East Coast Study Project - National Geomorphic Framework for the Management and Prediction of Coastal Erosion. May 2013.

Author:
Mariani, A; Turner, I L; Cox, R J; Gordon, A D; Guerry, N; Drummond, C; Carley, J T; Flocard, F

Publication details:
Report No. UNSW Water Research Laboratory Report No. 253
978-0-85824-092-6 (ISBN)

Publication Date:
2013

DOI:
https://doi.org/10.4225/53/5786f2cb94035

License:
https://creativecommons.org/licenses/by-nc-nd/3.0/au/
Link to license to see what you are allowed to do with this resource.

Downloaded from http://hdl.handle.net/1959.4/56040 in https://unsworks.unsw.edu.au on 2024-04-19

The quality of this digital copy is an accurate reproduction of the original print copy

WRL 628.105/5A

Water Research Laboratory

East Coast Study Project - National Geomorphic Framework for the Management and Prediction of Coastal Erosion

WRL Research Report 253
May 2013

A Mariani, F Flocard, J T Carley, C D Drummond, N Guerry, A D Gordon, R J Cox and I L Turner

UNSW
THE UNIVERSITY OF NEW SOUTH WALES

Water Research Laboratory
University of New South Wales
School of Civil and Environmental Engineering

UNIVERSITY OF NEW SOUTH WALES
WATER REFERENCE
LIBRARY

East Coast Study Project – National Geomorphic Framework for the Management and Prediction of Coastal Erosion

WRL Research Report 253
May 2013

by
A Mariani, F Flocard, J T Carley, C Drummond, N Guerry, A D Gordon, R J Cox and I L Turner

https://doi.org/10.4225/53/5786f2cb94035

Bibliographic Data Sheet

Report Title	East Coast Study Project – National Geomorphic Framework for the Management and Prediction of Coastal Erosion
Report Author(s)	A Mariani, F Flocard, J T Carley, C Drummond, N Guerry, A D Gordon, R J Cox and I L Turner
Report No.	253
Report Status	Final
Report Date	31 May 2013
ISBN	978-0-85824-092-6
Number of Pages	107
Distribution Statement	
Sponsoring Organisation	Geoscience Australia, Department of Climate Change and Energy Efficiency
Keywords	Beach Erosion, Recession, Climate Change, Probabilistic/Deterministic Approach

Document Status

Version	Reviewed By	Approved By	Date Issued
Final Draft	R J Cox, I L Turner, J T Carley	B M Miller	26/04/2013
Final Report	J T Carley	W C Glamore	31/05/2013

Water Research Laboratory
110 King Street, Manly Vale, NSW, 2093, Australia
Tel: +61 (2) 8071 9800 Fax: +61 (2) 9949 4188
ABN: 57 195 873 179
www.wrl.unsw.edu.au
Quality System certified to AS/NZS ISO 9001:2008

Expertise, research and training for industry and government since 1959

Abstract

Coastal response to extreme events and climate change was assessed at two case study sites along the coast of NSW, Australia. The applicability of deterministic and probabilistic approaches for the assessment of coastal response was evaluated.

The study sites were characterised in terms of geological, oceanic and sediment transport processes. Sediment budgets were inferred with consideration to present day and future climate change scenarios. Numerical modelling techniques were used to estimate beach erosion due to storm events with average return periods ranging from 1 to 100 years. Long-term recession due to sea level rise and ongoing sediment imbalance was estimated at the two study sites for the 2100 timeframe using a coastal compartment sediment budget approach.

The availability of long-term, high-quality beach and surfzone surveys was a key factor for the feasibility and reliability of both deterministic and probabilistic approaches. The investigation showed that storm sequencing and two-dimensional effects such as rip currents need to be considered in the evaluation of coastal response to extreme storm events. A sediment budget approach based on a probabilistic method provided a powerful framework for the evaluation of long-term shoreline response to climate changes.

Contents

List of Tables

List of Figures

*Figures are replicated within the main body of the report

Executive Summary

Introduction
The "East Coast Case Study" is part of the collaborative program "National Geomorphic Framework for the Management and Prediction of Coastal Erosion". The aim of the program is to develop a nationally consistent coastal compartment classification to inform and improve future assessments of coastal vulnerability to climate change, in particular sea level rise. The objective of the "East Coast Case Study" is to evaluate current approaches for the assessment of coastal response to climate change through the application at two study sites on the East Coast of Australia. The investigation consisted of three steps: (i) Site Characterisation, (ii) Assessment of Short-term Coastal Response and (iii) Assessment of Long-term Coastal Response.

Site Characterisation
Avoca Beach on the NSW Central Coast and Cabarita Beach on the Far NSW North Coast were selected for this study. The two sites represent different geological settings and sediment transport processes: cross-shore sediment transport processes are dominant within Avoca while both cross-shore and longshore processes are important at Cabarita Beach. While Avoca Beach is currently in a state of dynamic equilibrium with a relatively "closed" sediment budget, Cabarita Beach presents ongoing shoreline recession due to by littoral drift imbalance.

Short-term Coastal Response
The coastal response to extreme storm events was assessed at the two study sites. While data availability limited the application of fully probabilistic approaches, deterministic and semi-probabilistic methods were applied to estimate beach erosion for a range of storm events with probabilities ranging from 1 to 100 year ARI, and for single and sequences of two and three storms.

Long-term Coastal Response
A sediment budget approach was adopted at the two study sites to assess long-term recession due to (i) ongoing sediment imbalance within the coastal compartment and (ii) sea level rise. The sediment budget considered all potential sinks and sources within the coastal compartment including (where relevant) littoral drift, biogenic production/degradation, lagoon sequestration, onshore drift, dune overwash etc. A two-dimensional model was developed for this study to be used as a platform to provide deterministic predictions and to simulate probabilistic variations (using a Monte Carlo method) of future coastal response. The model was based on a long-term sediment budget approach and a two-dimensional profile geometric transformation.

Summary of Findings
Accurate surfzone and nearshore bathymetry is necessary for erosion modelling. To provide realistic predictions of beach erosion during storm events, storm clustering (sequencing) needs to be taken into consideration as well as two-dimensional effects such as rip currents and sediment loss due to longshore currents. The probabilistic approach provides a powerful tool for the analysis of the sensitivity of shoreline behaviour to future variability in sediment budget components. It allows consideration of potential changes in wave climate as these are likely to result in sediment budget changes. Within those coastal compartments where large uncertainty remains in the quantification of the sediment budget and future impacts of climate change, a probabilistic approach is useful to manage the uncertainty and relate it to future shoreline behaviour.

1. Introduction

1.1 Background

The Water Research Laboratory of the University of New South Wales undertook the "East Coast Study Project" as part of the collaborative program between Geoscience Australia (GA) and the Department of Climate Change and Energy Efficiency (DCCEE, now repealed): "National Geomorphic Framework for the Management and Prediction of Coastal Erosion".

