present sea level. South of Hale Road. to Cottesloe, the lower foredune is generally absent.

With rising sea level the potential for storm waves to overwash the lower foredunes (Figure 5-4) is greater between Hale Road and Trigg Beach. Overwash would lead to impoundment of sand and onshore migration of the foredune. This process also leads to a reduction in the downdrift sand supply, potentially leading to more rapid beach and dune recession rates toward Trigg Beach.

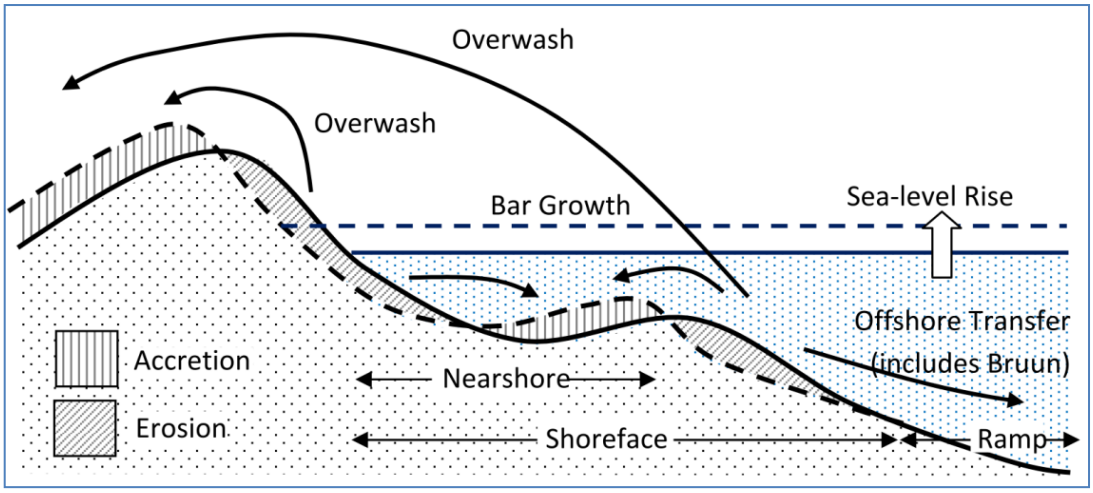


Figure 5-4: Cross-shore Response to Sea Level Rise (from Eliot, 2013)

Erosion of the dunes and potential increase in periods of narrow beach width may put remaining dune vegetation under increasing pressure due to requirements for public access to, and along the beach. Degraded dune vegetation would increase the potential for dune erosion by both wind and waves.

If rock platform, presently buried by beach sands is exposed during dune erosion or recession, this can be expected to provide a level of natural protection to the coast, dissipating wave energy nearshore and reducing the impacts of sea level rise on this segment of coast within the planning horizon. This highlights the importance of identifying the presence and extent of rock along the COS coastline.

Observations from aerial photos from 1953 and 1965 and anecdotal reports indicate there was a sand blowout immediately south of Trigg point which eroded back until limestone rock was exposed. The blowout was subsequently stabilised. The extent of rock within the dune south of Trigg Is. is otherwise unknown.

5.2.6 Onshore Transport

Onshore sand feed from sand banks is expected to be limited to the area north of Scarborough Beach.

With sea level rise some increase in the wave height can be expected for offshore swell penetrating the reefs adjacent to the study area as well as the shoals between Rottnest and Garden Islands. These longer period swell may enhance mobilisation of sediment banks in deeper water in comparison to the present short period sea waves predominant in the nearshore area.

5.3 Coastal Response North of Trigg Island

Trigg Is. marks a natural boundary between secondary sediment cells (26 and 27). Sediment transport northward past Trigg Is. exhibits significant seasonal and interannual variability and occurs as three pathways:

- Between the mainland and the islet (mainly Eolian transport)
- Around the seaward side of the islet over the intertidal rock platform
- Seaward around the toe of the rock platform (Figure 5-5).



Figure 5-5: Transport Pathways and Variability at Trigg Is. (from Eliot, 2013)

Sea level rise will increase the depth of water around the platform toe and is likely to reduce the capacity of this pathway due to reduced longshore current and wave orbital velocities near the seabed. The width of the rock platform around Trigg Is. and the islet itself will continue to dissipate most wave energy and a can be expected to maintain a tombolo on the lee side. However, storm conditions may result in wave overwash in this area with the potential to erode sand deposited in the gap during ambient summer conditions resulting in intermittently exposure of the rock platform between Trigg Is. and the mainland along with increased potential for local shoreline recession and dune erosion.

The northward transport of sand toward Trigg Is. is likely to experience increased variability, as a delayed response to significant storms resulting in dune erosion southward on the coast.

5.3.1 Sediment Pathways

North of Trigg Is. longshore sand transport pathways occur as:

- A narrow intertidal band hugging the limestone cliffs and embayment bluffs
- A sand wedge near the toe the rock platform
- Slowly migrating sand banks in deeper water.

Primary cross-shore transport pathways occur along:

- Sandy slopes of bay beaches (onshore during ambient conditions, offshore during storms)
- Gaps or channels in the rock platform (typically offshore during storms)
- Over the seaward edge of rock platforms (typically offshore during storms, onshore during low water levels)
- Across rough rock surfaces with sand being deposited in hollows well above mean water level
- Sand ramps connecting beaches with offshore sand banks.

These pathways connect to form sediment circulation routes. These routes have been generally characterised as closed cell or open cell circulation (Sanderson and Eliot, 1999). In open cells sediment is transported alongshore near the shoreline and further offshore, with significant cross-shore exchange of sediment between headlands.

Where the rock platform is narrow (abutting a cliff) or deeply incised and discontinuous, longshore transport and connectivity between perched beaches along the shoreline is low. In these areas sediment supply to the beach is primarily via deeper water seaward of the rock platform, for example, at the south end of Watermans Bay.

Where the rock platform is broader wave energy is dissipated further offshore creating a low energy environment near the shoreline conducive to accretion and gradual alongshore transport.

At the offshore edge of the rock platform the water depth typically increases suddenly by 1-2 m. As a consequence, onshore transport to beaches is primarily in areas where the rock platform is either absent or buried resulting in a gradual slope onshore, for example, at Bennion Street.

Clearly, the sediment pathways are closely linked with the morphology of the rock platform and its relationship to headlands and cliffs. As part of the Strategic Coastal Study, the presence of limestone rock was mapped along the length of the study area. The spatial extent of fringing rock platform was estimated using aerial photographs. These features along with illustrated transport pathways are shown in Figure 5-6.

While the presence and integrity of limestone rock was readily evident at most headlands north of Trigg Is., the continuity of rock features could not be confidently identified in the following settings:

- The onshore and along shore extent of intertidal rock platforms where the rock surface was buried by beach sand or dunes
- The extent of rocky cliffs where they receded into sandy and vegetated dunes; typically near the apex of perched beach embayments north of Trigg Is.
- The integrity of rocky faces where there was significant accumulation of toppled blocks of limestone seaward of eroded and collapsed cliffs.

This basic mapping of limestone cliffs and intertidal rock platform illustrates the variability in natural protective capacity of the coast north of Trigg Is.



Figure 5-6: Sediment Pathways and Estimated Extent of Rock Platform (red) and Visible Limestone Cliff (blue), from Trigg Is. (a) to Watermans Bay (d)

In some embayments there are gaps or a narrowing in the width of the rock platform. This results in alongshore gradients in wave breaking and water level setup which drives alongshore currents, typically toward the gap in the platform and often results in a current being directed offshore, capable of transporting sediment into deeper water during storm conditions.

Under storm conditions elevated water level and wave breaking may mobilise sediment on perched beaches leaving only the coarser fraction at the back of the beach while finer fractions are transported either through the gaps in the rock platform or over the edge of the platform into deeper water by return flows or reflected waves.

Accretion of perched beaches requires sediment to be transported back onshore during milder conditions. Sediment deposited at the toe of fringing rock platforms cannot be readily transported back up the platform step but is more likely to be transported gradually alongshore by wave action and ambient coastal currents. However, during lower energy summer conditions, gaps in the rock platform can facilitate onshore migration of sediment under the action of smaller shoaling waves and serve as a pathway for beach accretion.

In addition, sediment on perched beaches may be replenished where there is sufficient width of reef platform seaward of rocky headlands between adjacent embayments. Under the action of the summer seabreeze, wind and wave induced alongshore currents may transport sediment near the shoreline from one perched beach, past the headland into the adjoining perched beach.

As a consequence of increased water depth due to sea level rise, less wave energy is expected to be dissipated on the intertidal rock platforms and more wave energy will be dissipated against headland rock features and on sandy perched beaches.

The modelled increase in mean wave height of 10-20% north of Trigg Is. can be expected to increase nearshore currents and the potential for longshore sand transport. However, where transport pathways between adjacent beaches pass in front of relatively sheer rock cliffs, the increase in water depth with sea level rise may see a reduced sediment exchange between embayments; particularly if the width of fringing reef is narrow as increased wave reflection from the headland cliffs is likely to suspend some of the bypassing sediment and deposit it into deeper water at the toe of the reef.

The headland at North Beach Jetty is one example where increased water depth, vertical rock headland and very narrow/broken intertidal rock platform is likely to see reduced transmission of sediment at the shoreline between North Beach and the next beach northward.

Where adjacent beaches are joined by a gradually sloping headland, existing sediment transport pathways may simply migrate shoreward with sea level rise. Where the rock platform is wider around the headland, the capacity for these pathways to transmit sediment between embayments may increase.

In general, while sea level rise may support an increase in capacity for shoreline sand transport along some segments of the coast, the feed into these paths is typically from bay beaches. These beaches are likely to experience an increase in offshore transport during storms due to increased wave heights over the offshore reefs. Any erosion of bay bluffs may well be transported offshore, either as a rip or over the platform edge toward one of the headlands. As such, the variability in extent of perched beaches is also likely to increase.

The rate of erosion and recession of rocky cliffs can be expected to be variable. Factors affecting rate of physical weathering include the variability in degree of induration at the level of wave attack, nature of wave energy dissipation by progressive wave breaking on sloping ramps or wave slam against near-vertical cliffs.



Figure 5-7: Vertical Headland and Narrow Intertidal Rock Platform at North Beach



Figure 5-8: Sediment Pathway around Gradually Sloping Rocky Headland at Kathleen Street

5.4 Coastal Units

The study area coast was segmented into discrete coastal units based on the assessment of conditions, processes and landforms.

5.4.1 Unit 1: Peasholm Street – Scarborough Beach

Coastal Unit 1 extends from Peasholm Street to Scarborough Beach. This is a segment of straight, sandy coast backed by low foredunes, with no identified outcrops of rock. However, it is important to note that available information on the extent of limestone along the metropolitan coastline (Figure 2-2) indicates that the Unit 1 coastline is backed by limestone extending well above present sea level. If this is the case, this would be a major control limiting shoreline recession.

The unit is adjacent to a gap in the Spearwood Ridge/Reef.

Sediment pathways in this unit include:

- Net northward longshore sand transport from erosion of higher primary dunes south of Unit 1 and some erosion of low foredunes within the unit
- Diminishing onshore sand feed from deep sand banks
- Episodic transport southward from Unit 2 during storms
- Impounding of sand by overwash and recession of low foredunes.

Coastal response to SLR in this unit is likely to include:

- Dune erosion and recession of the shoreline. In the absence of rock the recession rate is expected to be more rapid compared to Unit 2. If rock is exposed by erosion then recession rates may be slowed substantially or essentially halted
- Increased variability in beach width and recovery time after erosion events
- Increased susceptibility of foredunes to erosion by wind and beach use due to diminishing vegetation cover by overwash in storms.

5.4.2 Unit 2: Scarborough Beach – Trigg Island

Coastal Unit 2 extends from Scarborough Beach to Trigg Is. This is a segment of straight, sandy coast backed by low foredunes. There are no identified outcrops of rock except for the prominent intertidal rock platform and subaerial limestone forming Trigg Is. at the northern limit of this unit. In stark contrast to Unit 1, available maps indicate an absence of coastal limestone along Unit 2 (Figure 2-2).

The unit is adjacent to the Spearwood Ridge.

Sediment pathways in this unit include:

- Net northward longshore sand transport from erosion of dunes south, and some erosion of low foredunes within the unit
- Continued onshore sand feed from deep sand banks
- Trapping of northward sand transport at Trigg Is.
- Episodic transport southward during storms from sand trapped at Trigg Is.
- Impounding of sand by overwash and recession of low foredunes.

Coastal response to SLR in this unit is likely to include:

- Dune erosion and recession of the shoreline. The recession rate is expected to be more rapid at the south end of the unit. At the north end, recession may be somewhat offset by accretion at Trigg Is.
- Increased variability in beach width and recovery time after erosion events
- Increased susceptibility of foredunes to erosion by wind and beach use due to diminishing vegetation cover by overwash in storms.

5.4.3 Unit 3: Trigg Island – Lynn Street

Coastal Unit 3 extends from Trigg Is. to Lynn Street (Mettams Pool). This segment of coastline forms a single broad rocky embayment comprised of several smaller embayments. The intertidal rock platform is almost continuous, although variable in width, and the back beach rock cliffs are almost continuous. The rock bench at -5 m AHD is exposed for the length of the unit except at the north and south ends. Offshore is a depression up to -18 m AHD.

Sediment pathways in this unit include:

- Very limited net northward longshore transport in a narrow band between Trigg Is. and the mainland. This shoreline pathway continues at the landward edge of the intertidal platform, bypassing the rocky headlands to feed the small perched beaches in each of the rocky embayments
- Transport of sand around Trigg Is., both on the intertidal rock platform and around the platform toe. This pathway splits as it encounters the rock bench at -5 m AHD, with some sand entering the depression and some continuing northward
- Cross-shore exchange of sand across the -5 m AHD bench and the intertidal platform is expected to be primarily directed offshore.

Coastal response to SLR in this unit is likely to include:

- Wave action toward the back of the beach will be moderated by wave dissipation on the intertidal platform. However, transport rate of sand near the shoreline may increase somewhat due to increased water levels. This may not be balanced by increased feed between Trigg Is and the mainland, leading to potential for depletion of perched beaches near the south end of the unit during summer
- Increase in cliff undercutting and instability between Bailey and Bennion Streets (Figure 5-9).



Figure 5-9: Stability of Lookout at Carpark between Bailey and Bennion Streets at Risk from Increased Undercutting and Instability

5.4.4 Unit 4: Lynn Street – Castle Street

Coastal Unit 4 extends from Lynn Street (Mettams Pool) to Castle Street (North Beach Jetty) and includes two main rocky embayments separated by the prominent rock headland at Hamersley Street. The intertidal rock platform is almost continuous except for the area between James and Malcolm Streets, but it is typically narrower than in Unit 3. The extent of visible rock cliffs is limited to outcrops at Hamersley Street, between Sorrento and James Streets and between Malcolm and Castle Streets. Offshore sand banks with accreting trends connect to the mainland near Saunders and Beachton Streets. These form sand ramps extending onshore of the -5 m AHD rock bench. Between these banks the -5 m AHD bench is exposed and is particularly pronounced along North Beach.

Sediment pathways in this unit include:

- Very limited net northward longshore transport along the shoreline toward Mettams Pool around the rocky headlands immediately to the south
- Longshore transport seaward of the intertidal platform and -5m AHD bench. These paths coalesce at the offshore sand bank ramp 200 m north of Mettams Pool
- Cross-shore exchange on- and offshore across the sand ramp near Giles Street
- The perched beach at Mettams Pool is most likely nourished by moderate winter events from the north resulting in southward transport from the Hamersley Street headland
- The headland at Hamersley Street is an effective barrier to longshore transport near the shoreline
- At North Beach road the offshore sand ramp almost bridges the -5 m AHD bench but sediment feed further onshore is limited by the intertidal platform. Sand feed from the deep bank is likely to be transported north and south on the -5 m AHD bench
- Cross-shore exchange between the -5 m AHD bench sediments and North Beach appears limited to the area between James and Malcolm Streets, just south of the North Beach Jetty.

Coastal response to SLR in this unit is likely to include:

- It is possible that increased submergence of the intertidal platform immediately south of Mettams Pool may result in increased northward transport near the shoreline from Unit 3.
- The narrow width of the intertidal platform north of Mettams Pool (Giles Street) and absence of visible back-beach rock is likely to see more rapid recession of the beach at this location
- Increased potential for erosion of perched beaches and back-beach dunes with sediment being moved seaward off the intertidal platform. Short term beach recovery will depend largely on sediment supply from adjacent embayments.

5.4.5 Unit 5: Castle Street – Beach Road

Coastal Unit 5 extends from Castle Street (North Beach Jetty) to Beach Road (north end of Watermans Bay). This segment of coast is characterised by almost continuous intertidal platform and, with the exception of Watermans Bay, almost continuous rock cliffs. The perched beaches to the north (Watermans) and south are separated by a broad, cliffed headland which includes the Marine Laboratory and carpark at Margaret Street.

Deep sand ramps connect to the coast at the north and south of this unit. The southern ramp shows an accreting trend nearshore, whereas the northern ramp adjacent to Watermans Beach shows a deepening trend. Between these ramps the -5 m AHD bench is pronounced and narrows around the headland at Margaret Street.

Sediment pathways in this unit include:

- Very limited net northward longshore transport along the shoreline past the headland at North Beach Jetty
- Cross-shore exchange between the deep sand bank, sand on the -5 m AHD bench and perched beaches at Castle and Hale Streets
- Predominantly offshore directed transport adjacent to the Marine Lab (supported by the accretion trend on the -5m AHD rock bench around the headland)
- Longshore transport between the north and south of this unit is predominantly along the -5 m AHD bench.
- Cross-shore exchange on- and offshore across the sand ramp near Elsie Street at the north end of Watermans Beach.

Coastal response to SLR in this unit is likely to include:

- Relatively narrow intertidal platform at the perched beaches at Castle and Hales Streets, and discontinuous rock cliffs may lead to locally enhanced erosion of the beaches and dunes at these locations
- Proximity of perched beaches at Castle and Hales Streets to onshore sand feeds may result in more rapid recovery of these beaches after erosion events
- Increased wave action along the rock headland is likely to accelerate deterioration of the block revetment adjacent to the Marine Lab
- It is likely that the present recession at Watermans will continue for some time. However, the interpreted onshore migration of the sand banks off Watermans Bay may, in the long term, see a reversal of the deepening trend off Watermans Bay.