This program aims to contribute towards the improvement of the ability, on a national level, to undertake coastal erosion and risk assessments, and enable a more integrated approach to the management of the coastal zone. The scope of the program is composed of two components:

(i) The development of a national coastal sediment system classification; and
(ii) The improvement of the prediction of shoreline erosion assessments through two case study projects: the East and West Coast projects.

The development of a national coastal "compartment" classification based on sediment processes help coastal managers and planners adopt the best approach to modelling shoreline erosion under future climate by identifying the geographic extent of discrete coastal sediment systems – the sources, sinks and pathways of sediments within a section of coast.

The case study projects demonstrate the potential utility of the coastal compartment classification for assessing and modelling coastal vulnerability and shoreline response to climate change, and in particular to sea level rise. The purpose of the "East Coast Study Project" was to evaluate approaches currently implemented by practitioners for the assessment of coastal response to climate change including sea level rise. In particular, the assessment of coastal response in the short and long-term at two case study sites is used to compare and evaluate the deterministic versus probabilistic approaches in the context of the coastal sediment compartment characterisation.

1.2 Scope of Works

The work undertaken was divided into the following tasks:

Task 1. Characterisation of the two study sites;
Task 2. Evaluation of the applicability of deterministic and probabilistic approaches for coastal response to extreme events and climate change at the two study sites; and
Task 3. Qualitative assessment of deterministic and probabilistic approaches and recommendations for best practice in coastal hazard definition.

Geological settings define how sediment is exchanged between and within compartments. In conjunction with GA, WRL selected as case study sites: Cabarita-Casuarina-Salt Beach on the NSW Far North Coast and Avoca Beach on the NSW Central Coast (Figure 1.1*). The two sites present constraining geological settings and process regimes that are representative of coastal sediment compartments and beach types located within the region. For simplicity, throughout the report, the Cabarita-Casuarina-Salt compartment is referred to as 'Cabarita Beach'.

As part of Task 1, WRL collated and reviewed a large amount of literature and existing data relevant to Avoca and Cabarita Beach, including:

- Coastal processes and management studies;
- Coastal hazard assessment studies;
- Photogrammetry data;
- Bathymetric data including recent Marine LiDAR data; and
- Geological and sedimentology mapping.

Characterisation of the study sites was completed in terms of geological, oceanic and sediment transport processes. Sediment budgets were inferred with consideration to present day and future climate change scenarios.

As part of Task 2, WRL undertook the evaluation of coastal response to extreme events and climate change. The evaluation included the analysis, at the two study sites, of:

- Short-term processes (storm erosion); and
- Long-term processes (shoreline recession).

Short-term processes considered erosion from individual extreme storm events and clustering of up to three extreme storm events. Long-term processes considered the effect of recession due to sediment imbalance within the coastal cell and sea level rise (SLR). Qualitative considerations of potential effects of changes in wave climatology were also addressed.

The evaluation of coastal response at Task 2, considered the application of deterministic and probabilistic approaches. As part of Task 3, relative merits of the two approaches are discussed with regards to the evaluation of short and long-term processes at the two study sites and recommendations are formulated for future direction in coastal erosion and risk assessments.

1.3 Deterministic and Probabilistic Approach

Coastal erosion and risk assessments involve the prediction/estimation of the future likely response of the coastline under different sets of initial conditions, including beach bathymetry, topography, wave and water level conditions, coastal geomorphology etc. The predictions are typically obtained through the setting up of a system or a series of models capable of delivering (empirical, analytical or numerical) estimates of coastal response (output) from a given initial state (input). It is important to note that the purpose of this study was the evaluation of deterministic and probabilistic approaches at two contrasting coastal sites, and that the choice of the model (or series of models) and their level of complexity was not, per se, relevant in the perspective of this study.

With a deterministic approach, the initial state is uniquely defined through a set of single-value variables as is the model output describing the future state. With a probabilistic (or stochastic) approach, the initial state is allowed to vary by defining the input variables using a range of possible values (probability distributions). Consequently, the future state will also be described through a probability distribution (estimates based on their likelihood) instead of a single deterministic estimate.