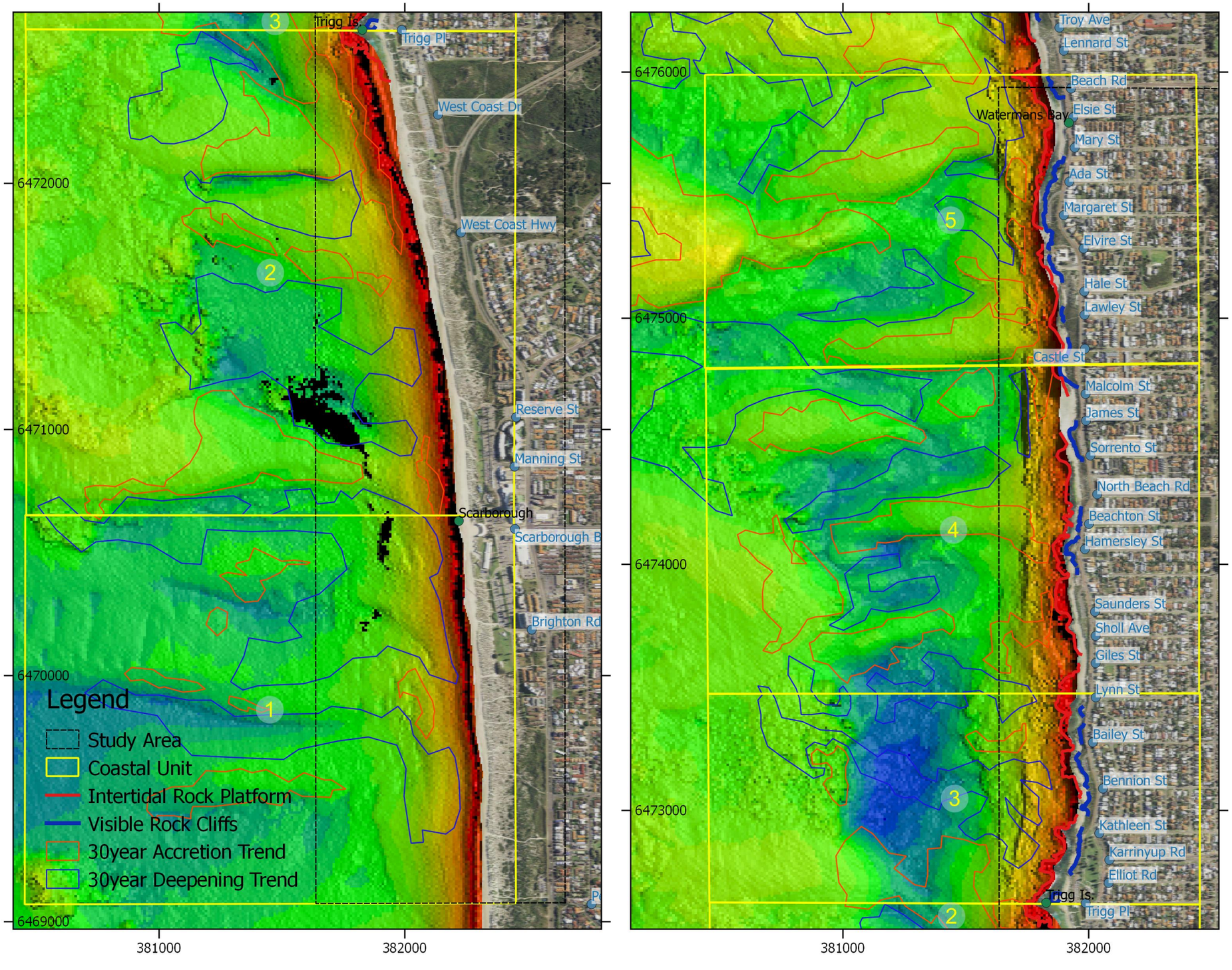


Figure 5-10: Coastal Units Based on Geomorphic Framework

6 VULNERABLE AREAS

As noted earlier in this report, this study is not a CHRMAP study. Section 7 of this report however, provides an outline of the process of hazard identification and risk assessment is conformance with SPP2.6 that will be required. However, the findings of data and literature review, and the framework of coastal processes and geomorphology for the area, provides some insight to the potential impacts along the CoS coastline and allows a basic and preliminary identification of vulnerable areas and assets within the study area as a result of sea level rise.

The Perth Metropolitan Redevelopment Authority presently has plans for significant redevelopment of facilities along the Scarborough foreshore between Brighton and Reserve Streets. This area falls within the study area however these plans and associated assets have not been reviewed as part of this study. It is recommended that redevelopment plans be reviewed during and incorporated into the CHRMAP phase. Management undertakings in development of the precinct should recognise the wider need for a CHRMAP response for the study area and may rely on work done in this study in the interim.

6.1 Risk Areas South of Trigg Island

The vulnerability to SLR along the sandy sections of coast (Coastal Units 1 and 2) is primarily associated with erosion of dunes and recession of the shoreline, as a result of increased water levels and nearshore wave energy. SPP2.6 provides guidance for determining setback distance from the shoreline with a basic allowance of 100 m setback for every 1m rise in sea level. This is more conservative than the empirical, long term observation of 8.5 m beach retreat for each 0.1 m rise in mean sea level (Clarke and Eliot, 1983, Eliot and Travers, 2011) at Scarborough Beach. As noted in Section 5.4, the actual rate of shoreline recession can be expected to vary for each of the coastal units depending on exposure to eroding forces, the erodibility of the landforms, and the supplies and losses of sediment.

Nevertheless, as a basis for a preliminary identification of potentially vulnerable areas, assets within distances of 30 m (+0.3 m SLR, year 2060) and 90 m (+0.9 m SLR, year 2110) of the present vegetation line within Coastal Units 1 and 2 (sandy coastline) were identified and are listed in Table 6-1.

Table 6-1: Potentially Vulnerable Assets - Peasholm Street to Trigg Is. (dark red indicates near-term risk, light red indicates long-term risk)

Asset	Coastal Unit	+0.3m (year 2060)	+0.9m (year 2110)
Brighton Road foreshore parking area	1		
Scarborough Surf Life Saving Club parking area	1		
Scarborough Surf Life Saving Club	1		

Asset	Coastal Unit	+0.3m (year 2060)	+0.9m (year 2110)
Scarborough Amphitheatre	1		
Scarborough foreshore park, BBQ and playground	2		
Scarborough foreshore parking area	2		
South Trigg Car Park and Beach Showers	2		
South Trigg public toilets	2		
South Trigg park and BBQ	2		
Dual use path, South Trigg to Trigg Is.	2		
Trigg Beach Car Park and outdoor showers	2		
Trigg Beach Surf School building	2		
Trigg Beach Surf Lifesaving Club	2		
Trigg Beach Surf Lifesaving tower	2		
Trigg Beach Café	2		
Parking area, Trigg Beach north	2		
Public toilets, opposite Trigg Is.	2		

The minimum distance between the West Coast Highway and the present vegetation line is approximately 120 m immediately south of the South Trigg parking area.

6.2 Risk Areas North of Trigg Island

The primary impacts of sea level rise north of Trigg Is. will be related to erosion of embayment bluffs encroaching on the West Coast Drive (WCD), dual use pathways, coastal parking areas and lookouts, as illustrated in Figure 6-1.

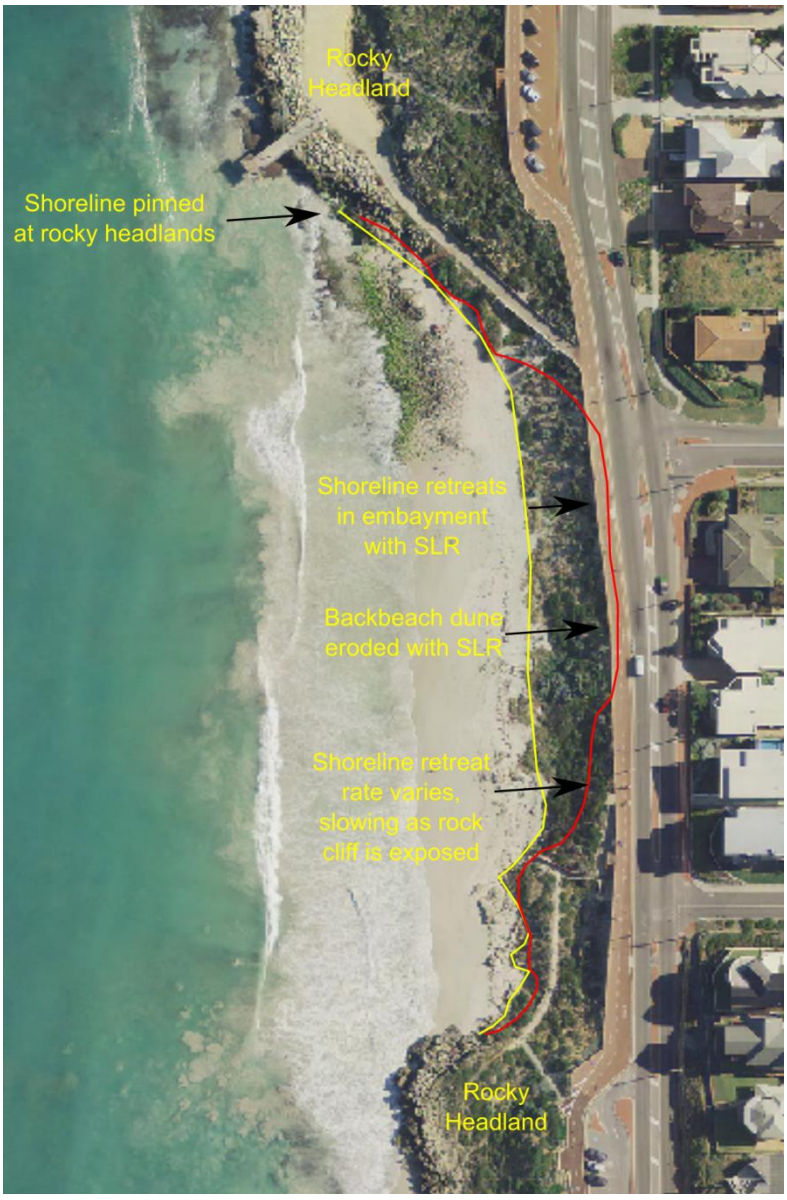


Figure 6-1: Illustrative Example of Shoreline Retreat along an Embayed Beach

Areas likely to be impacted are listed in Table 6-2. Depending on the adaptation strategies adopted, there may also be loss of beach amenity. Impacts to the Marmion Marine Park are likely to be limited. Given the rocky nature of the coast shoreline recession is expected to be less than for the sandy coastline to the south of Trigg Is.; however, there is a high level of uncertainty for the rate of shoreline recession where the extent of rock is unknown.

Table 6-2: Potentially Vulnerable Assets - Trigg Is. to Watermans Bay (red shading indicates ssets within 30 m of present vegetation line)

Asset	Coastal Unit	Comment
Trigg Beach boat ramp	3	No backbeach rock observed
Dual use path and beach access paths at Clarko Park	3	No backbeach rock observed Path within 12 m of vegetation line
Clarko Park car parking area	3	No backbeach rock observed Carpark with 17 m of vegetation line
WCH at Kathleen Street	3	No rock platform observed No backbeach rock observed WCD within 30 m of vegetation line
WCH at Bennion Street	3	No rock platform observed No backbeach rock observed WCD within 35 m of vegetation line
Carpark lookout between Bailey and Bennion Streets	3	Increased undercutting and cliff instability Within 5 m of vegetation line
WCH at Bailey Street	3	Narrow rock platform No backbeach rock observed WCD within 15 m of vegetation line
WCH between Lynn and Bailey Streets	3	Wide rock platform but rock revetment is seaward of vegetation line WCD within 5 m of revetment toe
Mettams Pool south beach access	3	Seaward of vegetation line
WCH at Lynn Street		No backbeach rock observed WCD within 14 m of vegetation line
Mettams Pool public toilets		Narrow rock platform No backbeach rock observed WCD within 8 m of vegetation line
WCH at Giles Street		No rock platform observed No backbeach rock observed WCD within 9 m of vegetation line
WCH at Sholl Ave	4	Narrow rock platform No backbeach rock observed WCD within 23 m of vegetation line
Saunders Street car parking area	4	No backbeach rock observed Car park 11 m from vegetation line
WCH between Hamersley and Beachton Streets	4	Wide rock platform but sand bag revetment is seaward of vegetation line WCD within 8 m of revetment toe

Asset	Coastal Unit	Comment
WCH between North Beach Road and Sorrento Street	4	No backbeach rock observed WCD within 31 m of vegetation line
WCH between James and Malcolm Streets	4	No backbeach rock observed WCD within 19 m of vegetation line
WCH between Castle and Lawley Streets	5	No backbeach rock observed WCD within 44 m of vegetation line
WCH at Bailey Street	5	Narrow rock platform No backbeach rock observed WCD within 50 m of vegetation line
Watermans Bay public toilets and sand bag revetment	5	Structures are seaward of vegetation line
WCH between Mary Street and Beach Road	5	Narrow rock platform No backbeach rock observed WCD within 9 m of sand bag revetment toe

6.3 Potential Hazard Zone

The detailed assessment of coastal setbacks in accordance with SPP2.6 will be a key component of the future CHRMAP process. For sandy coasts in Western Australia, the allowance for erosion over the 100-year planning timeframe for new development is in the order of 150 m. This would typically correspond to the setback distance from the present shoreline delineating a coastal foreshore reserve of sufficient width to accommodate the coastal erosion processes.

The allowance for erosion can be calculated as the sum of a number of “sub” allowances dedicated to specific processes or environmental constraints a given site. On sandy coast (Figure 6-2), the following 4 allowances are considered, including:

- Allowance for current risk of storm erosion
- Allowance for historic shoreline movement trends
- Allowance for erosion caused by future sea level rise
- Allowance of 0.2 m/year for uncertainty.

In addition, the coastal setting constraints of the project warrant considering the following 2 allowances, including:

- Allowance for erosion on rocky platform
- Allowance for erosion of fringing reefs.

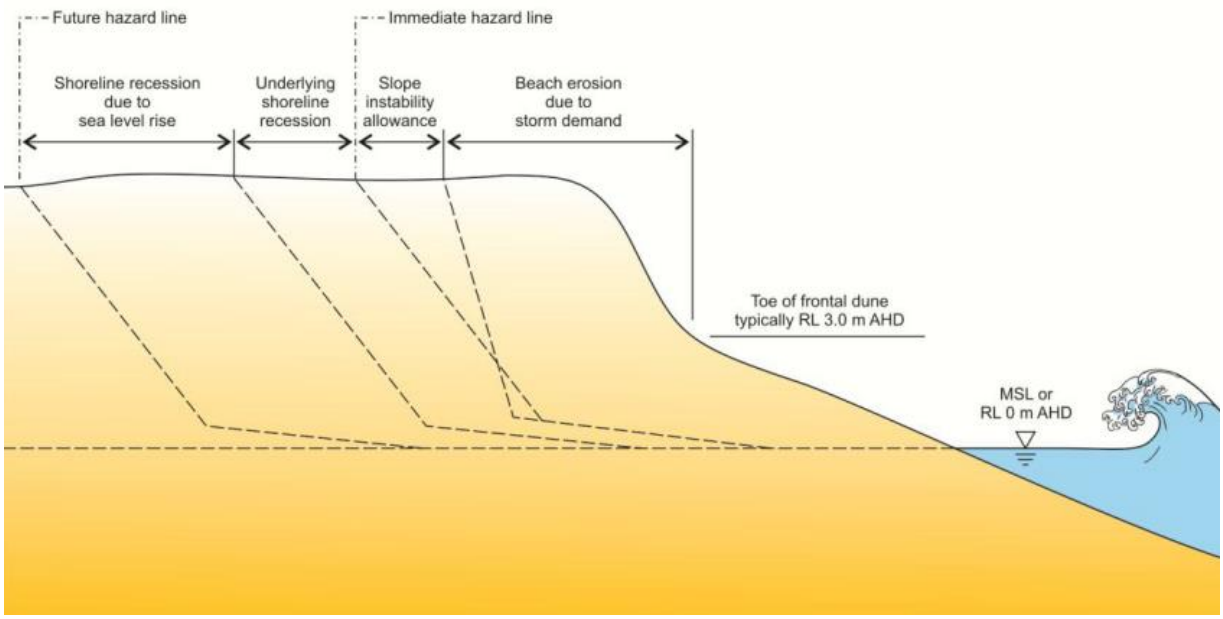


Figure 6-2: Schematic Diagram Showing the Typical Sandy Coast Erosion Hazard Allowances (as shown in Mariani et al, 2012)

Where development is allowed within the setback zone or already exists, it is important to re-evaluate the erosion allowance by considering in more detail each component of the erosion allowance and the site environmental characteristics. This would typically involve more detailed characterisation and modelling of coastal response at the site, with the aim of reducing the level of uncertainty surrounding the erosion allowance and potentially reducing the allowance itself. For the CoS, a fundamental input to re-evaluation of the erosion allowance would be demonstration of the presence of rock (elevation and durability).

A potential hazard zone extending inland 170 m from a horizontal shoreline datum (HSD, taken as +2 m AHD, based on total peak water level under a 100 ARI storm erosion event, including storm tide and wave set-up) has been shown in Figure 6-3 and illustrates the area within which assets could be considered to be at risk. This first-pass setback assessment is based on the following standard allowances:

- Storm erosion 40 m
- Historic shoreline movement trend 20 m
- Erosion caused by future sea level rise 90 m
- Uncertainty allowance 20 m.

This setback of 170 m is conservative compared to the 153 m setback (2115) adopted in a recent CHRMAP assessment for the proposed Scarborough Beach Pool development (MRA 2015) and for the rocky shorelines in the northern part of the study area erosion is less likely to reach this extent over the planning period.

Also shown on Figure 6-3 are ”hot spots”; defined for the purposes of this study as coastal segments where significant assets fall within the potential hazard zone. Table 6-3 lists potential hazard “hot spots” from south to north along the CoS sandy coast south of Trigg Is.

Table 6-3: Potential Hazard "Hot Spots" along the CoS Sandy Coast

Hot Spot	Area	Comment
1	Kay Street to Brighton Road	Brighton Reserve, kiosk and access road.
2	Brighton Road to Reserve Street	Scarborough surf lifesaving club, foreshore complex, amphitheatre (currently under redevelopment by MRA). The Esplanade and parking areas are at the shoreward limits of the projected beach recession and may come under threat particularly if historical accretion switches.
3	South of Trigg Beach	Approximately 500 m of West Coast Highway & portions of West Coast Drive are threatened in extreme erosion scenarios.
4	Trigg Beach	Trigg Beach parking areas, public beach amenities and dual use pathway (DUP).
5	Trigg Beach	Trigg Beach Surf School building, Trigg Beach Surf Lifesaving Club, lifesaving tower, Trigg Beach Café, dual use pathway. Some protection may be afforded by rock areas close to Trigg Is..

The sandy coast “hot spots” indicate the significant potential impacts at Scarborough and Trigg beaches and underline the importance of the likelihood of significant setbacks that will need to be taken into account for planning and development.

It is emphasised that this setback is provided primarily to illustrate the region along the CoS coastline within which current development planning and coastal management should be carefully considered until completion of the CHRMAP process. Actions in this zone should consider the following:

- Review or postpone development within the hazard zones for sandy shorelines south of Trigg Is. subject to development of adaptation plans to accommodate projected shoreline recession. Adaptation plans should be cognisant of the identified change triggers and the responsibility and the cost for adaptation as the shoreline recedes
- Development should be cognisant of design life and the projected loss of in the order of between 100 to 170 m of foreshore over time that is expected requiring adaptation planning for infrastructure sustainability
- Development that is proposed should be tolerant of variability in beach position including annual, seasonal and long term recession and aware that management decisions to site infrastructure in the seaward side of the hazard zone will require decisions on adaptation to manage the beach, protect the structures or ultimately may require consideration of options such as abandoning and resiting the infrastructure particularly if step jump recession responses occur
- Ongoing monitoring of beach profiles should be considered as the only meaningful measure to identify beach change trends in this segment which is highly affected by anthropogenic activities.