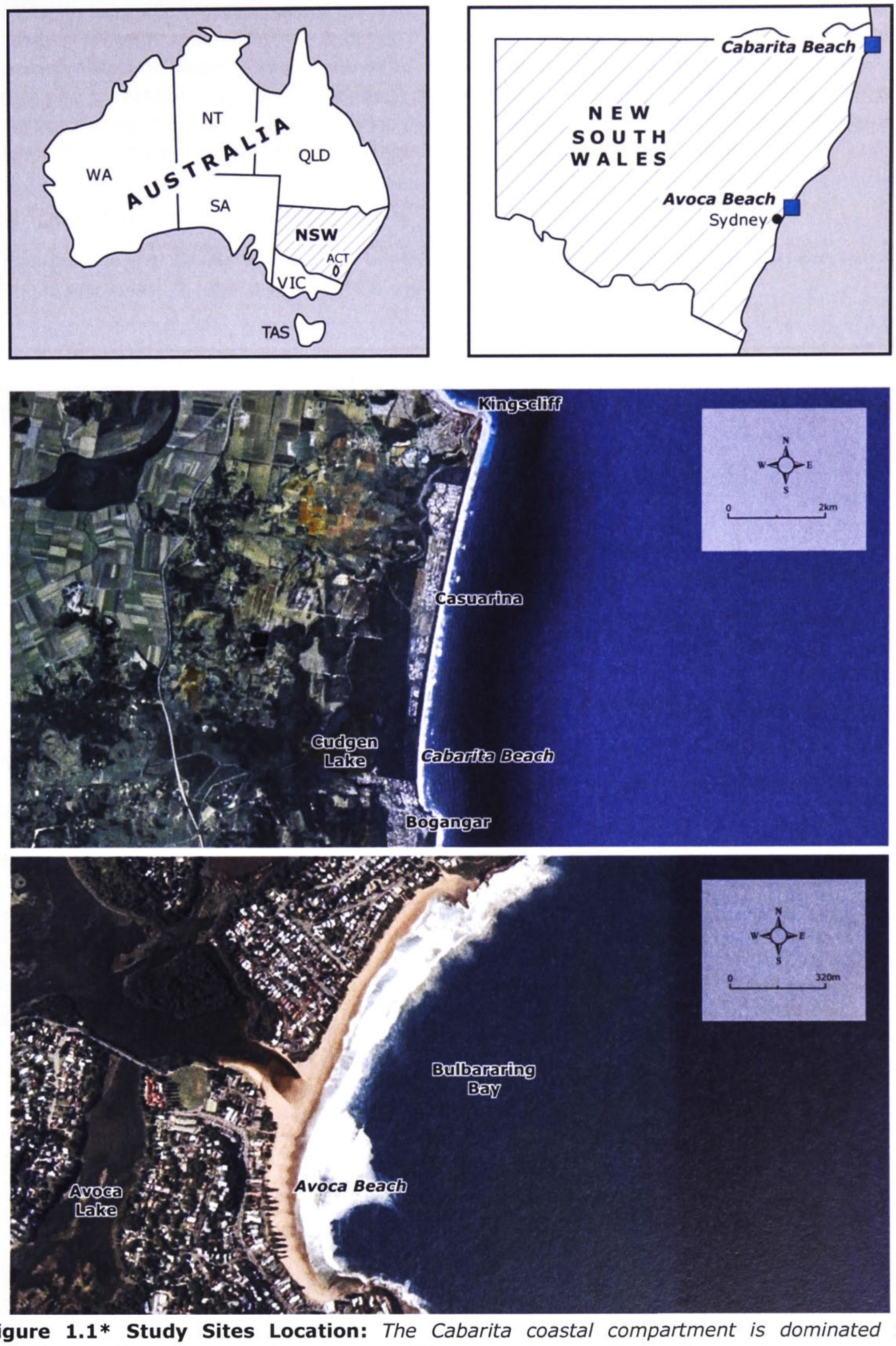


Figure 1.1* Study Sites Location: *The Cabarita coastal compartment is dominated by longshore sediment transport processes while cross-shore sediment transport processes are dominant within the Avoca compartment.*

To date, in Australia, coastal hazard assessments including the evaluation for planning purposes of coastal erosion and recession processes, are primarily undertaken using a deterministic approach. Recent studies (Woodroffe *et al.*, 2012; Cowell *et al.*, 2006) have highlighted the merits of a probabilistic approach to manage the often large uncertainty surrounding the physical variables driving the erosion and recession processes and the importance of providing forecasts coupled with a measure (probability) of the uncertainty related to the forecasts.

1.4 Data Collection and Sources

A summary of the literature and data collected for the characterisation of Avoca and Cabarita Beach is presented in Table 1 and Table 2, respectively.

Table 1: Avoca Beach Summary of Data and Literature Consulted for this Study

Year	Author/Source	Title	Type	Contents
2010	Cardno Lawson Treloar	Gosford Coastal Lagoons Processes Study	Technical Report	C.P.
2009	WorleyParsons	Ex-HMAS Adelaide Artificial Reef- Coastal and Oceanographic Processes	Technical Report	C.P.
2008	Department of Environment and Climate Change NSW	Marine LiDAR Survey- New South Wales Central Coast Bathymetry	Data	LiDAR
1999	Patterson Britton & Partners	Broken Bay Beaches Coastal Management Plan	Technical Report	C.P.
1995	WBM Oceanics Australia	Coastal Management Study and Coastal Management Plan - Gosford City Open Coast Beaches	Technical Report	C.P.
1994	Public Works Department, NSW	Gosford Coastal Process Investigation	Technical Report	C.P.
1989	Public Works Department, NSW	Topographic Setting and Offshore Sediment Distribution Terrigal/Wamberal Beach	Data	B.D.
1988	Higgs and Nittim (WRL)	Coastal Storms in NSW in August and November 1986 and their effect on the coast	Technical Report	C.P.
1987	A F Nielsen	Coastal Features of Gosford City Foreshores	Technical Report	C.P.
1985	Public Works Department, NSW	Gosford City Council Beach Management Strategies	Technical Report	C.P.
1985	Public Works Department, NSW	Wamberal Beach and Avoca Beach, Coastal Engineering Advice	Technical Report	C.P.
1960	Australian Hydrographic Service	AUS 809 - Port Jackson to Port Stephens 1:150000 Nautical Chart	Data	B.D.

Notes:
C.P. = coastal processes
B.D. = bathymetry data

Table 2: Cabarita Beach Summary of Data and Literature Consulted for this Study

Year	Author	Title	Type	Category
2011	Tweed Shire Council	Kingscliff and Bogangar survey	Data	B.D.
2010	Carley J, Mole M	Update of Tweed Shire Coastal Hazard Lines	Technical Report	C.P.
2008	Department of Environment and Climate Change NSW	Marine LiDAR Survey- New South Wales North Coast Bathymetry	Data	LiDAR
2006	Patterson Britton & Partners	Scoping Study on Byron Bay Sand Extraction	Technical Report	C.P.
2001	WBM Oceanics Australia	Tweed Coastline Hazard Definition Study	Technical Report	C.P.
1982	Chapman D, Geary M, Roy P, Thom B	Coastal Evolution and Erosion in New South Wales	Technical Report	Geology
1982	Public Works Department, NSW	Bogangar Beach Coastal Engineering Advice	Technical Report	C.P.
1981	Stephens A, Roy P, Jones M	Geological Model of Erosion on a Littoral Drift Coast	Conference Paper	Geology
1978	Public Works Department, NSW	Byron Bay- Hastings Point Erosion Study	Technical Report	C.P.
1974	Thom, B G	Coastal Erosion in Eastern Australia	Journal Paper	Geology
1970	Delft Hydraulics Laboratory	Queensland Coastal Erosion	Technical Report	C.P.
1962	Australian Hydrographic Service	AUS 813 - Clarence River to Danger Point 1:150000 Nautical Chart	Data	B.D.

Notes:
C.P. = coastal processes
B.D. = bathymetry data

1.5 Report Structure

Following this introduction, the main findings of the study are presented throughout the report as listed below:

Section 2: Presents a regional overview and a geological and geomorphic characterisation of the study sites;
Section 3: Summarises the assessment of coastal response to short-term processes within the two study sites;
Section 4: Summarises the assessment of coastal response to long-term processes within the two study sites;
Section 5: Presents the main conclusions and recommendations;
Section 6: Lists references and bibliography.

The study involved the generation of a large number of figures. While the most relevant and contextual figures are replicated within the main body of the Report, to improve readability, all figures are shown in a separate and subsequent section of the report. The figures that are replicated in the main body of the report are marked with an asterisk.

Five appendices were generated for this study:

Appendix A: Details the coastal processes characterisation of the two study sites;
Appendix B: Describes the numerical short-term erosion modelling;
Appendix C: Describes the numerical long-term recession modelling;
Appendix D: Summarises sensitivity to wave climate changes;
Appendix E: Provides a photographic depiction of the two study sites.

2. Site Characterisation

2.1 Regional Overview

2.1.1 Geological Evolution of the NSW Coast

Beach systems, and the shape and position of the shorelines formed by unconsolidated sandy sediments are dynamic in the short and medium term, and also evolve over geological timescales. A brief summary of the evolution of NSW beaches over the last two major interglacials provides a context in which to understand the current configuration of the unconsolidated coastal sediments and the likely developments that will potentially occur with a changing climate.