Table 6-4: Potential Hazard "Hot Spots" along the CoS Rocky Marmion Coast

Hot Spot	Area	Comment
6	North Beach	Beach with limited buffer and some rock but recession will impinge WCD
7	Mettams	Public beach amenities and DUP & portions of WCD are threatened in extreme erosion scenarios
8	Watermans	Public beach amenities and DUP & portions of WCD are threatened in extreme erosion scenarios
9	Lennard Street	Beach with > buffer and some rock but recession will impinge WCD
10	Bennion Street to Kathleen Street	Beach with > buffer and rock cliffs and platform but recession at the middle of the embayment will impinge WCD and threaten DUP
11	Marine Labs - Elvire Street	Limited buffer, weak rock at back of beach – even reduced erosion rates will see pathways and Building threatened
12	Minor perched beaches	A number of locations where the DUP is founded on coastal limestone and despite reduced rates of coastal erosion in the rock may be impacted

Along the rocky coast north of Trigg Is. the 170 m potential hazard zone covers major infrastructure, amenities and residential areas. However, as noted in Section 6.2, erosion of the sandy portions of this coast at the centre of embayments can see increased erosion over time. This may be less evident where there are rocky cliffs and headlands that significantly reduce shoreline recession, and rock platforms offer a level of natural protection against coastal erosion and recession. Hence, this area is marked as a dashed line because it is expected that detailed CHRMAP assessments here will significantly reduce the width of the setback north of Trigg Is. when considering the reduced erosion rates of the rocky shorelines of the Marmion coast.

The most vulnerable sections of this coast are the sandy beach embayments where infrastructure, particularly WCD, impinge on the active dune systems behind them and rock is at a lower level. Importantly, the potential hazard zone north of Trigg Is. highlights that definition of rock along that coastal segment is imperative prior to commencing the CHRMAP process with priorities being the identified sandy embayment “hot spots”. Additional lower priority sites are 10 to 12 in Table 6-4 the Bennion Street to Kathleen Street beach and Marine Labs segments where despite the presence of rock, infrastructure is threatened and further definition of the natural rock protection is required.

CHRMAP assessments will rank DUP and WCD infrastructure impacted by recession of the embayment with high values. Decisions on how to adapt to recession and the threat to this infrastructure will be required as part of that process. Additionally, the high value of residential property and the wider community values of WCD will influence management of these areas. This high value ranking will drive the need for ongoing monitoring and further detailed modelling and assessments of these priority “hot spots” that will be required to develop detailed adaptation and management actions into the future to address the impacts of projected SLR.

It is again emphasised that this setback is provided primarily to illustrate the region along the CoS coastline within which current development planning and coastal management should be carefully considered until completion of the CHRMAP process. Actions in this zone should consider the following:

- Review or postpone development within the hazard zones for sandy shoreline embayments north of Trigg Is. Subject to development of adaptation plans to accommodate projected shoreline recession. Adaptation plans should be cognisant of the triggers to identify change in the perched beaches at these sites and the responsibility and cost of adaptation as the shoreline recedes
- Review relocation of amenities in embayments to more protected headland or rock protected locations at the end of their design life in preference to refurbishing and protecting those threatened in embayed sandy beach locations with no underlying rock protection to reduce shoreline retreat
- Consider responses to beach recession at the rear of these embayments on the highly valued DUP and the possible restriction of road width in the future as part of the range of options as alternatives to coastal protection structures at pinch points on these embayed beaches
- Continue beach monitoring to better characterise perched beach behaviours.

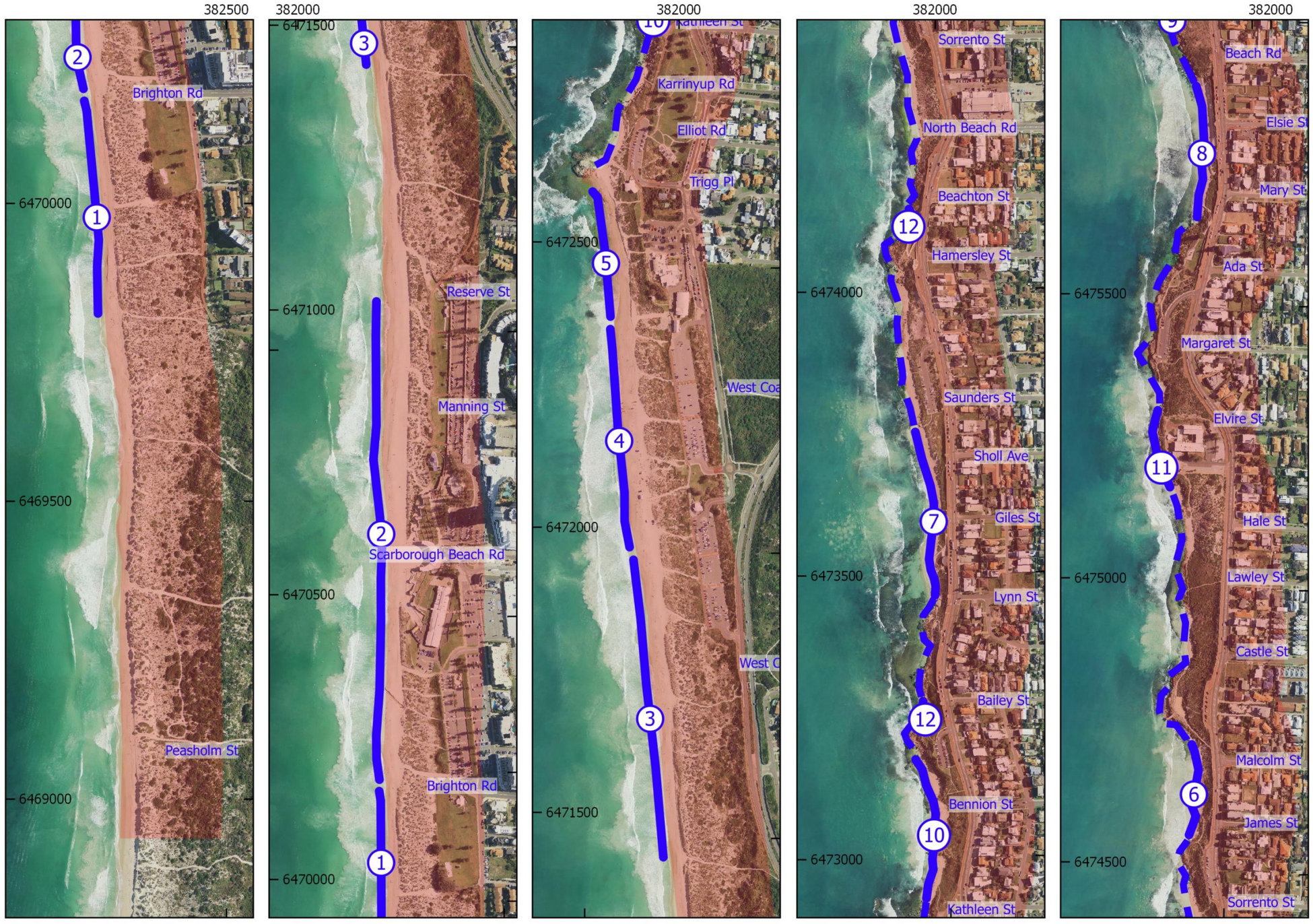


Figure 6-3: Potential Hazard Zone (preliminary 170 m setback) and Risk "hot spots" (sandy coast - solid blue line; rocky coast – dashed blue line) along City of Stirling Coastline

7 PREPARATION OF A COASTAL RISK MANAGEMENT AND ADAPTATION PLAN (CHRMAP)

7.1 CHRMAP Requirements in Accordance with SPP2.6 Guidelines

The State Planning Policy No. 2.6 State Coastal Planning Policy (SPP2.6) is a State Planning Policy made under Part 3 of the Planning and Development Act 2005.

Section 77 of the Planning and Development Act 2005 requires local governments, when preparing or amending a local planning scheme, to have due regard to this State Coastal Planning Policy where it affects its district. The local governments may decide to make a new or amended scheme consistent with particular aspects of this State Coastal Planning Policy, or include in a new or amended scheme a provision that this State Coastal Planning Policy is to be read as part of the scheme.

SPP2.6 applies state-wide and draws on and is supported by other WAPC state planning policies, development control policies and guidelines relevant to the coastal zone.

For coastal matters this State Planning Policy No. 2.6 State Coastal Planning Policy is to be viewed as the higher order and prevailing policy.

The coastal planning process recognises the complementary State, Regional and local strategic activities and initiatives across State Government planning, regional development and local government. The State planning framework is summarised in Figure 7-1.

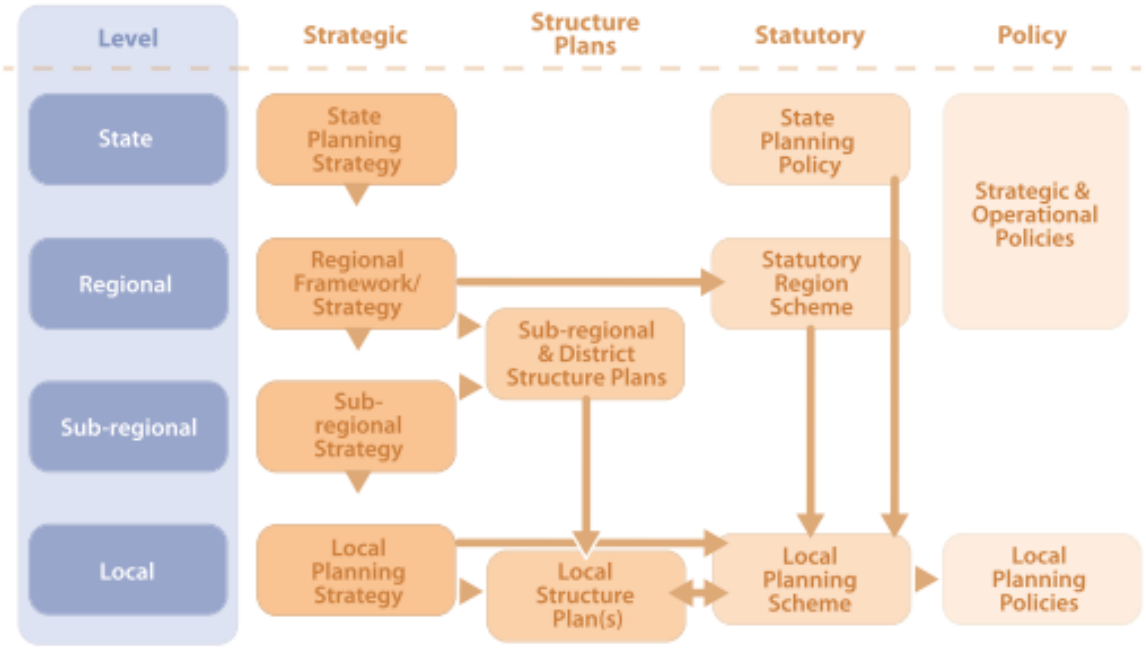


Figure 7-1: WA State Planning Framework (WAPC, 2014)

Adequate coastal hazard risk management and adaptation planning (CHRMAP) should be undertaken by the responsible management authority and/or proponent where existing or proposed development or landholders are in an area at risk of being affected by coastal hazards over the planning timeframe.

CHRMAP should include as a minimum, a process that establishes the context, vulnerability assessment, risk identification, analysis, evaluation, adaptation, funding arrangements, maintenance, monitoring and review, and communicate and consult. This process is illustrated in Figure 7-2 and highlights the fundamental role of the present Strategic Coastal Study in the overall CHRMAP process.

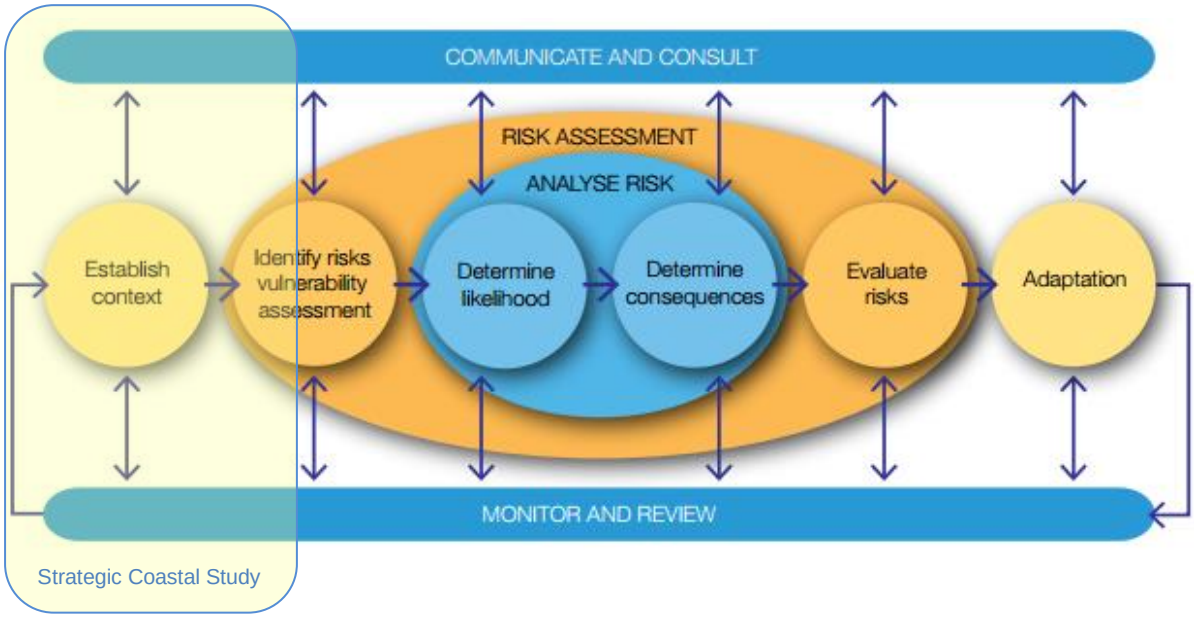


Figure 7-2: Role of the Strategic Coastal Study within the CHRMAP Process for Risk Management and Adaptation (WAPC, 2014)

The Strategic Coastal Study establishes the process-based physical context for the planning area. There are additional elements of the context to be identified through consultation with stakeholders such as infrastructure, recreational and environmental assets and values. Where the assessed levels of risk to these assets and values is considered to be unacceptable to the affected community or proposed development, adaptation measures need to be prepared to reduce those risks down to acceptable or tolerable levels. The Western Australian Planning Commission (WAPC) and the Department of Planning published guidelines which provide more detail on CHRMAP to assist statutory decision makers to:

- Consider coastal hazards and to evaluate their likelihood and the consequence for specific assets
- Identify realistic and effective management and adaptation responses to those risks
- Prioritise the management and adaptation responses.

7.2 Suggested Approach

The suggested approach to deliver the CHRMAP in accordance with WAPC guidelines (2014) is illustrated in the flowchart Figure 7-2 where the key elements of the CHRMAP are shown on the left hand panel and the corresponding key tasks to be undertaken as part of the project delivery are shown on the right hand panel.

As a minimum, the CHRMAP should include the following 6 elements:

- Establish the Context
- Coastal Hazard Risk Identification
- Coastal Hazard Risk Analysis
- Coastal Hazard Risk Evaluation
- Coastal Hazard Risk Adaptation Planning
- Monitor and Review.

Because of the CHRMAP broad reach, it is also important to communicate and consult throughout the process.

7.2.1 Establish the Context

It is important to establish a clear understanding of the following items at the outset of the CHRMAP process:

- Purpose, Objectives, Scope, Study Area
- Existing Planning Controls, Assets (Values) at risk
- Success Criteria.

In establishing this framework, the CoS planning documents must be incorporated and the unique present condition of the study area must be reflected for key asset categories including:

- Parks, reserves, beaches and other recreational assets
- Community infrastructure
- Transport infrastructure
- Water and sewage infrastructure
- Power infrastructures
- Telecommunication infrastructure
- Coastal protections infrastructure
- Residential development
- Commercial and industrial development
- Institutional infrastructures.

7.2.2 Community and Stakeholders Consultation Strategy

Approach – The Community and Stakeholders Consultation Strategy has an overarching influence throughout the CHRMAP project delivery. It underpins and facilitates greater understanding and appreciation of issues to be resolved through the CHRMAP. Some key objectives in the consultation process are to a) confirm values at risk, b) influence the adaptation option appraisal and c) get feedback on the draft strategy.

7.2.3 Coastal Hazard Risk Identification

The planning timeframe should typically be 100-years from when the CHRMAP is being prepared and the coastal hazard scenarios applied within this timeframe. Typically 3 horizons would be considered; for example, the Present, to year 2060, and to year 2110. This assists in gaining insight into the risk level over the short-, mid- and long-term, by extracting important information from key scenarios that reflect SPP2.6 requirements. In this task information from previous studies and reports is exploited to develop each component of the vulnerability assessment (i.e. Exposure, Sensitivity, Potential Impacts, Physical Controls and Adaptive Capacity).

This body of work leads to the mapping of erosion and inundation hazard zones, and highlights existing controls with their area of influence on the hazard zones. Defined hazard zones are intersected with key assets as a precursor to the Risk Analysis.

7.2.4 Coastal Hazard Risk Analysis

In the CHRMAP context (and consistent with the Australian Standard Risk Management Principles and Guidelines ISO 31000:2009) risk analysis pertains to the characterisation of two principal dimensions of the risk assessment, namely likelihood of hazard and consequence for the value at risk. For a given asset impacted by a given hazard, the combination of the likelihood rating and consequence rating translate into a risk level and its associated management priorities. It is important that the consequence rating be developed in conjunction with the CoS and Stakeholders to reflect appropriate values.

This phase of work leads to the quantification of the likelihood rating and consequence rating for each identified value at risk at various timeframes, as illustrated in

Table 7-1 and Table 7-2.

Risk and consequence ratings would be modified to align with the CoS ratings.