Approximately 125,000 years before present (BP), evidence indicates that sea level was 4 to 6 m above its present level (Marshall and Thom, 1976; Stephens *et al.*, 1981) as shown in Figure 2.1. Figure 2.1 also presents schematically temporal and spatial scales relevant for coastal evolution and processes.

Coastal processes associated with the sea level rise, leading up to the Pleistocene high still stand 125,000 years BP, moved sand onshore from the continental shelf. This sand formed coastal plains and dune systems which can still be observed today in many of the deeper embayments of the NSW coast, such as Newcastle Bight (Roy and Crawford, 1980), and along much of the NSW north coast (Roy and Thom, 1981; PWD, 1982; Stephens *et al.*, 1981). As the sea level receded following the Pleistocene high stand, many of these coastal plains and dune formations were left stranded.

After the Pleistocene high still stand the Last Glacial saw sea level fluctuating between 20 and 80 m on several occasions, while progressively trending down to a low still stand approximately 120 to 130 m below present. This low still stand occurred around 17,000 to 18,000 years BP (Roy and Thom, 1981; see Figure 2.1).

With the coast well out on the present day continental shelf, creeks and rivers eroded paths through these Pleistocene deposits transporting some of the sediment back down the shelf to the "new" ("low stand") coast. The creeks and rivers incised themselves into the underlying rock forming new, or deepening existing, watercourses. For the smaller coastal compartments, or for those with steep sided bedrock and/or large rivers, the Pleistocene still stand deposits may have been truncated or completely removed by erosion. However, for the larger coastal compartments, particularly those without major rivers, the beach ridges and dunes of the Pleistocene coastal plains remain today, albeit somewhat modified in form by wind and vegetation.

At around 17,000 years BP a progressive de-glaciation commenced, eventually resulting in sea level rising to approximately its present level around 6,000 to 6,500 years BP: the Holocene epoch. As the sea level rose, the sandy sediments moved progressively up to establish the current coastal profile (Thom, 1978; Stephens *et al.*, 1981). The de-glaciation, and resulting sea level rise over the terrain, produced what is referred to as a drowned coast. The valleys incised by the rivers and creeks at the lower sea level became what are classified as "drowned river valleys" (Chapman *et al.*, 1982).

As with the Pleistocene sea level rise, the Holocene sea level rise moved shelf sand back onshore to form the precursor to the present day coast. During the 6,000 years of the Holocene still stand the sea level may have varied at times by up to ± 1 m (Chapman *et al.*, 1982).

Additionally, longshore drift of sand into and out of compartments, and climatic variations in the net wave energy flux, have modified the coastal form to produce what is the present day shoreline beach alignment.

2.1.2 Water Levels

Storm erosion of beaches can be exacerbated due to elevated water levels, as they allow larger waves to reach the beach face. Elevated water levels consist of (predictable) tides, which are forced by the sun, moon and planets (astronomical tides), and a tidal anomaly. Tidal anomalies primarily result from factors such as wind setup (or setdown) and barometric effects, which are often combined and referred to as "storm surge". Water levels within the surf zone are also subject to wave setup and wave runup. Figure 2.2 diagrammatically represents some of the different components contributing to elevated coastal water levels.

The open coast tidal planes in NSW are usually considered to be equivalent to the tidal planes calculated for Sydney's Fort Denison (considered to be an open ocean tide site) which are shown in Table 3, with a minor north-south variation. A summary of studies (non-exhaustive) is presented in Table 4. It should be noted that storm surge can be very site-specific with local topography and bathymetry significantly affecting levels. A site specific review of the elevated water levels at the two study sites is presented in Appendix A.

Table 3: Tidal Planes at Sydney (Source DECC, 2008)

Tidal Plane	Elevation (m AHD)
Highest Astronomical Tide (HAT)	1.15
Mean High Water Springs (MHWS)	0.68
Mean High Water Neaps (MHWN)	0.43
Mean Sea Level (MSL)	0.05
Mean Low Water Neaps (MLWN)	-0.33
Mean Low Water Springs (MLWS)	-0.58
Lowest Astronomical Tide (LAT)	-0.88

Table 4: Design Water Levels Tide + Storm Surge

Average Recurrence Interval ARI (yr)	**MHL (1992)** (m AHD)	**Watson and Lord (2008)/ DECCW (2010) (Wollongong to Newcastle)** (m AHD)	**MHL (2010) (Tweed Heads)** (m AHD)
1	-	1.24	-
10	-	1.35	1.51 (10.4 yr)
50	1.38 -1.46	1.41	-
100	1.41 – 1.49	1.44	1.72

2.1.3 Wave Climate

The NSW coast is subject to a generally moderate wave climate predominantly from the south to south-east. Previous studies have found an average offshore significant wave height of 1.5 m to 1.6 m and average peak period of 9.4 s to 9.7 s (Lord and Kulmar, 2000). This generally moderate wave climate is periodically affected by large wave events originating from offshore storm systems. These storms vary both spatially and temporally in their genesis, intensity and track. Storm types which affect the NSW coast and are most relevant for beach erosion potential include tropical cyclones, easterly trough lows (east coast lows) and southern secondary lows.

Very large storm events such as those which occurred in 1974 (*'Sygna Storm'*), 1997 (the *'Mothers Day Storm'*), 2001 and 2007 (the *'Pasha Bulker Storm'*) episodically impact the coastline and, particularly when they are co-incident with high water levels, may cause beach erosion, damage to property and marine structures, coastal inundation and risks to public safety (Figure 2.3). Accurate estimation of the likelihood and magnitude of large wave events is essential for the quantification of extreme beach erosion and inundation levels, design of nearshore structures and long-term coastal management.

Shand *et al.*, (2010) derived extreme values of significant wave heights (H_{sig}) for durations between 1 and 144 hours for nine wave buoys along the NSW coast to investigate short and longer duration extreme events. Wave buoy data accuracy and completeness are extensively discussed in Shand *et al.*, (2010) to which the reader is referred for details. Table 5 shows the 1 hour duration H_{sig} for events with ARI from 1 to 100 years.