Table 7-1: Sample Likelihood Scale and Corresponding Hazard Scenarios (erosion shown)

Exceedance probability over timeframe	Likelihood rating (Level)	1 years (2010 to 2010, 0m SLR)	50 years (2010 to 2060, +0.3m SLR)	100 years (2010 to 2110, +0.9m SLR)
> 90%	Almost Certain	-	-	2010 1%AEP Storm
60% - 90%	Likely	-	-	-
40% - 60%	Possible	-	2010 1%AEP Storm	2060 1%AEP Storm
10% - 40%	Unlikely	-	-	-
≤ 10%	Rare	2010 1%AEP Storm	2060 1%AEP Storm	2110 1%AEP Storm

Table 7-2: Sample Consequence Scale

Consequence Rating (Level)	Social			Economical			Environmental
	Safety / Health (Physical)	Safety / Health (Psychological)	Services	Financial	Compliance	Reputational	Environment
Insignificant (1)	Negligible injuries/ First aid injuries	Temporary, no leave taken, short term with full recovery	No material service interruption	Less than $5,000	No noticeable regulatory or statutory impact	Unsubstantiated, low impact, low profile or 'no news' item	Contained, reversible impact managed by on site response
Minor (2)	Medical type injuries (</= 9 days lost time)	Sick leave, short term impact, recovery 1-3 weeks	Short term temporary interruption – backlog cleared < 1 day	$5,001 - $50,000	Some temporary non compliances	Substantiated, low impact, low news item	Contained, reversible impact managed by internal response
Moderate (3)	Medical type injuries (10 days - 3 months lost time)	Significant non-permanent, longer term illness, recovery 1-6 months	Medium term temporary interruption – backlog cleared by additional resources < 1 week	Up to $500,000	Short term non-compliance but with significant regulatory requirements imposed	Substantiated, public embarrassment, moderate impact, moderate news profile	Contained, reversible impact managed by external agencies
Major (4)	Medical type injuries (> 3 months lost time)	Longer term illness, severe trauma, extended incapacity	Prolonged interruption of services – additional resources; performance affected < 1 month	Up to $1.5M	Non-compliance results in termination of services or imposed penalties	Substantiated, public embarrassment, high impact, high news profile, third party actions	Uncontained, reversible impact managed by a coordinated response from external agencies
Catastrophic (5)	Fatality, permanent disability	Death, permanent severely disabling illness, e.g. Post-Traumatic Stress Disorder	Indeterminate prolonged interruption of services – non-performance > 1 month	More than $1.5M	Non-compliance results in litigation, criminal charges or significant damages or penalties	Substantiated, public embarrassment, very high multiple impacts, high widespread multiple news profile, third party actions	Uncontained, irreversible impact

Table 7-3: Sample Consequence Scale to Coastal Hazard Applicable to Identified Coastal Asset

Asset ID	Asset Type	Description	Function/Service	Consequence Category:	Consequence of Erosion	Inundation Consequence	Stakeholders Confirmation
1	Essential Services Facilities and corridors	Hospital School Aged Care Emergency access corridors	Essential Services Public Safety and Emergency Response	Safety / Health Services Financial Compliance Reputational	5-Catastrophic	5-Catastrophic	Confirmed
2	Residential zone	Private dwelling	Housing	Safety / Health Financial Reputational	5-Catastrophic	4-Major	Confirmed
3	Utilities and Infrastructures	Sealed Road Rail Ocean outfall Buried services Overhead services	Essential Services Water supply Wastewater discharge Power supply Gas supply Telecommunication Transport of goods Public Access	Safety / Health Services Financial Compliance Reputational Environment	5-Catastrophic	3-Moderate	Confirmed
3	Park/Reserve Area	Park Foreshore reserve	Ecosystem services Public Access	Safety / Health Environment	3-Moderate	2-Minor	Confirmed

7.2.5 Coastal Hazard Risk Evaluation

The evaluation stage of the risk assessment establishes the risk scale (rating) and high level subsequent management action resulting from the likelihood rating and consequence rating defined previously. Once the likelihood, consequence and risk rating matrices are defined, working maps (Figure 7-3) showings the key asset/values overlaid on the coastal hazards zones can be used to assign a risk rating for each identified values at risk. Then, the risk rating for each identified value at risk (or asset group at risk) can be compared and ranked by order of priority, thereby bringing to the fore top priority “hot spots”. The performance of existing mitigation measures (controls) should also be evaluated to confirm the present and future risk level of each asset under each scenario. This process establishes an “initial” baseline risk profile from when the CHRMAP is being prepared.

This task leads to the quantification of the risk rating and the prioritisation of the CoS value at risk at various timeframes.

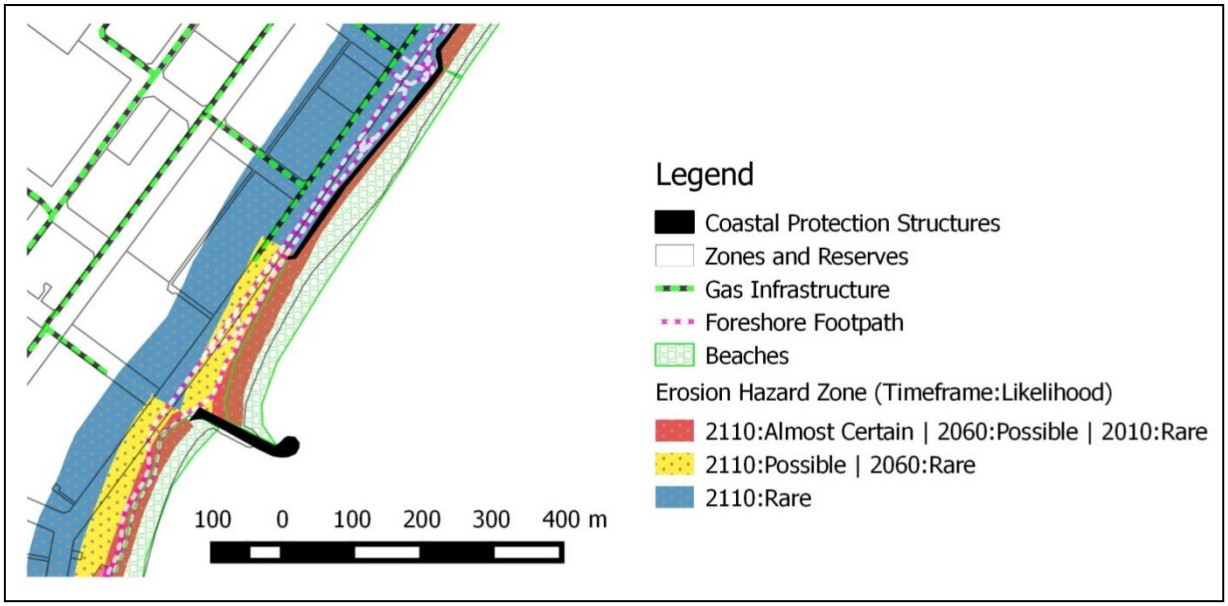


Figure 7-3: Sample Erosion Hazard Map showing Values at Risk and Protection Measures

7.2.6 Coastal Hazard Risk Planning

The adaptation planning stage is about how to respond to the identified coastal hazards risks. A suggested approach follows the following three steps:

- Step 1 - Define creative, practical adaptation measures/options which offer a range of potential future risk management options. We will consider the suitability of adaptation pathways from the four primary categories, namely Avoid, Planned or Managed Retreat, Accommodate and Protect, with due consideration for the hierarchy which underpins the concept of maintaining future flexibility. Practical adaptation options will be further defined by our team specialist engineers who have experience with civil infrastructure exposed to coastal flooding and erosion hazards. Potential options to consider may include the following, where applicable:
  - Regenerative options
    - Beach nourishment
    - Dune construction and regeneration.
  - Coastal engineering options
    - Artificial reefs
    - Detached breakwaters
    - Groynes and artificial headlands
    - Sea dykes
    - Seawalls
    - Storm surge barriers.
  - Coastal settlements design options
    - Building retrofitting and improved design
    - Flood-resilient public infrastructure

        - Raise land levels.
    - Planning options
        - Development setbacks
        - Land buy-back
        - Land swap
        - Land-use planning.

    Many adaptation actions can be incremental modifications of existing management approaches to account for the increasing risk of coastal hazard. However, at some point in the decision making process, it may be more appropriate to undertake a more transformative approach to adaptation. The options should be defined at a high level with sufficient details to enable the differentiation process during the multi-criteria assessment undertaken at subsequent option appraisal (Step 2).

- Step 2 - Clarify values and trade-offs by considering a semi-quantitative appraisal of the adaptation options against an explicit set of performance criteria. The appraisal process involves weighting criteria, scoring each option, ranking each option across non overlapping considerations, such as:
    - Residual risk – Is it successful in producing the intended result?
    - Flexibility – Is it easy to modify after implementation?
    - Reversibility – Is it easy to completely remove?
    - No regret – Is there any positive impact on asset values?
    - Decision time horizon – Does it help buy time/delay major decision?
    - Conflict with other options – Is there synergies with other options?
    - Accessibility – Does it enhance foreshore value?
    - Landscape value - Does it enhance Landscape value?
    - Recreational value - Does it enhance Recreational value?
    - Property value - Does it enhance Property value?
    - Ecosystem value - Does it enhance ecosystem value?
    - Disaster emergency procedures - Does it benefit disaster emergency response?
    - Initial cost – Is it low cost?
    - Cost of Maintenance - Is it low cost?
    - Legal/approval risk – Is the minimal approval required?
    - Financing – Can it be internally funded?

    Sensitivity of these results should also be included by testing various weighting of the criteria. This process leads to a systematic comparison of the potential alternatives and provides the rationale behind the selection of the preferred options to be further detailed in the implementation plan (Step 3).

- Step 3 - Develop a practical implementation plan for the preferred options. The plan should build on the high level description of the option provided in Step 1 and its subsequent appraisal characteristics provided in Step 2. It provides further details on:
  - Proposed action
  - Resource requirements
  - Responsibility
  - Timing
  - Performance measure
  - Reporting and monitoring.

  This task leads to the determination of practical management actions derived from a logically correct reasoning and forms the basis of a Management and Adaption Plan which should be reviewed and refined in consultation with community and stakeholders.

7.2.7 Monitor and Review

An adaptation pathway approach allows for evaluation, monitoring and learning at regular intervals. This is especially appropriate for incremental adaptation actions. Insights gained from evaluation and monitoring - and from the consideration of new or improved scientific knowledge as it develops - then allows for modification of the pathway or, if appropriate, the switch to a more transformative adaptation pathway.

Regular monitoring and review of CHRMAP ensures that each step of the process and its outcome remains relevant and aligned with quality decision dimensions, including:

- Appropriate Frame
- Meaningful, reliable information
- Clear values and trade-offs
- Creative doable alternatives
- Logically correct reasoning
- Commitment to action.

Throughout the CHRMAP delivery, it is important to engage with key stakeholders and seek formal reviews of deliverables by a Reference Group with appropriate representation from the COS and external stakeholders. This provides a direct feedback mechanism to enhance the quality of the project deliverables.

7.2.8 Inherent Uncertainty

While the scientific community has established that human-induced climate change is occurring, uncertainty remains about the magnitude and extent of the impacts from these changes. Despite the uncertainty, early consideration of coastal hazards and the adaptation and management of appropriate planning responses can provide economic, environmental and social benefits, but there will usually still be significant residual risks and damage even after appropriate adaptation.

The nature of risk is such that both contributing factors namely likelihood (frequency, probability) and consequence (impacts, damages) are important. A better understanding of the risk profile can be achieved by adding any amount of information that provided incremental insight into these factors. For example, the likelihood rating can be refined by modelling of joint probability of fully coupled metocean, hydrological and climate change process, or the consequence rating can be improved by a detailed economic assessment of expected benefits and costs.

8 ADAPTATION OPTIONS

As noted throughout this report, the scope of this study is to develop an understanding of the factors affecting the CoS coastlines response to sea level rise. This work contributes to the broader context for the CHRMAP process. As such, detailed assessment of adaptation options at this stage is premature. However, this section provides an overview of adaptation pathways hierarchy and options.

Along the City of Stirling coast there are a variety of assets likely to require development of adaptation strategies. Along the sandy coast (Units 1 and 2) these include surf lifesaving clubs, Scarborough Beach amphitheatre, parking areas, paths and parks, and any future development of facilities at Scarborough Beach by the Metropolitan Redevelopment Authority. Along the rocky coast (Units 3, 4 and 5) careful consideration needs to be given to strategies for major assets such as the West Coast Highway and associated services infrastructure within the WCH corridor, and the key recreational beaches. Other elements will include car parks, beach access points, and public facilities.

8.1 Adaption Options

Potential options to consider may fall in one of the following broad categories:

- Regenerative options, including beaches, dunes, riparian vegetation and wetlands restoration
- Coastal engineering options, including a range of structures for erosion and flood control.
- Planning options, including development setbacks, buy-backs schemes, land swap and land-use change
- Coastal settlement design options, covering building and infrastructure retrofitting and design, and the raising of land levels.

A structured appraisal process is used to determine which of the adaption options will provide the greatest benefit, relative to the cost of implementing it, in treating the highest priority risks. This analysis of cost and benefits for multiple success criteria clarifies trade-offs and ensures that other coastal management objectives are not compromised by the preferred option.

8.2 Adaption Measures

The four adaptation pathways categories are described below with examples:

- Avoid – may consider elements such as:
  - requirement for disclosure of hazards/vulnerability, e.g. notification on title
  - rejecting the site and finding another
  - transferring development rights to another parcel better able to accommodate development
  - avoiding development within primary and fore dunes and low-lying coastal areas.
- Planned or Managed Retreat – may consider elements such as:
  - requirement for disclosure of hazards/vulnerability, e.g. notification on title

  - prevention of further development
  - leaving land and resources unprotected
  - demolition and removal of infrastructure as they become at risk by coastal hazards
  - applying easements or planning zones to allow for rolling change of land-use as it becomes affected by coastal hazards
  - Prohibiting high value developments and infrastructure in at risk areas in favour of low cost activities (such as recreation, grazing etc.)
  - locating major roads and key community infrastructure away from the coast with sacrificial connecting roads to vulnerable areas
  - retaining public coastal land in public ownership.
- Accommodate – may consider elements such as:
  - requirement for disclosure of hazards/vulnerability e.g. notification on title
  - preparation of emergency evacuation plans to reduce the human consequences of coastal hazards
  - applying easements or planning zones to allow for rolling change of land-use as it becomes affected by coastal hazards
  - raised buildings and infrastructure in areas prone to inundation and flooding, for which:
    - building foundations should remain intact and functional
    - habitable rooms and/or floors should be sufficiently elevated to prevent floodwaters from entering the elevated building envelope during the design event
    - utility connections (e.g. electricity, water, sewer, natural gas) should remain intact or be easily restored
    - buildings should be accessible and useable following a design-level event
    - damage to enclosures below the design flood level should not result in damage to the foundation, the utility connections, or the elevated portion of the building
  - locating development on the least hazardous portion of the site
  - combining lots or parcels
  - reducing the footprint of the proposed building, and shifting the footprint away from the hazard
  - shifting the location of the building on the site by modifying or eliminating ancillary structures and development
  - seeking variances to lot line setbacks along the landward and side property lines (in the case of development along a shoreline)
  - modifying the building design and site development to facilitate future relocation of the building
  - altering the site to reduce its risk to coastal hazards

- only permit development of temporary or low value assets
- do not permit increases in development density (rezoning/ subdivisions)
- do not permit development of high value assets (community centres, schools, hospitals)
- reduce risk to defined acceptable levels for an estimated time period
- be designed to be durable and effective for the estimated time period and/or have reasonably well known maintenance and operating costs for the design period
- indicate the anticipated response at the end of the estimated extended period when risks again approach intolerable levels
- lower portions of structures are constructed of flood resistant materials and are designed to withstand water forces
- for roads, alternative routes or other emergency contingency plans exist
- apply appropriate risk management strategies to vulnerable areas
- the design of temporary or relocatable structures, or structures that could be readily repaired or reinstated following the impacts of the likely coastal hazards.

- Protect – may consider elements such as:
  - requirement for disclosure of hazards/vulnerability, e.g. notification on title
  - implementation of a protection scheme
  - beach nourishment or replenishment
  - dune management
  - flood and sea walls
  - groynes
  - off-shore breakwaters or reefs
  - there is likely to be long-term commitment to a high level of development in the area to justify the long-term costs
  - the area will remain ultimately defendable
  - there are compelling reasons why this area rather than a less vulnerable, higher elevation areas nearby should attract continued development and occupation
  - development is located and designed so that it can be appropriately protected from risks and impacts such as inundation and coastal erosion
  - construction of coastal protective structures, or allowing space for their future construction
  - emergency management
  - Construction methods or materials that reduce the consequences of inundation and/or reduce the costs of relocation.

Further to the above adaptation options, particular consideration should be given to the following development in location outside of coastal hazard risk areas:

- Major infrastructure and services including roads, power and drainage
- Hospitals
- Schools
- Child-care
- Aged-care facilities
- Storage of hazardous or dangerous materials
- Waste disposal.

9 SUMMARY AND RECOMMENDATIONS

A broad range of environmental influences, physical processes and landform information has been reviewed and a geomorphic framework for the coastline between Peasholm Street and Beach Road has been developed. Five Coastal Units have been defined within the study area and the potential influences and responses of the coast to sea level rise has been discussed at regional and local scales for planning timeframes of 2060 (50-years) and 2110 (100-years).

Along the sandy coast, dune erosion and dune recession is expected win response to increased water level and wave action, with recession rates being higher south of Scarborough Beach (Unit 1) in comparison to the area between Scarborough and Trigg Is. (Unit 2). An increase in the seasonal and interannual variation in beach width is expected.

Along the rocky coast (Units 3, 4 and 5) mean wave height is estimated to increase by 10-20%. Embayments with low or no rock behind the perched beaches can be expected to erode and recede, potentially encroaching on the West Coast Highway in places or other structures and facilities. The amount of sand on perched beaches is expected to reduce, particularly on rock-backed beaches, and the recovery rate of perched beaches is expected to become more variable. The trend of erosion at Watermans beach is expected to continue, however there is some indication that this may reverse within the 100-year planning timeframe. In areas, undercutting and instability of cliffs is expected to increase.

9.1 Recommendations

9.1.1 Rock Investigation

The presence and extent of coastal rock in the study area is a fundamental factor in the assessment of coastal vulnerability. There were no observations of exposed rock along the sandy coast (Units 1 and 2). However, intertidal rock platform is exposed at points near Cottesloe Beach 10 km south of Scarborough Beach and available maps indicate extensive rock along Unit 1, but the absence of rock along Unit 2.

North of Trigg Is. there are several embayments with no visual identification of rock cliff at the back of the beach. In some cases the back of the beach is less than 10 m from major infrastructure. The vulnerability of this infrastructure hinges on the presence or absence of rock.

Consequently, one of the key recommendations arising from this study is that a detailed seismic investigation be undertaken to map the presence and elevation of coastal rock from Cottesloe to Hillarys Harbour. This data is considered to be an essential input to the CHRMAP process. Although the coast from Peasholm Street to Cottesloe is not managed by CoS the response of this segment to SLR will depend on the presence of rock and will affect the longshore sediment feed into the CoS coastal management area. Consequently, it is recommended that the CoS collaborate with the local governments of the Town of Cambridge, City of Nedlands and Town of Cottesloe to investigate the possibility of coordinating a regional seismic survey and a data sharing arrangement.

Specifically, the seismic survey within the CoS coastal management area should extend from Hillarys Harbour to Peasholm Street and extend from the waterline to approximately 200 m inland from Peasholm Street to Trigg Is. and approximately 100 m inland north of Trigg Is. The survey is likely to employ a combination of methods including ground penetrating radar (GPR), Multi-channel Analysis of Surface Waves (MASW) and Cone Penetrometer Testing to provide quantitative depth to any sand/limestone interface, variations in rock strengths and presence of karstic features.

9.1.2 Additional LADS Bathymetry

The 2009 LADS bathymetry has provided key data for numerical wave modelling and illuminated the bathymetric complexity within about 1 km of the shoreline. In conjunction with the compiled sounding data circa 1978, the differences in seabed elevation over the period from 1978 to 2009 provide the only observations of changes to regional benthic morphology on timescales comparable with the coastal planning timeframe.

Although the compiled sounding data has some issues with noise and accuracy it provides an invaluable baseline. New technology used for the LADS data set produces an accurate high resolution data set. It is understood that the State government is planning to collect new LADS data from Two Rocks to Geraldton early in 2016. Extending this coverage to include a band within about 2 km of the shore between Hillarys Harbour and Fremantle would provide an additional synoptic view of changes over the last 6-years. Although this period is much shorter than the 30-year interval, the vertical accuracy of the method is estimated to be <0.5 m and should allow detection of areas where the rate of change is greater than about 3-4 mm/yr.

This additional data is expected to provide greater confidence in the trends in accretion or deepening assessed so far, and provide an indication of recent changes, in the dynamic nearshore areas out to a depth of about 5 m, particularly adjacent to Watermans Bay and Mettams Pool.

9.1.3 CHRMAP Process

The next stage of the CHRMAP process is the risk analysis and development of adaptation strategies, in accordance with SPP2.6. These tasks must be undertaken in consultation and collaboration with stakeholders to clearly identify the values and constraints to ensure acceptable or tolerable outcomes are achieved.

As noted earlier, the completion of a detailed survey of the extent of coastal rock is considered essential as a key input into the risk analysis.

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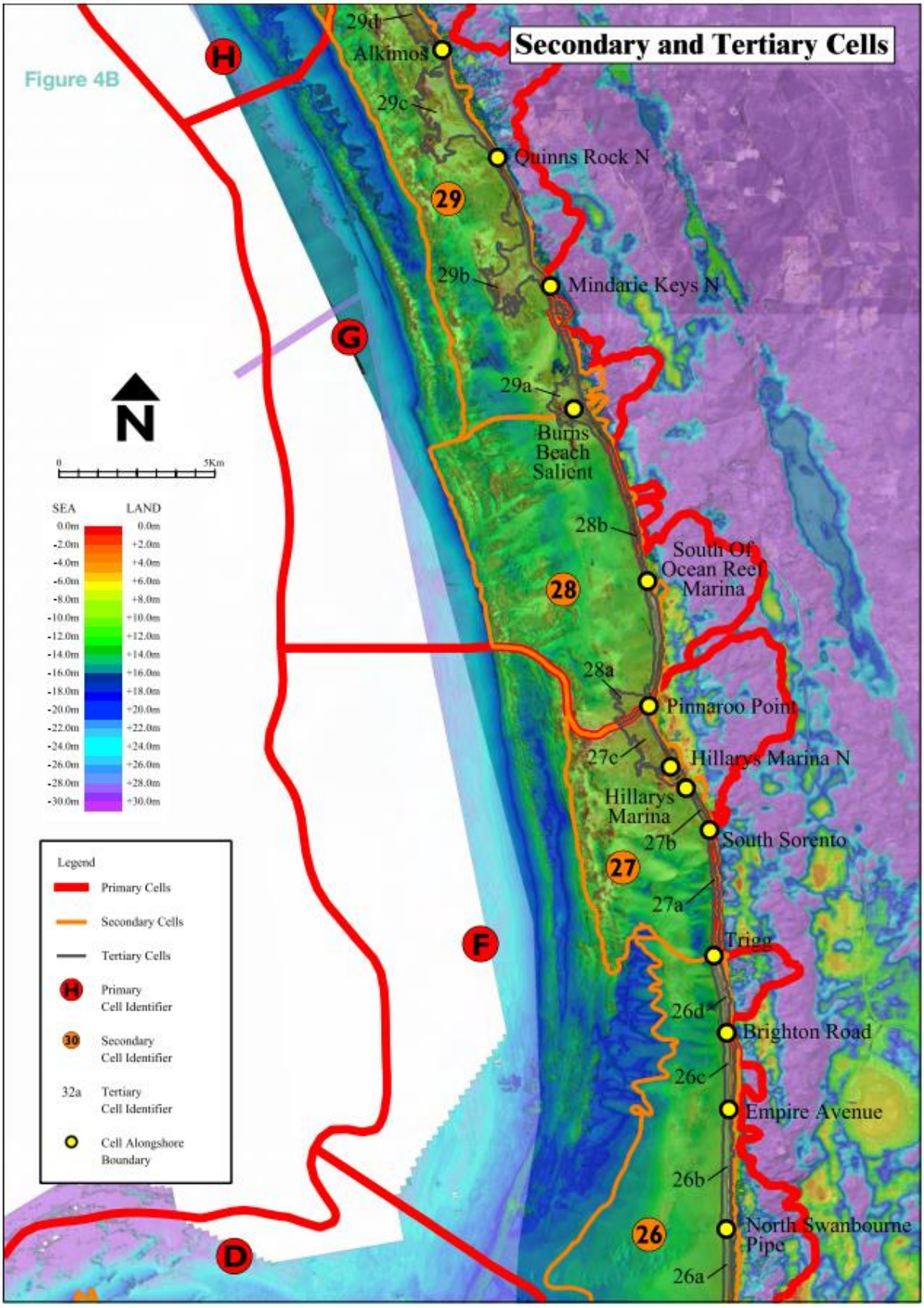
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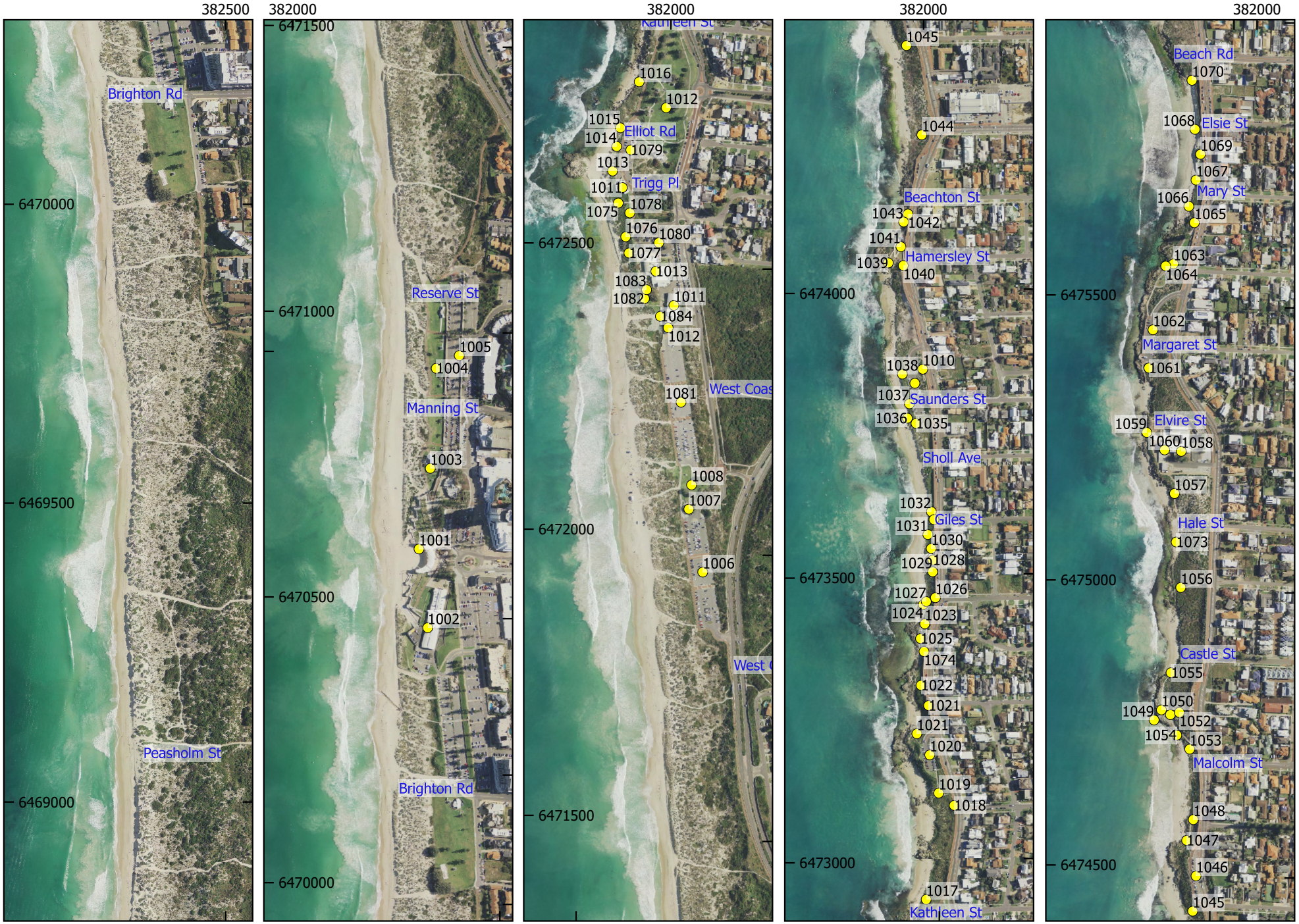
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APPENDIX A:
COASTAL SEDIMENT CELLS



Coastal Sediment Cells across the Strategic Coastal Study area (DoT, July 2012)

APPENDIX B:
STRUCTURES LOG


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Elliot Rd
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Hamersley St
Margaret St
Saunders St
Elvire St
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City of Stirling Coastal Amenities

Feature ID	Description	Easting (m)	Northing (m)
1001	Scarborough Amphitheatre	382,302	6,470,608
1002	Scarborough Surf Life Saving Club	382,329	6,470,471
1003	Scarborough Playground and BBQ	382,309	6,470,751
1004	Scarborough Park and BBQ	382,304	6,470,927
1005	Scarborough Beach Carpark	382,343	6,470,953
1006	Trigg Beach Car Park and Beach Showers	382,157	6,471,958
1007	South Trigg Toilet Block	382,121	6,472,065
1008	South Trigg Park	382,122	6,472,108
1010	Dual Use Path - South Trigg to North CoS Boundary	381,988	6,473,863
1011	Trigg Surf Lookout	381,946	6,472,615
1011	Trigg Beach Surf Lifesaving Club 01	382,058	6,472,419
1012	Clarko Reserve	382,008	6,472,763
1012	Trigg Beach Surf Lifesaving Club 02	382,052	6,472,379
1013	North Trigg boat ramp	381,926	6,472,642
1013	Trigg Beach Cafe	382,020	6,472,475
1014	Beach Access Path from Clarko Park parking area	381,929	6,472,686
1015	Beach access ramp from Clarko Park parking area	381,932	6,472,719
1016	Beach access ramp from Clarko Park	381,956	6,472,803
1017	Beach access path at Kathleen St	381,978	6,472,931
1018	Lookout area Bennion St	382,030	6,473,095
1019	Beach access paths Bennion St	382,003	6,473,118
1020	Car park between Bennion and Bailey Streets	381,988	6,473,185
1021	Lookout Bailey St	381,988	6,473,272
1021	Beach access path from Bennion St parking area	381,966	6,473,223
1022	Beach access path Bailey St	381,975	6,473,308
1023	Access Path to Mettams Pool	381,984	6,473,415
1024	Mettams Pool change area and ramp to water	381,982	6,473,449
1025	Beach access path south of Mettams Pool	381,976	6,473,390
1026	Lookout Giles St	382,003	6,473,461
1027	Mettams Pool retaining wall	381,987	6,473,455
1028	Mettams Pool public toilets	382,000	6,473,527
1029	Beach access steps south of Mettams Pool toilets	381,999	6,473,507
1030	Beach access ramp north of Mettams Pool toilets	381,997	6,473,548
1031	Storm Drain outlet - Giles St	381,992	6,473,572
1032	Beach Access steps - Giles St	381,999	6,473,612
1033	Lookout - Giles St	382,003	6,473,598
1034	Parking Area - Saunders St	381,974	6,473,839
1035	Beach walkway & steps, Saunders St parking, south	381,975	6,473,768
1036	Drainage outfall - Saunders St	381,960	6,473,777
1037	Beach steps, Saunders St Parking, west	381,963	6,473,803
1038	Beach steps, Saunders St parking, north	381,952	6,473,855
1039	Beach walkway, Hamersley St	381,931	6,474,051
1040	Lookout, Hamersley St	381,957	6,474,046
1041	Paths & Public amenities, Hamersley St	381,953	6,474,079
1042	Revetment & walkway, Hamersley St	381,967	6,474,136
1043	Beach access steps, Hamersley St	381,959	6,474,122
1044	Beach access ramp, North Beach Rd	381,994	6,474,275

Feature ID	Description	Easting (m)	Northing (m)
1045	Beach access ramp & steps, Sorrento St	381,969	6,474,432
1046	Parking Area, Sorrento St	381,972	6,474,494
1047	Walkway, James St	381,952	6,474,556
1048	Walkway and beach steps, James St	381,962	6,474,593
1049	North Beach Jetty	381,884	6,474,764
1050	North Beach revetment	381,896	6,474,783
1051	North Beach Jetty walkway	381,912	6,474,775
1052	North Beach walkway from carpark	381,928	6,474,780
1053	North Beach access steps	381,949	6,474,716
1054	North Beach access steps	381,925	6,474,740
1055	Beach access steps, Castle St	381,909	6,474,849
1056	Beach access paths, Lawley St	381,919	6,474,999
1057	Beach access track from Marine Labs south	381,899	6,475,164
1058	Marine Lab, Elvire St	381,907	6,475,238
1059	Beach steps & revetment, Marine Lab	381,845	6,475,268
1060	Walkway, perimeter Marine Labs	381,878	6,475,239
1061	Walkway and beach access ramp, Margaret St	381,842	6,475,382
1062	Car park and lookout, Margaret St	381,846	6,475,449
1063	Walkway and Ada St park	381,876	6,475,566
1064	Beach steps, Ada St	381,863	6,475,562
1065	Walkway, Watermans Bay south	381,909	6,475,641
1066	Beach access ramp, Watermans Bay south	381,898	6,475,669
1067	Stormwater drain outflow, Watermans Bay south	381,908	6,475,716
1068	Geofabric sandbag revetment & beach, Watermans Bay	381,901	6,475,805
1069	Lookout and amenities, Watermans Bay	381,913	6,475,761
1070	Beach steps, Watermans Bay north	381,892	6,475,890
1071	Beach steps, Lennard St	381,862	6,476,082
1072	Beach steps, Troy Ave	381,846	6,476,160
1073	Storm water drain, Hale St	381,906	6,475,079
1074	Revetment between Lynn & Bailey St	381,982	6,473,367
1075	Beach access track, Trigg north	381,942	6,472,587
1076	Beach access track, Trigg north	381,961	6,472,530
1077	Beach access track, Trigg north	381,970	6,472,502
1078	Beachfront grass picnic areas, Trigg north	381,964	6,472,572
1079	Parking area, Trigg Place	381,954	6,472,683
1080	Parking area, Trigg Beach north	382,020	6,472,526
1081	Parking area, Trigg Beach central	382,088	6,472,251
1082	Surf lifeguard tower, Trigg Beach	382,005	6,472,425
1083	Beachfront picnic area, Trigg central	382,007	6,472,441
1084	Showers, Trigg Beach central	382,036	6,472,397

APPENDIX C:
NUMERICAL MODELLING OF NEARSHORE WAVES AND RESPONSE TO MEAN SEA LEVEL RISE

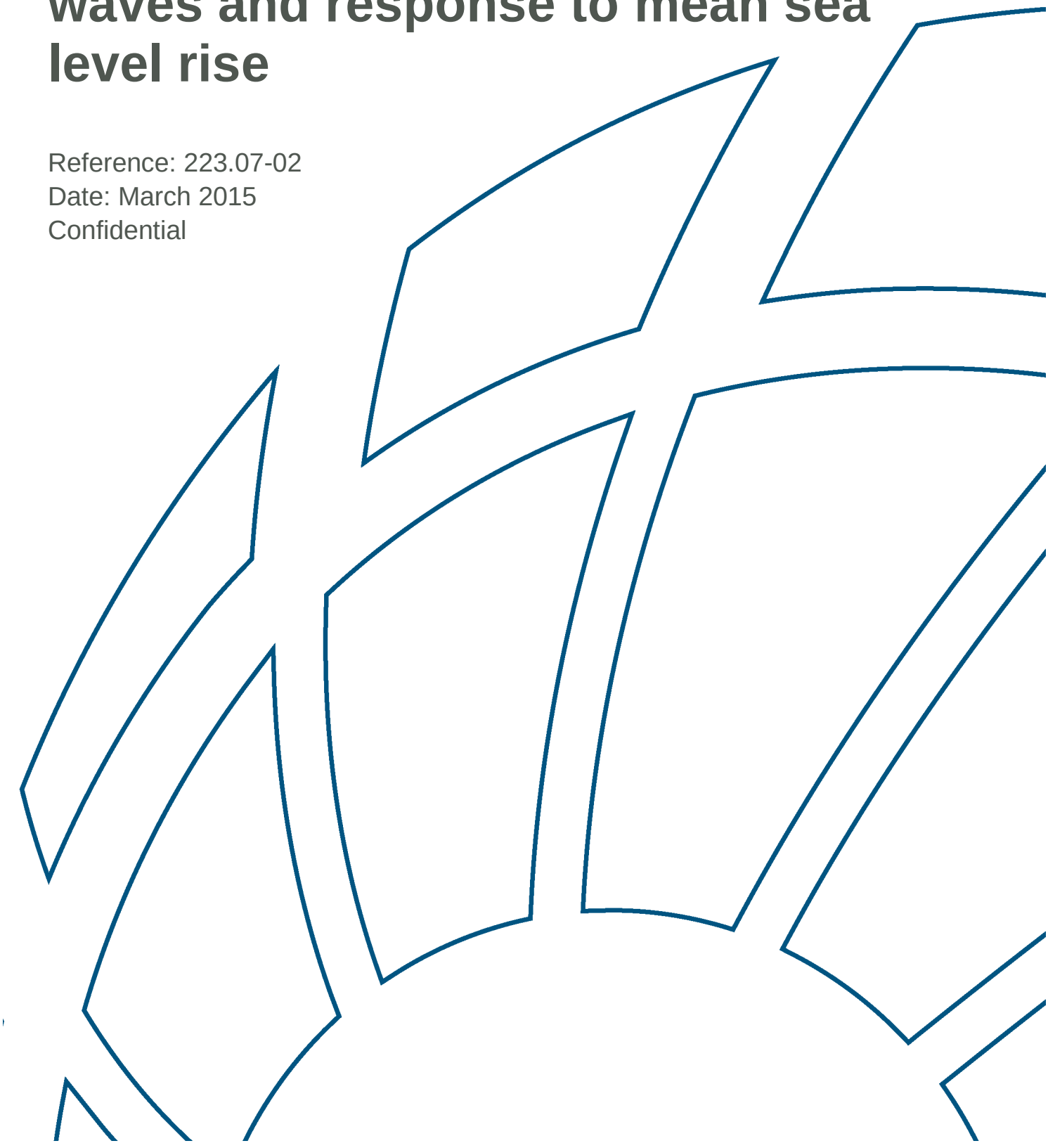
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STRATEGIC COASTAL STUDY

Numerical modelling of nearshore waves and response to mean sea level rise

Reference: 223.07-02
Date: March 2015
Confidential



CITY OF STIRLING

STRATEGIC COASTAL STUDY

NUMERICAL MODELLING OF NEARSHORE WAVES AND RESPONSE TO MEAN SEA LEVEL RISE

Prepared for

City of Stirling

By

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B	Draft Second Review	ST	Hamid Fanaie	18/03/2015	1 elec
0	Draft for Client Review	ST	City of Stirling		
1	Issued for Use/Info/Tender				

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GLOSSARY AND ACRONYMS

BOM: Bureau of Meteorology

DoT: Department of Transport

IPCC: Intergovernmental Panel on Climate Change

MSL: Mean Sea Level

MSLR: Mean Sea Level Rise

NOAA: National Oceanic and Atmospheric Administration

OTIS: Oregon State University Tidal Inversion Software

H_s: Significant Wave Height

T_1: Mean wave period

T_p: Peak wave period

Θ_{sp}: Directional spreading

MWD: Mean wave direction

1 INTRODUCTION

The City of Stirling seeks a detailed report on which long-term decisions can be based to produce effective coastal management plans for the coastline between Peasholm Street beach in the south and Sorrento to the north. The strategic coastal study will provide a rigorous, scientifically-based understanding of the primary behavioural trends of the Stirling coastline, in particular focussing on key activity nodes such as Watermans Bay and Mettams Pool.