Table 5: Summary of Spatial Variation in One Hour Exceedance H_{sig} along the NSW Coast (Shand *et al.*, 2010)

Buoy	H_{sig} (m) ± 90% CI			
	1 yr ARI	**10 yr ARI**	**50 yr ARI**	**100 yr ARI**
Brisbane	5.1 (± 0.2)	6.6 (± 0.3)	7.6 (± 0.4)	8.0 (± 0.4)
Byron Bay	5.2 (± 0.2)	6.4 (± 0.2)	7.2 (± 0.3)	7.6 (± 0.3)
Coffs Harbour	5.2 (± 0.2)	6.7 (± 0.3)	7.7 (± 0.4)	8.1 (± 0.4)
Crowdy Head	5.4 (± 0.2)	7.0 (± 0.4)	8.0 (± 0.5)	8.5 (± 0.5)
Sydney	5.9 (± 0.2)	7.5 (± 0.4)	8.6 (± 0.5)	9.0 (± 0.5)
Botany Bay	5.7 (± 0.2)	7.4 (± 0.3)	8.6 (± 0.4)	9.1 (± 0.4)
Port Kembla	5.4 (± 0.2)	7.1 (± 0.3)	8.3 (± 0.4)	8.8 (± 0.5)
Batemans Bay	4.9 (± 0.2)	6.3 (± 0.4)	7.3 (± 0.5)	7.7 (± 0.5)
Eden	5.4 (± 0.2)	7.0 (± 0.3)	8.1 (± 0.4)	8.5 (± 0.5)

Results from Shand *et al.,* (2010) showed the mid NSW coast to exhibit the highest extreme wave climate with 100 year ARI (1 hour H_s) heights of 9.0 m at Sydney and 9.1 m at Botany Bay. Extreme wave height decreases for locations to the north and south, with 100 year ARI (1 hour H_s) values of 8.0 m at Brisbane and 8.5 m at Eden. Batemans Bay and Byron Bay exhibit the lowest extreme heights, with 100 year ARI (1 hour H_s) heights of 7.7 and 7.6 m respectively. The extreme values of waves arriving from the north to east directions were found to be approximately 25% lower than the 'all direction' values. Extreme wave events from the east to south-east were approximately 5% lower than the 'all direction' values and extreme waves arriving from south of south-east were typically equivalent to the 'all direction' values.

2.1.4 *Climate Variability on the NSW Coast – El Niño, La Niña and the IPO*

El Niño and La Niña are short-term phases of variability in climate that generally last 2 to 4 years. While the physical features, and effects, defining the two phases are well known, the causation mechanism is not. During either phase one of the phenomena are dominant but the other may still occur from time to time.

The El Niño phase produces relatively quiescent conditions on the NSW coast. Hence the El Niño phase is usually associated with periods of beach and dune building where the modal beach profile reflects the bulk of active sediment being onshore and there being weak offshore bar conditions. The La Niña phase tends to produce stormier coastal conditions on the NSW coast with a greater tendency for onshore winds and storm cell development in the lower Coral and the Tasman Seas. During a La Niña-dominated period the modal beach profile has less sand in the sub-aerial beach and dune system, and more in the offshore bar formations.

There is mounting evidence of a cyclic phenomenon with a periodicity of 60 or so years. This may be associated with the phenomenon termed the Inter-decadal Pacific Oscillation (IPO). Presently, relatively little is known about this phenomenon; its generating mechanisms and impacts. However, the available coastal information points to periods of approximately 30 years of dominantly quiescent periods, though still with some storms during strong La Niña phases, followed by approximately 30 years which are dominated by storms, again with some breaks during strong El Niño phases. The usual feature of the 30 years of storms is not just their intensity but also their tendency to group or follow on before full beach recovery can occur. Helman (2007) and Callaghan and Helman (2008) have recently examined the available information in some detail and their work supports the concept of inter-decadal cycles of storm activity and coastal response.

From the mid-1970s until recently there were few tropical cyclones that tracked down from the Coral Sea and had impacts on the NSW coast. Also during that 30 year period there were few intense east coast lows. Therefore this period featured a marked beach and dune-building phase. Since about 2005 there has been a notable increase in the development of intense low-pressure cells in the Coral and Tasman Seas, often following on from one another before the beach has had the opportunity to recover.

The 30 years from the mid-1940s until the mid-1970s were marked by a succession of storms that caused major coastal damage and a number of cyclones that tracked south from the Coral Sea and along the northern NSW coast. Prior to the 1940s reliable evidence is more difficult to access due to the paucity of the weather records. However, early aerial photos, family snapshots and tourist postcards show wide sandy beaches during the 1920s and 1930s and there are few reports of storm damage, with one or two exceptions. Callaghan and Helman, (2008) provide a detailed tabulation of storm activity on the northern NSW coast.

2.1.5 *Climate Change – Coastal Impact Implications for the NSW Coast*

Changes in storminess (i.e. intensity, frequency and direction) are likely to alter the modal position, shape and dynamic equilibrium of beach profiles. A greater storminess would tend to shift the equilibrium profile and therefore the shoreline, landward. Lesser storminess will likely have the opposite effect. A change in the net wave energy flux due to weather systems shifting latitudes (Hemer, 2012) is anticipated to alter beach alignments on exposed and semi-exposed coasts. This in turn will exacerbate existing beach response e.g. erosion or accretion of different ends of a beach compartment (Short *et al.*, 2000).

A further issue is the enhancement (or reduction) of longshore drift systems around headlands. This could cause the re-starting (or conversely a reduction) of supply into a compartment as well as an enhancement of losses around down-drift headlands.

The impact of changes in wind energy flux and rainfall on dune stability is often overlooked. An enhancement of wind born losses inland as a result of losses in dune stability can produce significant shoreline erosion (Gordon, 1992). Changes in rainfall regimes and patterns may impact dune stability through elevated phreatic levels, pore pressure changes and vegetation changes (Engineers Australia 2012).

A recent development has been the postulation that anthropogenic climate change could bring with it an increased acidification of the oceans (Geosciences Australia, Oz Coast - Australia Online Coastal Information, Laxton 2009). It has also been proposed that such an increase in acidification will reduce shell production and increase shell degradation. Beaches with adjacent offshore reefs commonly have moderate to high percentages of shell making up their bulk volume. A loss of shell content would translate to a loss of sediment bulk and hence enhanced shoreline recession.

To date, most emphasis has been placed on sea level rise. The warming of the oceans with a consequent expansion of the water will affect differently coastlines depending on location including latitude and resident ocean current systems. Additionally, the delayed influence of land-based ice melt will also contribute to sea level rise, however, this may be offset by the increased precipitation at higher elevations and hence the growth of high altitude ice fields.

To date the IPCC (2001; 2007a and 2007b) has produced a range of sea level rise scenarios of which Australian states and the Commonwealth have tended to adopt the highest (DCC, 2009), although some argue the highest IPCC scenario is less than the potential highest sea level rise scenarios if ice melt is included at an earlier stage. Currently there is a proclivity, in NSW, to use a sea level rise projection of 0.4 m by 2050 and 0.9 m by 2100 (DECCW NSW, 2009, now repealed). While it has no jurisdictional power, the Commonwealth assumed a sea level rise of 1.1 m in its 2009 national coastal vulnerability assessment (DCC, 2009).