The strategic study is based upon the analysis of five key data and information sources. Numerical modelling of the wave climate is one of these key information sources and this document outlines the process undertaken in setting up the numerical model, calibration of results and key observations taken from the final modelling outputs. This document therefore sits as an addendum to the overall final report (BMT JFA_R-233 07-01).

1.1 Scope of Work for numerical wave modelling

This study aims to establish nearshore wave conditions, assess the effects of the submerged reef system in focussing and diverging waves along the coastline between Trigg Island and Sorrento and determine the response of the wave climate to Mean Sea Level Rise (MSLR).

The following steps were undertaken to achieve these objectives:

- Available metocean and bathymetric data from global models and local observations were collected and analysed.
- Relevant quality controlled data were used in setting up the model e.g. grid files, boundary conditions and forcing with reasonable model parameters in two calibration periods.
- The model results were calibrated against observations through graphical comparisons and error parameters.
- The validated wave model was simulated for a long period i.e. one year, for 2010 Mean Sea Level (MSL), 50-years and 100-years MSLR with a combination of two-dimensional and single point outputs at the areas of interest.
- The alongshore variations in wave parameters, the influence of the limestone reef system, MSLR and offshore wave directions were investigated and discussed.
- The quantitative results from the wave model have been presented together with key observations.

The outputs from this task are seen to provide a sound basis for the sediment transport estimation and coastal risk assessment undertaken in the latter part of the overall strategic study.

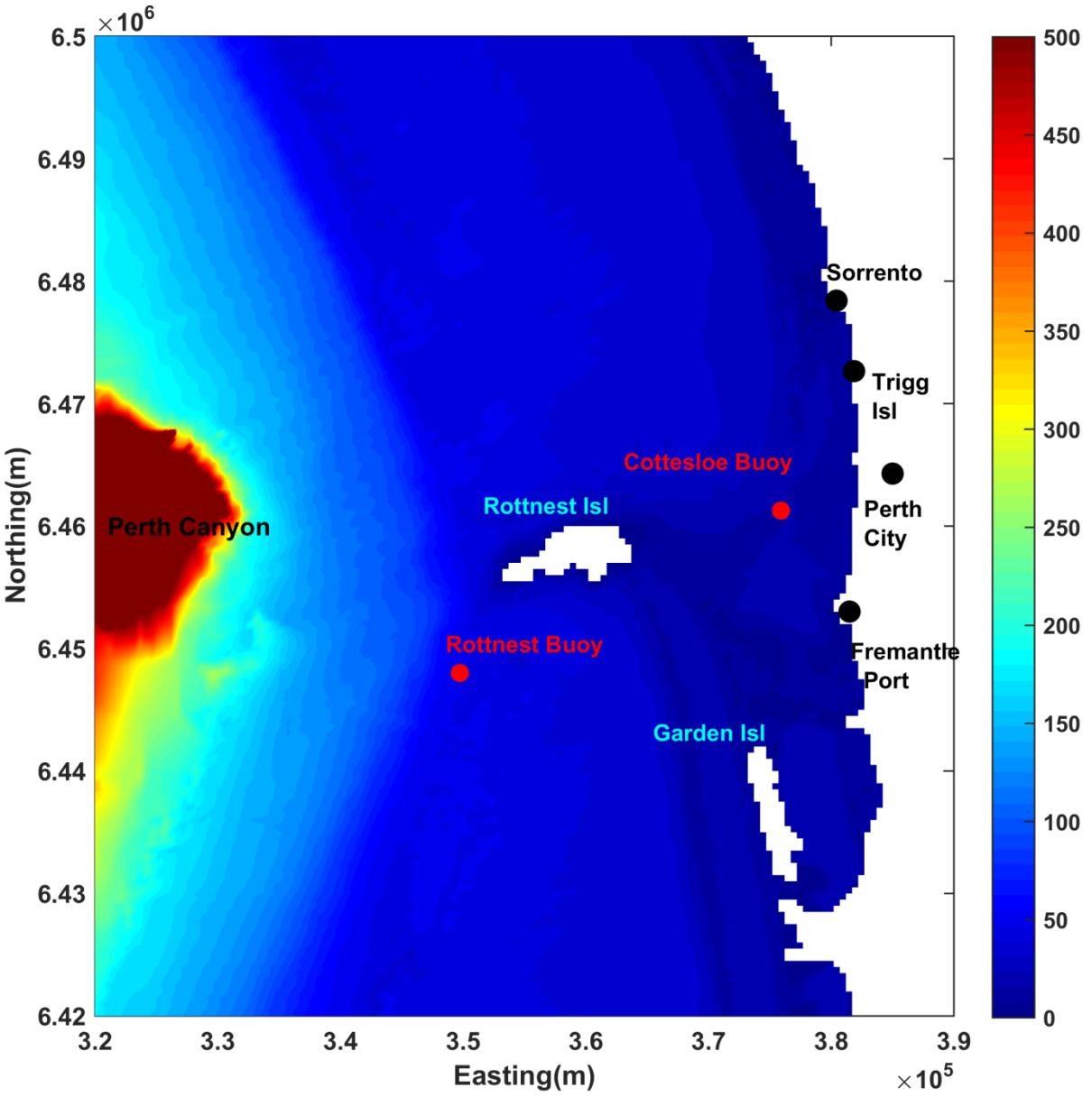


Figure 1. Bathymetry of study site (m)

The bathymetry used for modelling the nearshore wave climate of the study site extends well to the north and south of the Stirling coastline as shown in Figure 1. It also extends to the Perth Canyon in the offshore direction. Rottnest Island and Garden Island are identified as two of the main features of the offshore bathymetry. Long-term (and ongoing) measured wave observations are available at two locations - Rottnest Island and Cottesloe, plus a short-term measured dataset for Quinns Rocks.

2 METHODS

Historical metocean observations, bathymetric data and global atmospheric and oceanic models covering the study site were identified and reviewed for the area of interest. The quality of wave hindcast data depends to a large extent on the quality of the forcing and boundary conditions; hence quality controlling the data and selection of appropriate ones is a crucial part of numerical modelling. The SWAN wave model was setup using selected data for one year to reconstruct ambient wave condition at present MSL and two scenarios of MSLR.

2.1 Observed Data

Wave parameters have been observed and recorded south-west of Rottnest Island by the Department of Transport (DoT) since 1991. The data was originally collected using non-directional wave buoys which measured wave heights and periods. Hourly continuous data was recorded from February 1994 and a directional wave buoy was deployed in 2004 in 48 m water depth (Department for Planning and Infrastructure 2009).

The Cottesloe wave buoy was installed in 17 m water depth by DoT in 2008. It measures wave height, period and direction for wind waves and swells.

2.2 Bathymetry

Bathymetric data for Perth coastal areas was first collected in 1978. The single beam echo sounder survey was undertaken using 100 m grid centres along and cross shore and provided a reasonable coverage for deep waters and shallow limestone reefs. The most recent bathymetric data of the study area was collected in 2008 via bathymetric LiDAR. Blocks of data at 5 m resolution were corrected for the Fremantle tide gauge chart datum. The survey covered up to 10 km off shoreline and also the areas around Rottnest Island. The bathymetry for the remaining offshore area was collected from different sources - mainly Navy data.

2.3 Numerical Modelling

SWAN is a third-generation wave model, developed at Delft University of Technology that computes random, short-crested wind-generated waves in coastal regions and inland waters (Booij, Ris et al. 1999). The model is based on the wave action balance equation with sources and sinks and can be used on any scale relevant for wind generated surface gravity waves.

The model however has poor approximation in modelling wave spectrum for long-crested waves such as surf beats, harbour resonance, seiche and tsunamis. It does not calculate wave-induced currents and uses a phase-decoupled approach for computation of diffraction in arbitrary complex geophysical conditions.

Resolving wind waves propagating from deep to shallow waters in a large scale would require local refinement of the mesh near the coast. This was achieved by employing a nesting approach i.e. computing the waves on a coarse grid for a larger region and then on a finer grid for a smaller region close to the shoreline (Figure 2).

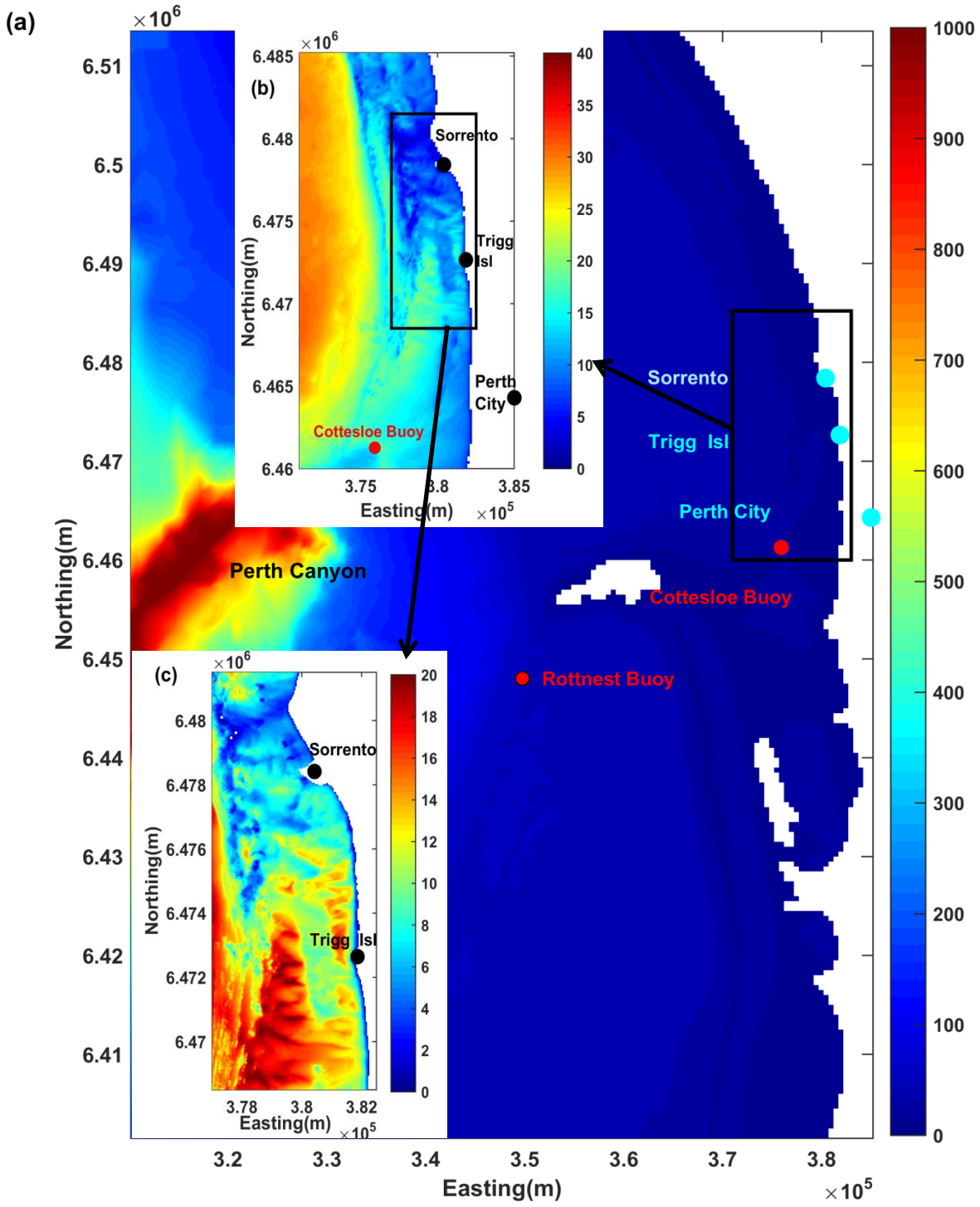


Figure 2. Bathymetry of three levels of nesting and key locations in a) A Grid at 500 m resolution, b) B Grid at 150 m resolution and c) C Grid at 40 m resolution.

While A Grid allowed for generation of wind waves in the domain, propagation of swells and wave diffraction around offshore islands (Figure 2a), significant dissipation in wave energy occurred in B Grid due to the presence of a submerged limestone reef system ~5 km off the shoreline (Figure 2b). Reef density increased toward the northern part of C Grid and a number of dry grid cells i.e. higher elevations than MSL were present off Sorrento (Figure 2c).

Wave generation, whitecapping, diffraction and dissipation by both depth-induced wave breaking and bottom friction were allowed to occur within the model in non-stationary mode. Given the complexity of the bathymetry and uncertainties in the appropriate model parameters in reef systems, several sensitivity tests were required to enhance model setup and results (Taebi, Lowe et al. 2012). That includes choosing the wave generation method, whitecapping parameters, and bottom roughness value. The roughness length (K_n) is related but not identical to the physical roughness of the seabed (Lowe, Falter et al. 2005). Therefore higher values should be considered for the sites within a reef system than for sandy beaches. To quantify the ability of the model to predict waves, hindcast simulations were conducted for two 3-week periods in September and December 2013 as representatives of winter and summer wave climates.

2.3.1 Forcing and boundary conditions

Waves on the surface of the ocean with periods of 3 to 25 sec are primarily generated by winds and are a fundamental feature of coastal regions around the world. Wave heights approximately scale with the square of the wind speed. This implies an error of 10% in the wind speed leads to an error of 20% in the wave height (Tolman 1998). Most wave models obtain their wind from numerical hindcasts and the accuracy of these atmospheric models depends on the quality of the forcing at the boundaries and the availability of observed wind data in the area of interest (Tolman 1998, Weisse and Feser 2003). Therefore, the selection of appropriate wind source data is a vital step in the wave modelling.

For this study, hourly Climate Forecast System Reanalysis (CFSR) wind field data were extracted from the National Oceanic and Atmospheric Administration (NOAA) climate models (Bao and Zhang 2012). Wind observations at Rottnest Island were also obtained from the Bureau of Meteorology (BOM) and modified to wind speed at a 10-meter elevation (U. S. Army Corps of Engineers 2002):

$$U_{10} = U_z \left(\frac{10}{z}\right)^{\frac{1}{7}} \qquad \text{(Eq. 1)}$$

where U_{10} and U_z are wind speeds at 10 and z meters over the ground level, respectively.

The incident swells were prescribed on open boundaries by specifying the significant wave height (H_s), the peak period (T_p), the mean wave direction (MWD) and the directional spreading (Θ_{sp}), assuming JONSWAP frequency distribution. Three-hourly wave conditions were obtained from the NOAA global wave model along the open boundaries (Chawla, Spindler et al. 2013). Hourly tidal levels were also extracted from global Oregon State University Tidal Inversion Software (OTIS) based on TOPEX/Poseidon and Jason altimeter data (Egbert and Erofeeva 2002). The Indian Ocean regional model used for this study is at 1/12º resolution and about the same quality of OTIS former tidal solution known as TPXO7.2 for the open ocean, but essentially better in shallow water.

Preliminary results from SWAN using all forcing and boundary conditions indicated the advantage of observed wind data at Rottnest over the CFSR global model for wave modelling purposes. The model parameters for bottom friction and whitecapping were then co-varied, and then outputs from the wave model were quantitatively compared to the field observations by evaluating model skill, the root-mean-square error (RMSE) and the bias (Willmott 1984, Warner, Geyer et al. 2005), defined respectively as:

$$Skill = 1 - \frac{\sum|X_m - X_o|^2}{\sum(|X_m - \overline{X_o}| + |X_o - \overline{X_o}|)^2} \quad \text{(Eq. 2)}$$

$$RMSE = \sqrt{\overline{(X_m{}^2 - X_o{}^2)}} \quad \text{(Eq. 3)}$$

$$Bias = \overline{(X_m - X_o)} \quad \text{(Eq. 4)}$$

In Eqs. 2-4, X_o is the observed variable (e.g. buoy wave height), $X_m$is the model predicted result, and the overbar denotes time averaging.

2.4 Mean Sea Level Rise Scenarios

Mean sea level rise is perhaps the most clearly documented impact of climate change. Most global climate models assimilated or validated with recent observations predict MSLR of 0.5 m to 1 m within the next century (IPCC 2007). Whilst sea-level rise is one of the most certain and important impacts of climate change, quantifying the amount of both global-averaged and regional sea-level rise remains one of the important climate change challenges (Church, White et al. 2008). There has been an evolution in global climate models achieved by the Intergovernmental Panel on Climate Change (IPCC) during the last few decades (IPCC 2014). A decrease in the range of sea-level rise projections for 2030 has been observed from First Assessment Report (FAR) to Second Assessment Report (SAR), Third Assessment Report (TAR) and scenarios of B1, A2 and A1B (Warrick and Oerlemans 1990, IPCC 1999, IPCC 2001, Church and White 2011). The sea-level observations from tide gauges and sea-surface altimetry since 1950 were consistent with the estimates of MSLR and probably closer to the higher rates of predictions (Figure 3).