2.2 Avoca Beach, NSW

Avoca Beach is located within Bulbararing Bay between Broken Head and Tudibaring Head near the northern boundary of the Sydney Metropolitan Area and it includes the townships of South and North Avoca (Figure 2.4). In this section an overview of the site, including geomorphology and geological evolution, is presented followed by discussion on the compartment sediment budget. An in-depth description of relevant coastal processes at the study site, including wave and water level characterisation, is presented in Appendix A.

2.2.1 Evolution

Avoca is a classic example of the upper reaches of a small drowned river valley. At the sea level minimum 17,000 years BP, today's Avoca region would have consisted of four small creeks, deeply incised into the bedrock, joining together just to the west of the current lagoon entrance. From there they flowed out towards the coast, over 20 km away, initially through a valley whose ridges are now characterised by the offshore reef extensions of the headlands (Figure 2.5*).

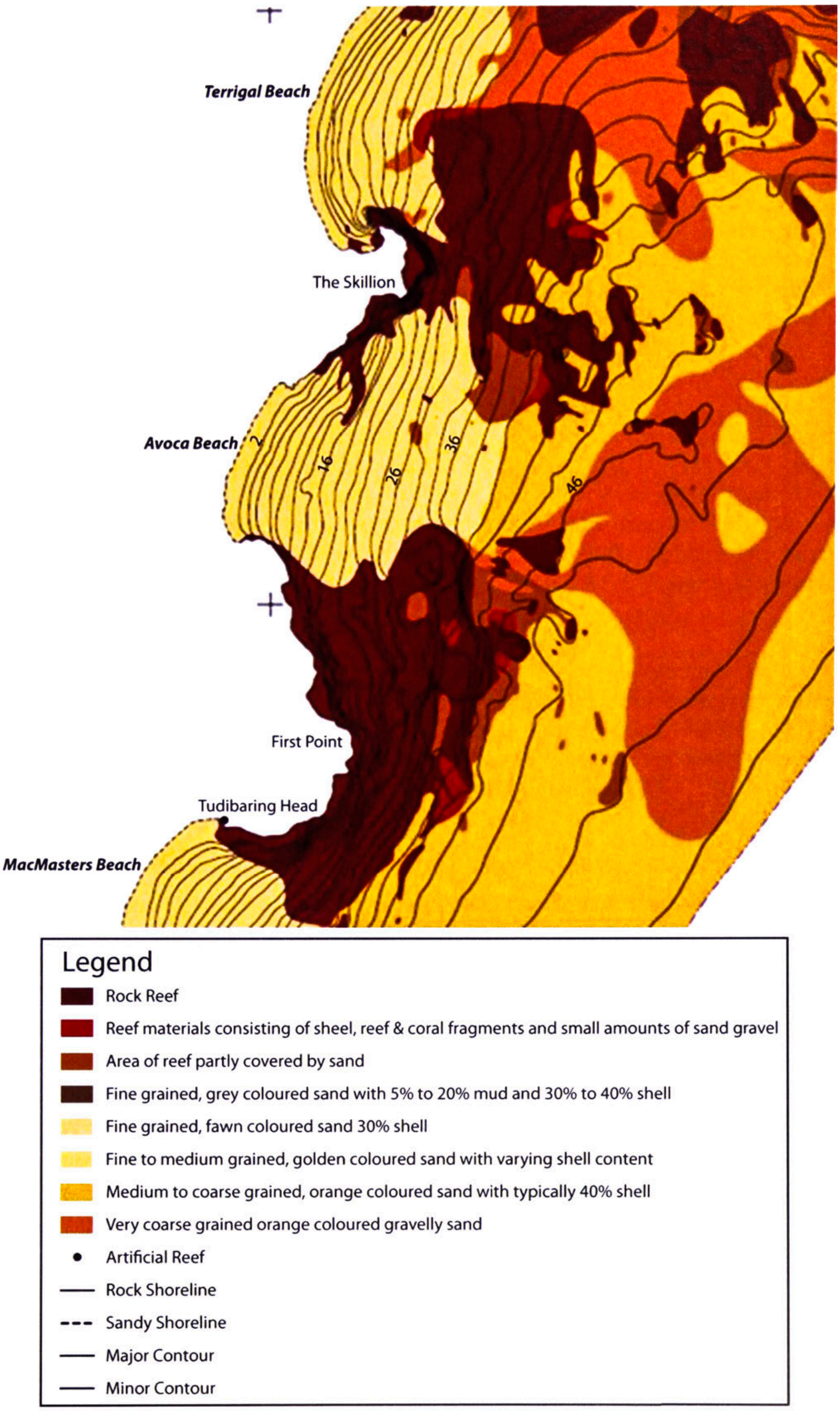


Figure 2.5* Avoca Beach Sedimentology (Source: NSW Department of Commerce): *The Avoca coastal compartment is characterised by large headlands and extensive offshore reefs isolating it from adjacent coastal compartments.*

The steepness of the catchments of the creek system in the vicinity of the present day Avoca area would have likely resulted in the scouring out of any of the old Pleistocene beach deposits during the low still stand.

As the sea level again rose, during the Holocene transgression, sediments were transported up the offshore Avoca valley to form the present day beach system. Given the strong valley/ridge formation offshore of the present day shoreline, it is likely that a fixed volume of sediment was available to the beach building process. As the Holocene still stand was reached the beach system stabilised, forming a sand berm across the headwaters of the four creeks, thereby creating a lagoon, with four arms. While there was some infill at the entrance, as a berm was formed, the main infilling of the lagoon has been from terrestrial sediments washed down from the catchments of the creeks. This terrestrial sediment infill is progressively turning the open water areas of the lagoon into wetlands.

The present day lagoon entrance demonstrates the characteristics expected of an Intermittently Closed and Open Lake or Lagoon (ICOLL). This includes breakouts and entrance scour during times of heavy rain and infill, a short period of tidal behaviour, then reformation of the berm from sand in the active beach system (Gordon, 1990). The lagoon entrance reportedly sometimes displays a tendency to drift south during breakout (PWD, 1994). This is possibly a function of differential wave set-up in the embayment. Figure 2.5*.1 shows a conceptual model of coastal lagoon/ICOLL.

The configuration of the hinterland, the tendency of the unconsolidated sediments to adopt a planform dictated by the net wave energy flux, and the limited volume of sediment available from the Holocene sea level rise process have produced a relatively low, narrow, back-of-beach coastal strip to the south of the lagoon entrance. To the north of the entrance, these same factors have resulted in a broader, higher, back-of-beach dune formation.

2.2.2 Site Description

The 1.7 km long Avoca Beach is a moderately embayed beach that lies between two prominent 60 m high sandstone headlands. First Point, including Tudibaring Head to the south forms the southern boundary to the Avoca compartment. First Point is part of Cape Three Points, a large and dominant coastal feature with extensive offshore reefs (Figures 2.4 and 2.5). Broken Head, incorporating The Skillion, and again an extensive offshore reef formation (PWD 1989), is the northern headland for the Avoca embayment.