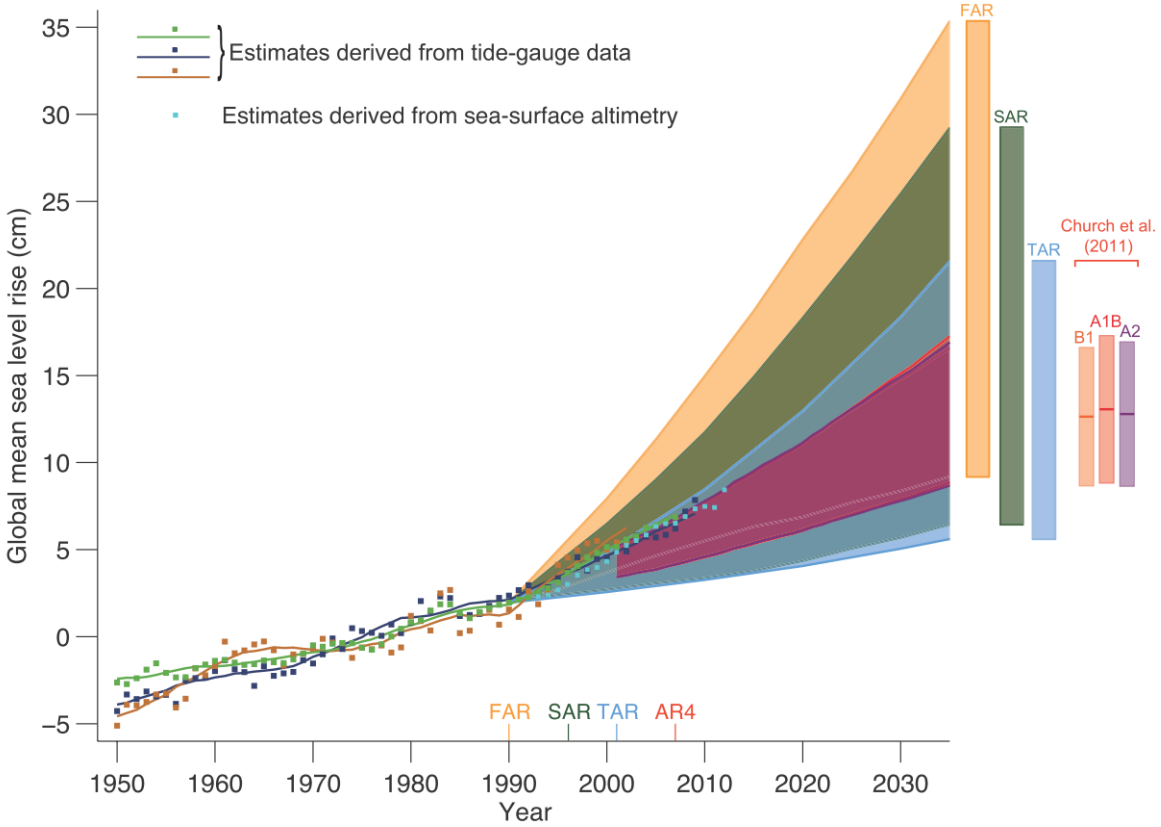


Figure 3. Estimated changes in the observed global annual MSL since 1950 relative to 1961–1990 (Cubasch et al., 2013).

The altimetry data collection shown in Figure 3 commenced in 1993 and are harmonized to start from the mean 1993 value of the tide gauge data. The shading shows the largest model projected range of global annual sea level rise from 1950 to 2035 for FAR, SAR, TAR and for Church et al. B1, A1B and A2 scenarios (adapted from IPCC 2014).

The recommended projection by DoT in Western Australia considers the sea-level rise rates from global models and local tide gages and suggests 0.3 m rise by 2060 and 0.9 m by 2110 in MSL (Bicknell, 2010). The recommended values were applied in the SWAN model for this study as a vertical increase in MSL. The wave model does not consider the impacts of MSLR on transition of littoral zones; that includes deformation of limestone reefs and any changes in the beach morphology.

3 RESULTS AND DISCUSSION

SWAN model results including wave height, period and direction were stored for the whole domain and also a number of discrete sites. 33 sites were chosen based on the locations of the 19 beach survey profiles together with an extra 14 sites to provide high spatial resolution coverage along the 3 m and 10 m depth contours. Temporal resolution of outputs varied between 72-hour in A Grid to hourly in the sites extracted from C Grid.

As previously noted, directional wave data for both Rottnest and Cottesloe are available since mid-2008. Maximum Hs was observed in July 2009 at Rottnest (8.9 m) and in July 2012 at Cottesloe (3.3 m). 2010 was relatively calm year for wave climate amongst six years of observations. Therefore 2013 with a typical wave climate and occurrence of a severe tropical cyclone in January was chosen for modelling the ambient wave conditions and MSLR scenarios.

3.1 Model Performance

SWAN wave model outputs, evaluated for a range of model parameters, were compared to the observed wave heights and periods at two sites and two calibration periods. Close comparisons were observed between wave height, period and direction for both sites/calibration periods (Figures 4&5). South-westerly swells dominated at both sites with occasional occurrence of wind waves observed in the Peak Wave Period (Tp) (Figures 4&5 c).

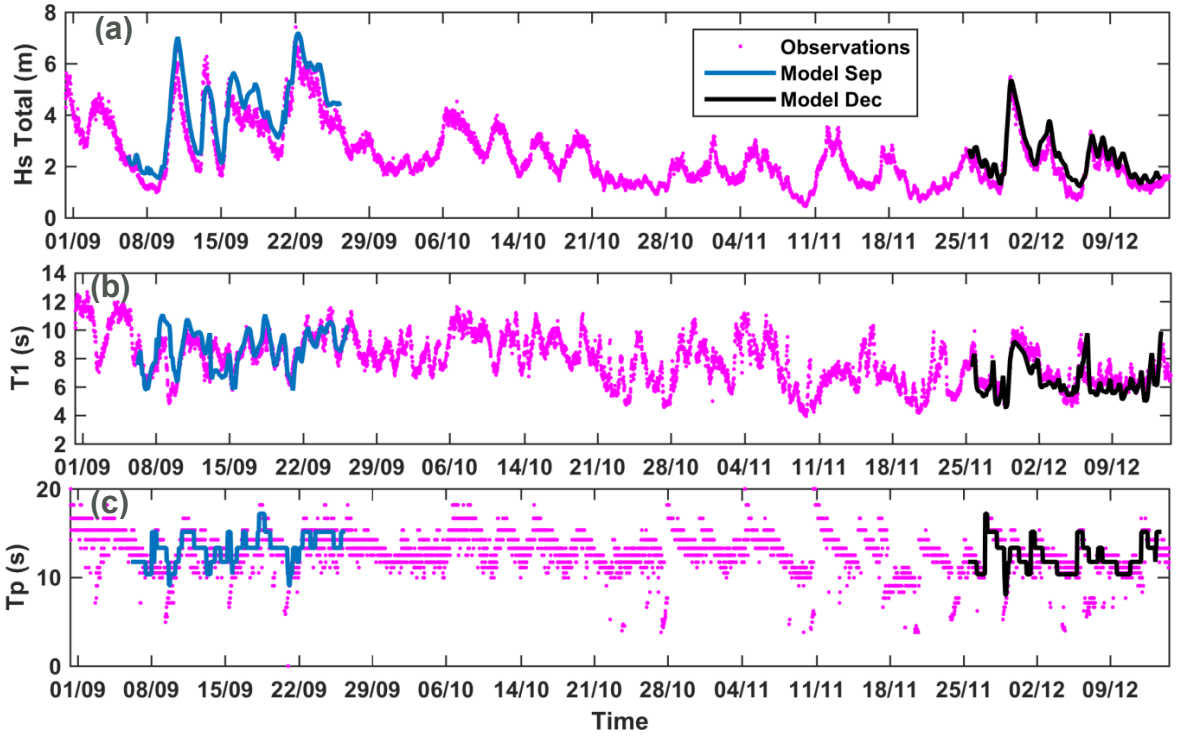


Figure 4. Wave comparisons in Rottnest buoy for September and December 2013, a) Significant wave height, b) Mean wave period and c) Peak wave period.

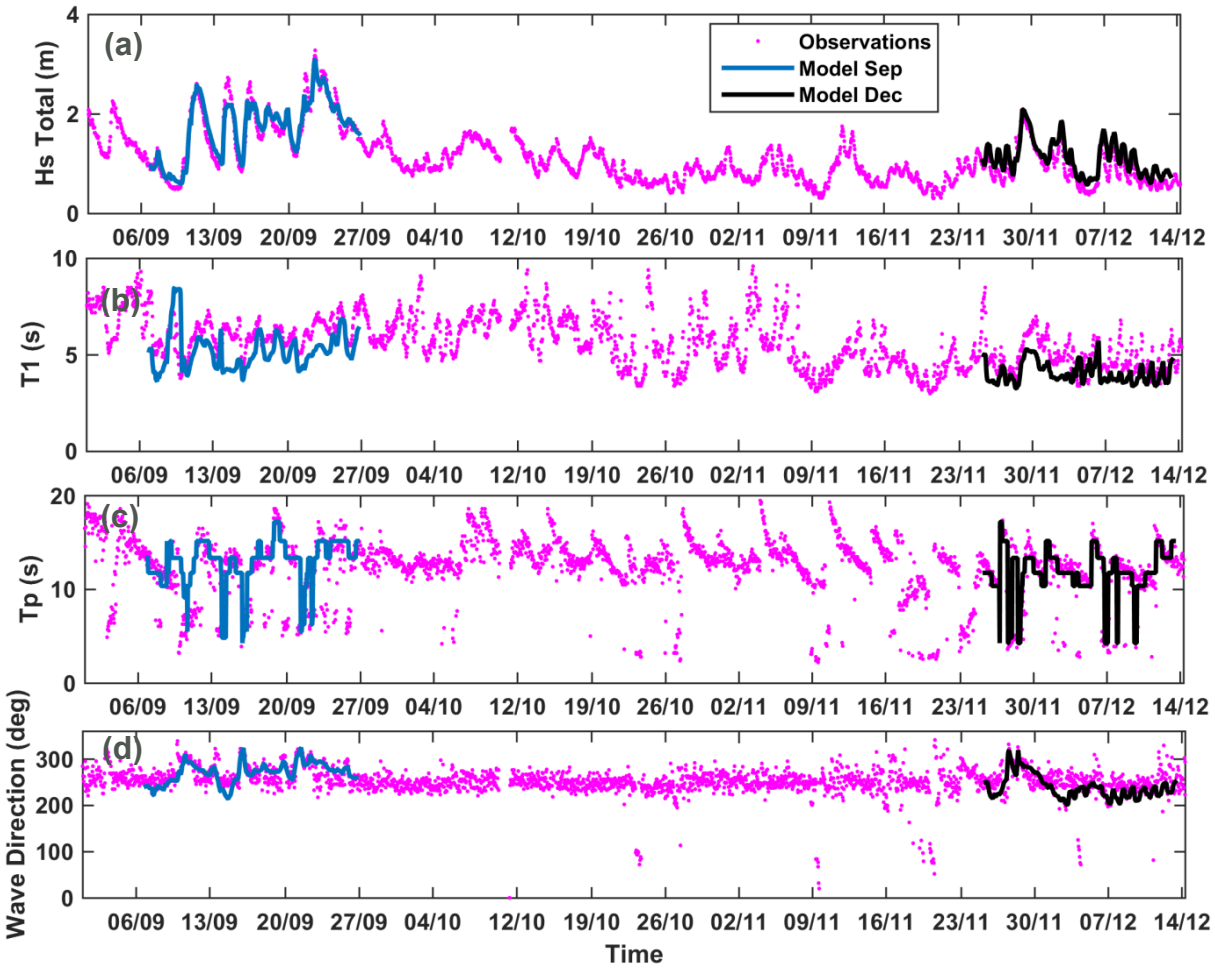


Figure 5. Wave comparisons in Cottesloe buoy for September and December 2013, a) Significant wave height, b) Mean wave period, c) Peak wave period and d) Mean wave direction.

Statistical comparisons of model and observations revealed that high model skills for wave height (~90%for all sites/periods) were achieved by adjusting model parameters (Table 1). The model skill was remarkably high for Cottesloe wave height during September (97%). The bias and RMSE values were reasonably low and all positive, indicating a small overestimation in wave height.

The model also accurately predicted wave period with ~70% model skill and -0.4 sec bias.

Table 1: Model skill and error parameters derived from the predicted and observed wave heights, for Rottnest and Cottesloe sites at two calibration periods in September and December 2013

	Rottnest Bias (m)	Cottesloe Bias (m)	Rottnest RMSE (m)	Cottesloe RMSE (m)	Rottnest Model Skill	Cottesloe Model Skill
Hs Sep	0.63	0.04	0.83	0.20	0.93	0.97
Hs Dec	0.40	0.21	0.47	0.26	0.93	0.88

3.2 Offshore and Nearshore Wave Processes

The two-dimensional model results revealed the major role bathymetry plays in the offshore and nearshore wave processes. Significant wave diffraction occurred around Rottnest Island, reducing the southerly wave component and dissipating wave energy (Figure 6). The submerged limestone reef system offshore of the study site also reduced the wave energy by depth-induced wave breaking and bottom friction.

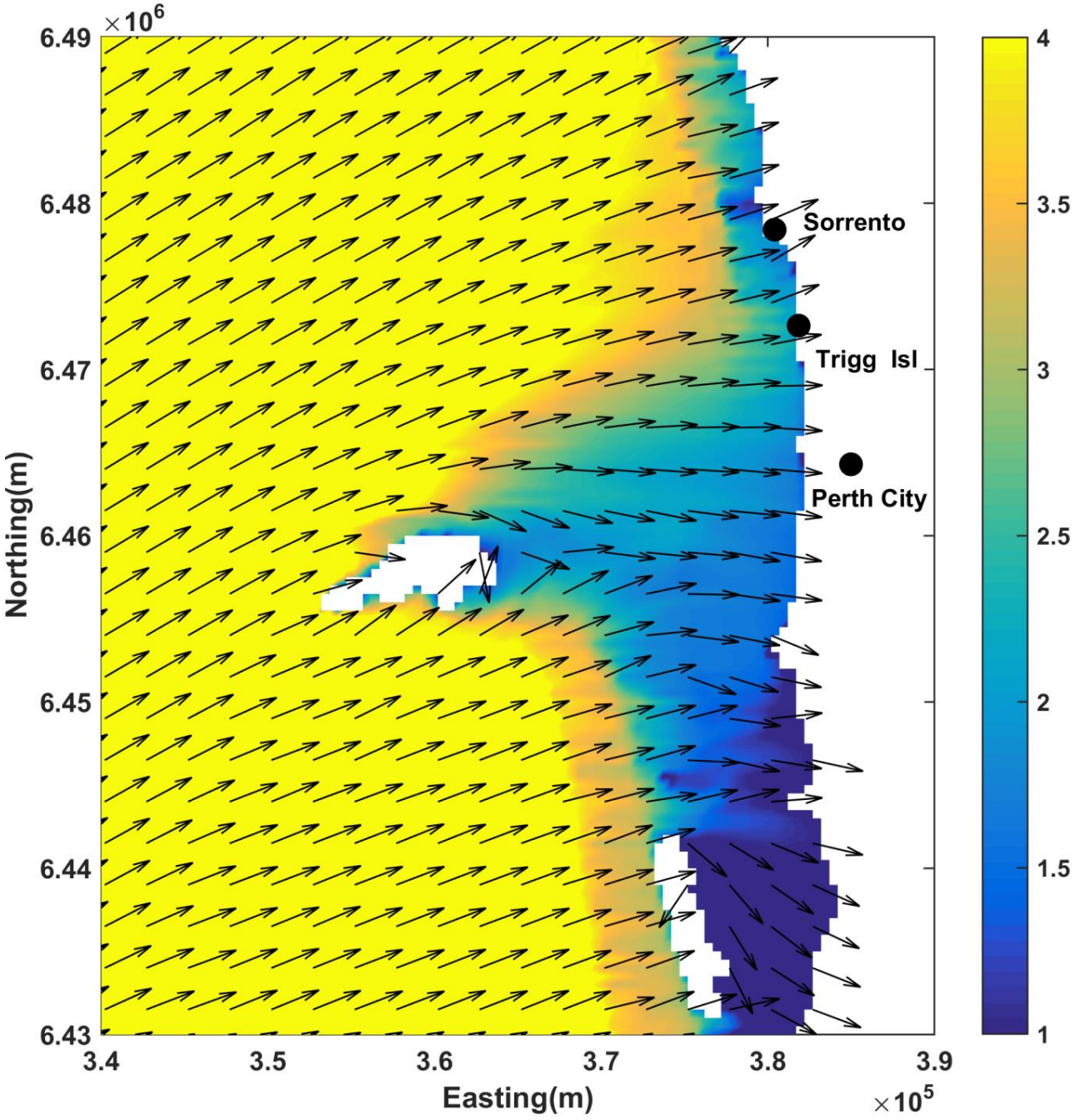


Figure 6. Significant wave height and mean wave direction from two-dimensional model results

3.3 Wave Response to MSLR

The exceedance probability for 33 sites at two different depths (3 m and 10 m) showed larger wave heights for higher MSLR. The increase in wave height in response to MSLR was more significant in northern sites e.g. around Sorrento and Hillarys boat harbour. The increase in mean significant wave heights from present MSL to 0.9 m MSLR varied between 5% at the southern boundary to almost 30% at the northern boundary of the study site (Figure 7a & b). Such an increase in wave heights translates to a larger increase in wave energy (Eq. 5).

$$E = \frac{1}{8}\rho g {H_s}^2 \qquad \text{(Eq. 5)}$$

Where E is wave energy in $({}^{N}/_{m})$, ρ is ocean water density $({}^{kg}/_{m^3})$ and g is acceleration gravity $({}^{m}/_{s^2})$.

The increase in mean wave energy at 33 sites varied between 10% in the south (around the Scarborough area) to over 90% (almost double the existing wave energy) in the north (Hillarys) (Figures 7c & d).

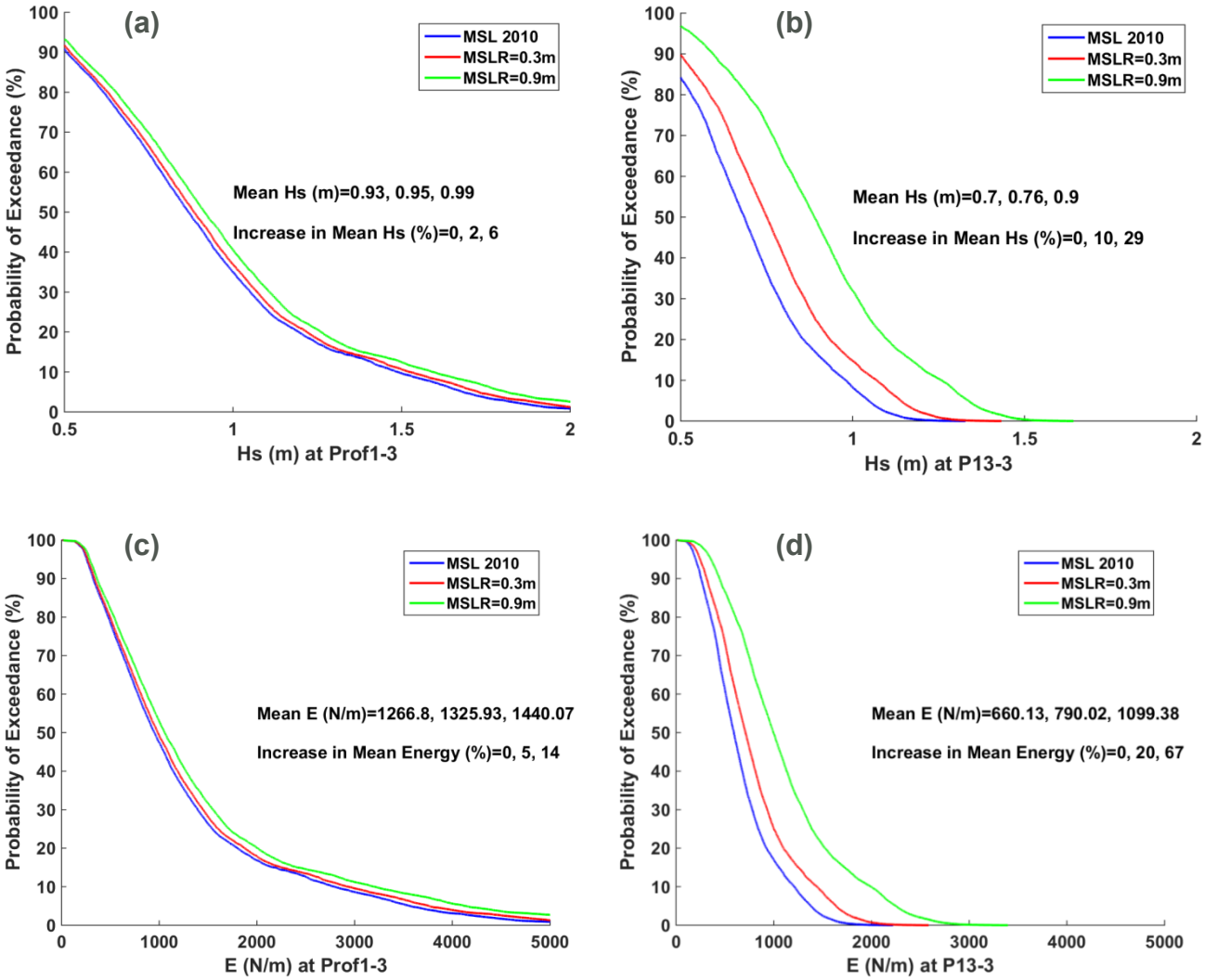


Figure 7. Significant wave height exceedance probabilities for a) a site in the southern part of the study site and b) a site in the northern part (b). c & d) Wave enery exceedance probabilities for the same sites in southern and northern part of study site.