The headlands are of the Terrigal Formation, which comprises a series of siltstones and sandstones with minor breccia, claystone and conglomerate (PWD, 1994). The sandstone tends to be near water level and is overlain by the siltstone, so its slow erosion is unlikely to add much sandy material to the beach because the siltstone materials do not produce beach sized sediments as they erode.

The northern and central sections of Avoca Beach face approximately east-south-east (ESE), which is the predominant wave direction. The southern part of the beach faces north-east (NE) and is therefore more sheltered from wave action by the adjacent headland. The beach has a zeta planform shape; its alignment reflects the refraction/diffraction characteristics of the net wave energy flux from the SSE to SE direction and the dominance of the south and north headlands. Although not apparently deeply embayed, the extensive offshore reef extensions of the headlands (PWD, 1989) results in a greater level of embayment than might otherwise be assumed, based on the above water headland features.

The beach morphology is generally rhythmic with transverse bars and rips grading to rhythmic bars in the northern part of the beach. The beach face is relatively steep and swash zone grain size is coarse (PWD, 1994). The beach nearshore sediments extend seaward to a depth of about 35 m along a relatively steep nearshore profile (average slope of 1V:50H out to 35 m water depth). Rock reef separates this nearshore sediment from the adjacent nearshore sand bodies within the MacMasters (to the south) and Terrigal/Wamberal (to the north) embayments, although as the reef offshore of North Avoca is quite low in relief, it is unlikely to prevent sediment transport during storms. Typical sediment characteristics for Avoca are shown in Table 6.

Table 6: Sediment Characteristics in Avoca Beach (source: ABSAMP Surf Life Saving Australia)

Site	Location	Grain Size D_{50} (mm)	% Carbonate
North Avoca	Swash	0.31	45
Avoca	Swash	0.26	30

In the offshore region there is a change in sediment from more typical beach and active offshore profile sand to the coarser "Inner Shelf Sand" at a depth of 35 m. Given that in the Greater Metropolitan Region the outer limit of active profile movement is approximately 40 m (Gordon 1990b, 2009) the clear sediment break at 35 m could reasonably be adopted for the purpose of this study as the outer limit of the coastal processes for the Avoca coastal compartment.

Avoca Lake backs the centre of the beach and opens during flood events. The beach north of the lake's entrance is generally referred to as North Avoca with the beach to the south referred to as Avoca.

The beach is backed by a dune system which increases in height towards the north due to its greater exposure to prevailing onshore winds and wave action. This beach/barrier encloses Avoca Lake, which like Cockrone Lake to the south at Copacabana-MacMasters, and Terrigal and Wamberal Lagoons to the north, is only occasionally open to the ocean. The southern portion of the beach has a relatively flat beach and offshore slope due to the sheltered nature of this end of the embayment. It is backed by a now residentially developed, but underlying, sandy dune area that has an elevation of approximately 3 to 5 m above mean sea level at the seaward end of the residential lots.

To the north of the lagoon entrance, the northern section of the embayment demonstrates its exposure to a higher wave climate than the southern end. Hence there are more commonly offshore bar formations. Between the residential development and the back of the sandy beach there is a well-developed dune region that is generally 20 to 30 m wide. This provides a storm cut buffer that has, at times such as in the 1970s, been eroded back to the property boundaries. Subsequent dune restoration works have re-established this buffer. However, its vulnerability to changes in sea level and net wave energy flux requires careful consideration. Figure 2.5.2 shows diagrams of representative beach profiles for North and South Avoca.

Cliff erosion may add some sediment to the compartment over time, however, much of the cliff material in this area is siltstone, mudstone and clay (PWD, 1994) with only very small percentages of sandstone, or sandy material suitable to be retained in the coastal processes of the embayment. The finer material contained in much of the cliff formations is rapidly transported offshore to be deposited in the mid shelf muddy zone.

2.2.3 Sediment Budget Considerations Present Day

There is no evidence of present day longshore drift into or out of the Avoca Beach embayment. The extensive offshore reefs and the large headlands isolate it from the adjacent compartments. The reefs, which extend down to near the offshore limit at 35 m depth, 2 km offshore, combined with the fact that the offshore profile is concave up, means there is likely to be no present day supply of sand to the sediment budget of the compartment. Figure 2.5.3* presents a conceptual model of sediment budget within the Avoca compartment and nearshore bathymetry.

While the entrance berm of the lagoon is of a dynamic nature, there is no evidence suggesting any long-term migration of beach sand into the lagoon. This is because the relatively short time the lagoon is tidal and hence the lack of an enduring process to develop a flood tide delta. The coarser fraction of the terrestrial sediments from the catchment are being trapped towards the rear of the lagoon, in each of the four embayments, and do not appear to be supplying beach sized material into the open coast compartment, although much of the finer fractions of terrestrial sediments are discharged during breakout.

Assuming that the shell supply to the beach from the offshore reefs has reached a long-term state of balance with the rate of shell breakdown, Avoca demonstrates the characteristics of a closed coastal compartment. During severe storms, the beach and dunes, erode and escarpments form at the back of the beach. The sand moves offshore to form bars but is contained within the compartment by the headlands and offshore reefs. During the ensuing quieter periods, the sand moves onshore again to reform the beach and the dunes. Depending on the severity of the storm, the recovery phase may be relatively short or may take some years, as it did following the storms of the 1970s.

During the extreme storm events, large scale "mega rips" tend to form within the relatively embayed beaches of the Central Coast (Short, 1985; Evans *et al.*, 2000). Mega rips provide a mechanism for the seaward transport of sediment to considerable depths and possibly even the inner continental shelf where it may have difficulty returning to the beach (i.e. permanently lost to the compartment). Localised erosion associated with rip development has been observed by Council officers on Avoca beach both during and immediately following storms in both 1974 and 1978 (PWD, 1994). Large scale mega rips have been observed by Council officers on the beach during storms. The erosion associated with these rips is reported in PWD (1994) to have directly threatened development north of Avoca lagoon entrance.

Similarly the lagoon entrance and the adjacent beach experiences a state of dynamic equilibrium with breakouts and closures resulting in short-term beach cut and fill of the adjacent berm. That is, while in the very short-term the lagoon entrance berm is a source of sand for the surf zone, it rapidly becomes a sink as the entrance closes. However, overall it is neither a source nor sink in the medium term as the berm simply rebuilds to its former shape. Only lagoon entrances that remain open for extended periods because of the tidal volume of the estuary, such as Narrabeen Lagoon, behave as a sink as the flood tide delta progressively encroaches into the lagoon.