The changes in mean wave period in response to MSLR were slightly different and at a smaller scale. Scatter diagrams of T_1 from present MSL and MSLR predictions revealed both an increase and decrease at different wave periods (Figure 8a & b). While the wave period response in the northern part of the study site was observed as different from the rest of the study site due to the characteristics of the bathymetry, a small decrease in T_1 for high wave periods were observed almost in the sites.

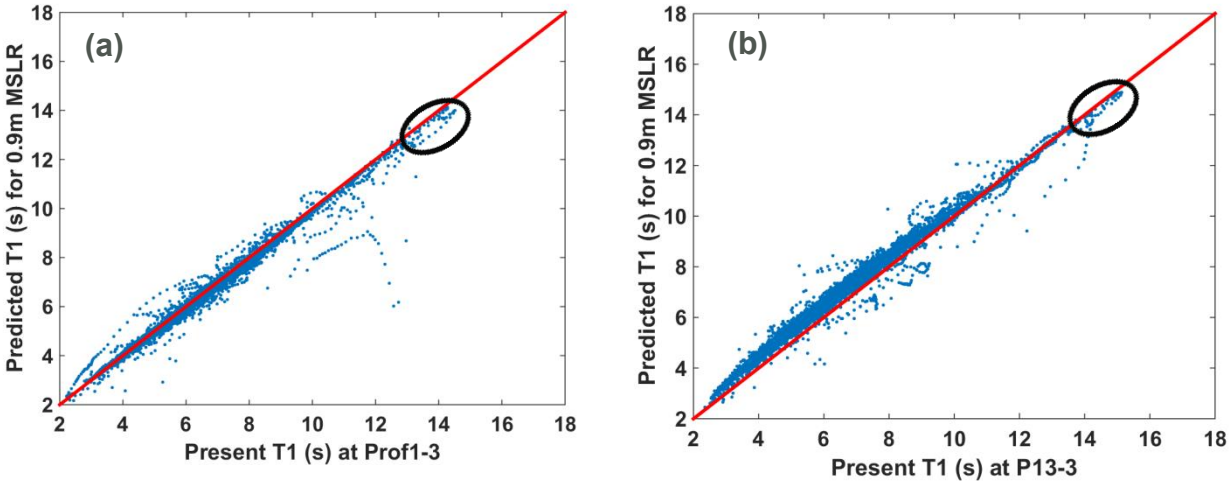


Figure 8. Mean wave period scatter diagrams in response to MSLR for a site in the southern part of the study site (a) and a site in the northern part (b).

The offshore barrier (limestone reef in this case) appears to filter the nearshore waves based on their frequencies, allowing more high period waves (swells) to penetrate into the nearshore area. The filtering effect appeared to decrease by deepening the reef resulted in a small decrease of wave period at higher range of T_1highlighted by black ellipses.

3.4 Alongshore Profiles

A better understanding of wave climate and the response to MSLR was achieved by plotting wave parameters (H_s, T_1,MWD) along the coastline. The wave height for a number of exceedance probabilities (50%, 5% and 1%) were plotted for the 33 sites over the 3m depth contour and showed a consistent increase in Hs in response to MSLR (Figure 9). The wave height was greater in the sites within the southern and central areas of the study coast with some peaks at profile 3 (Trigg island), profile 10 and 13 (between Mettams Pool and Watermans Bay). The increase in wave height was however more significant toward the northern boundary areas which are currently protected by shallow submerged and occasionally exposed limestone reefs.

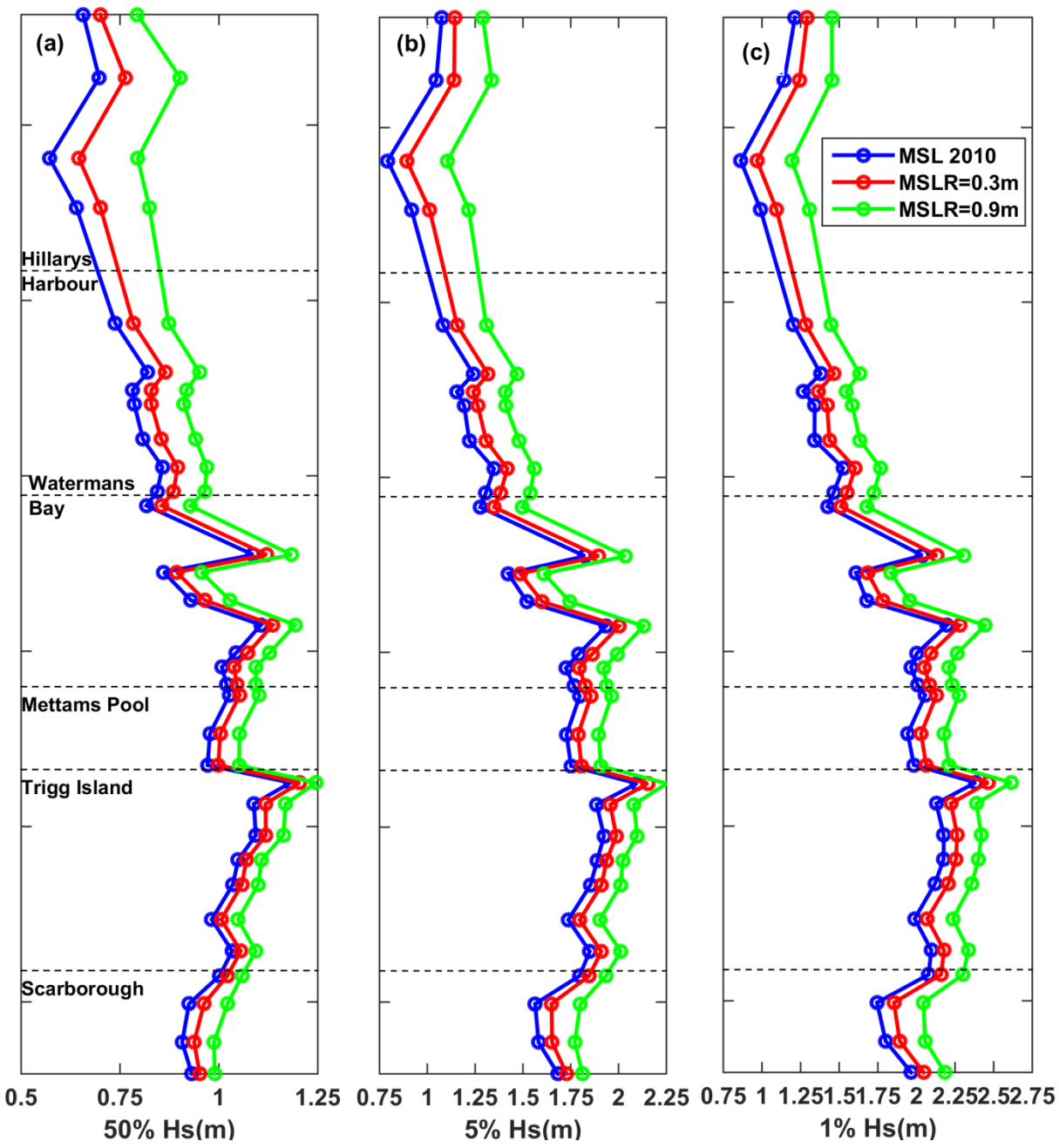


Figure 9. Wave height for fixed exceedance probabilities along the C grid shoreline a) mean H_s, b) 5% large H_s, and c) 1% large H_s.

The changes in mean wave period appeared to be smaller than wave height. The mean wave period was influenced by both swells and wind waves and a small decrease (and increase) was observed in the southern (and northern) areas in response to MSLR (Figure 10a). A consistent decrease (0.5 sec or less) in T_1 was predicted at all sites with 0.9 m MSLR due to the reduction in filtering wave periods by limestone reef (Figure 10c). The response of MWD to MSLR was also investigated and did not seem to be sensitive in modelled scenarios (profiles not shown).

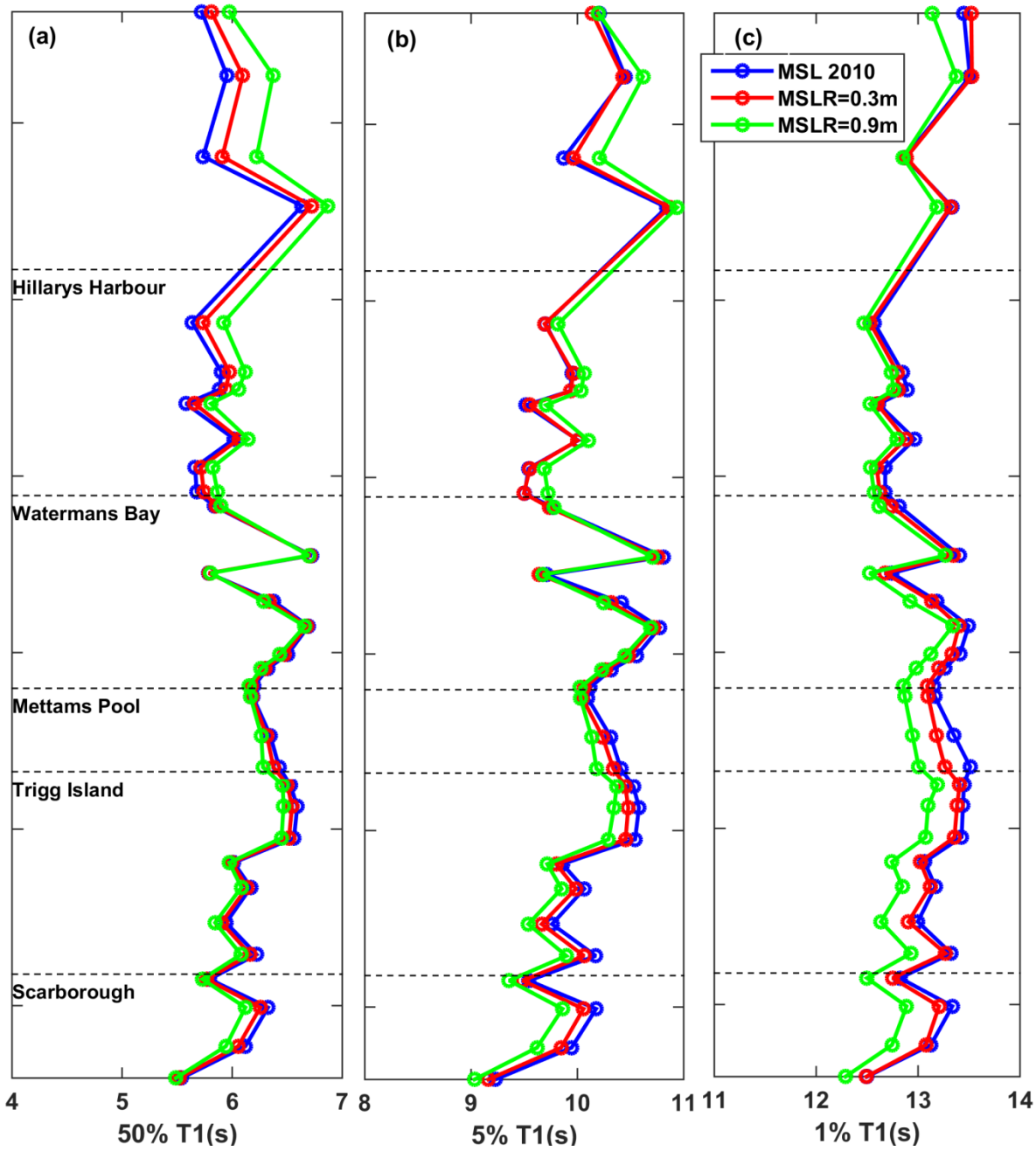


Figure 10. Mean wave period for fixed exceedance probabilities along the C grid shoreline a) mean T_1, b) 5% large T_1, and c) 1% large T_1.

The nearshore wave response to changes in offshore wave direction was investigated for a number of events. While south-westerly swells were dominant off the Perth region, smaller westerly waves were observed at shorter durations. The southerly component of the wave climate was noted to be reduced for the study site due to the diffraction of swells around Rottnest Island.

Large significant wave height for both westerly and south-westerly waves generated by tropical cyclone Narelle (Category 4) occurred at the same sites (Figure 11). Few new peaks emerged in the alongshore wave profile south Hillary's boat harbour for south-westerly direction. These peaks however were not larger than those previously observed at Profile 3 (South Trigg Island), Profile 10 and Profile13 (between Mettams Pool and Watermans Bay).

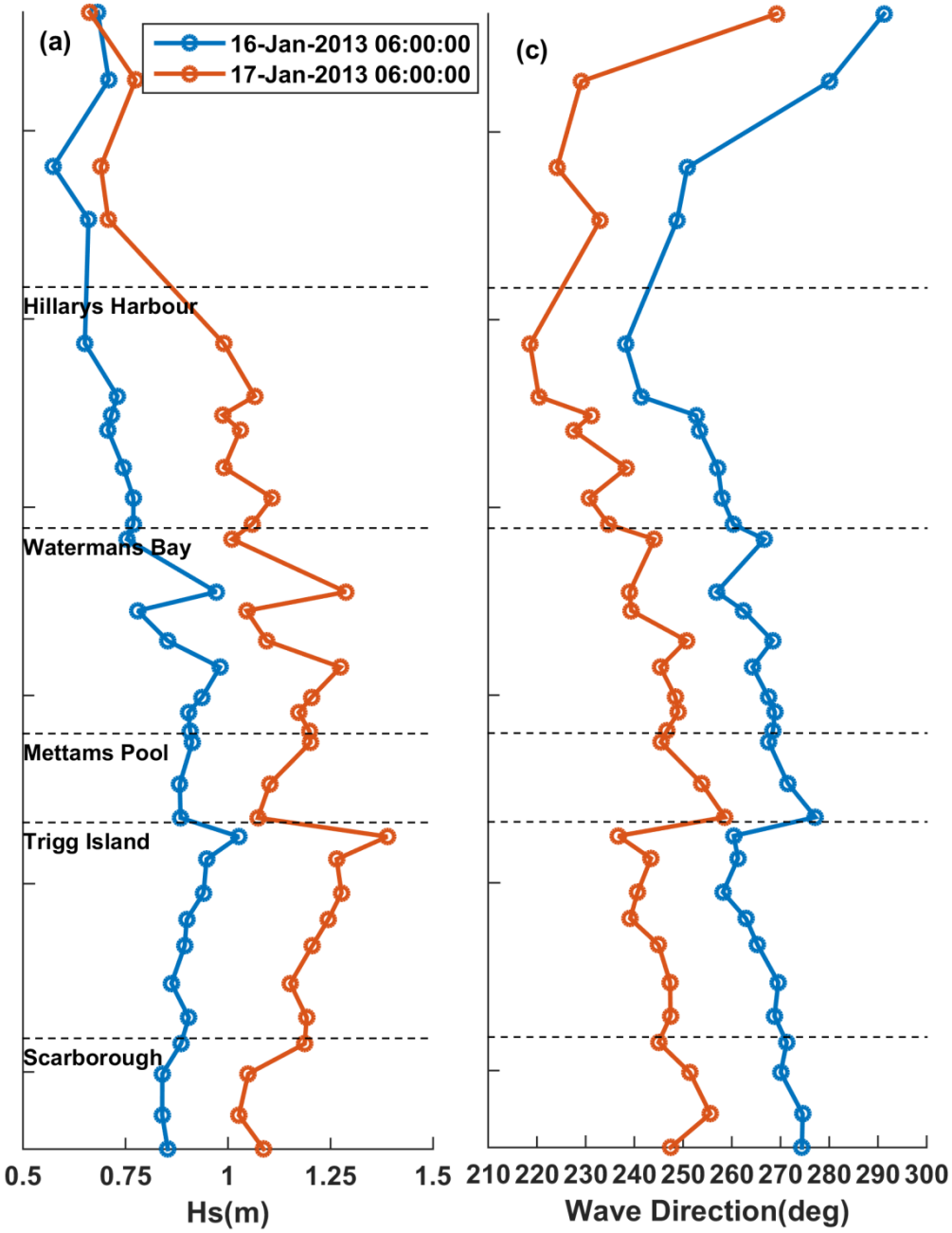


Figure 11. Significant wave height and mean wave direction in a cyclone generate event (south-westerly wave in red and westerly wave in blue).

4 CONCLUSIONS

- Graphical and statistical comparisons of the model with observations taken from the Rottnest and Cottesloe wave buoys revealed the capability of model to accurately predict wave conditions in the area of interest (Figures 4 & 5 and Table 1).
- Dominant wave processes such as diffraction by offshore islands and wave energy dissipation by limestone reefs were captured in the nested model, indicating the major role played by the bathymetry in dictating the nearshore wave climate (two-dimensional results from Grid A shown in Figure 6).
- The depth of the offshore reefs played a significant role in dissipation of wave energy, therefore larger wave heights were predicted as a direct response to MSLR. The increase in the wave height was much higher in the northern part of the study site currently protected by shallow submerged and occasionally exposed reefs (Figures 7a & b). The increase in wave energy was even more significant and varied between 10% to over 90% in response to 0.9 m MSLR (Figures 7c & d). The influence of increasing water depths over the reef was also observed in wave periods (Figure 8).
- The increase in significant wave heights was predicted for all 33 output sites for the entire range of wave heights (mean and large waves). Results confirmed a greater increase in wave heights in response to MSLR in the most northerly part of the study area in comparison with more southerly areas (Figure 9). Alongshore plots of wave periods indicated that a small decrease in mean wave period may occur in response to MSLR at high periods (Figure 10).
- The alongshore wave height profile, the location of large peaks in particular, did not seem to be sensitive to offshore wave direction (Figure 11).

5 RECOMMENDATIONS

Wave data for this study were observed at Rottnest and Cottesloe buoys located in Grid A and B of the model domain. Long term measurements of wave parameters within the study site off the reef and on the leeward side of the reef is highly recommended for better understanding of wave climate and the influence of the limestone reef.

Coupling a hydrodynamic/ morphology model to the wave model can improve the wave model results by updating the model bathymetry especially at reef and nearshore sites likely to experience higher values of erosion and accretion due to MSLR.

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