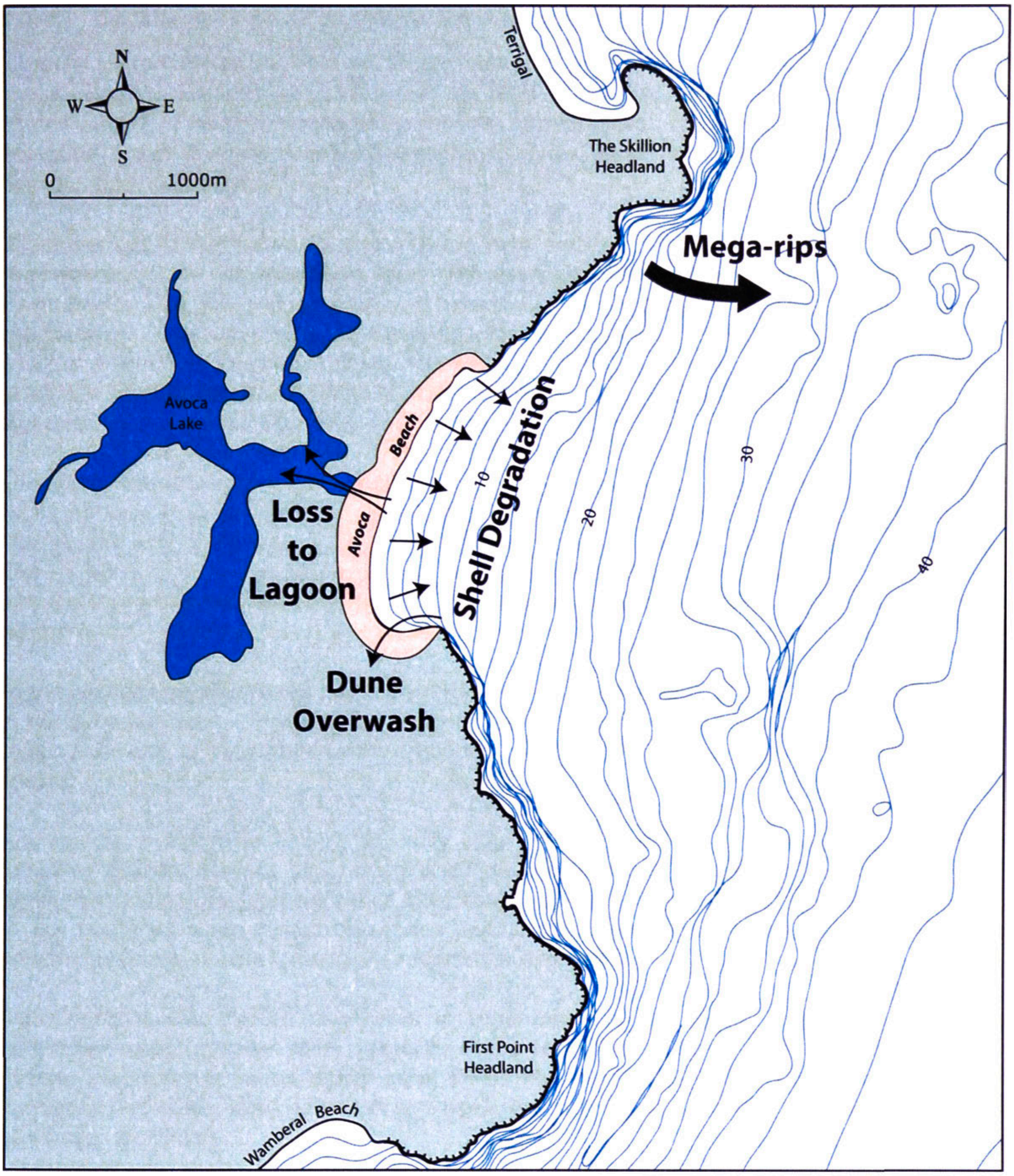


Figure 2.5.3* Avoca Bathymetry and Conceptual Sediment Budget: *There is likely no sand supply to the compartment sediment budget; potential sediment losses are through (i) lagoon sequestration, (ii) dune overwash, (iii) mega rips and (iv) shell degradation.*

2.2.4 Sediment Budget Considerations with Climate Change

Although Avoca Beach is believed to be currently in a state of dynamic equilibrium it is potentially quite vulnerable to changes in sea level and/or net wave energy flux because of the limited volume of sediment contained within the compartment. It has a potential vulnerability to alteration in shell production or shell degradation rates, lagoon sequestration, loss through mega rips and dune overwash.

Given the size of the headlands and offshore reefs and the lack of excess sediment in adjacent compartments it is not considered likely that even significant changes in sea level and/or net wave energy flux will trigger longshore movement of sand into or out of the Avoca Beach compartment. Similarly, it is considered highly unlikely that climate change will trigger any onshore or offshore movement across the offshore boundary of the compartment. However, a rising sea level and/or an increase in wave energy is likely to cause the entrance berm of the lagoon to be overtopped and rolled back further into the lagoon.

Combined with the impacts of a sea level rise and/or change in wave energy flux the lagoon berm roll back is likely to produce a three dimensional response from the active beach system. That is, not only is there likely to be shoreline recession in response to sea level rise but also there is likely to be a component of recession produced by the on-shore loss of beach sediment into the lagoon as the berm will need to be larger in order to accommodate the greater berm height.

In the northern section of the bay the principal issue is the limited amount of material available in the dune formation. Experience during the 1970s suggests that well developed dunes in this region were only just sufficient to withstand the storm cut produced by the combination of 1970s storms.

Any change in net wave energy flux may alter the alignment of the embayment. Given the relatively delicate balance and proximity of developed assets to the back of the beach any significant change of alignment would have consequences for both ends of the beach. A review of the predicted wave climate scenarios and a qualitative assessment of the sensitivity to potential changes in wave climate are reported in Appendix D.

Climatic changes to rainfall may result in either more or less lagoon breakouts. A greater number of breakouts mean more instability of the beach in the vicinity of the entrance. A lesser number of breakouts mean higher berm levels and hence higher flood levels in the lagoon. Further, a rise of sea level will result in a higher berm and hence higher flood levels, regardless of changes in rainfall.

An increase in average lagoon levels will result from increased entrance berm levels. This will produce two separate impacts. Firstly the elevated lagoon levels will be akin to setting the lagoon back in time in regard to the fringing ecology and the ability to accept sediments from the catchment. Secondly, it will also increase the water table elevation in the beach and the phreatic line profile through the back-of-beach sediment deposits thereby decreasing the stability of the foundations of the residential development in this region.

The question of shell production and degradation also need to be considered (Laxton, 2009). Given the relatively high proportion of shell material making up the total volume of material available in the compartment, a reduction in the volume could significantly increase shoreline recession, over and above what would otherwise be expected. However, this vulnerability is expected to be minor within the timeframe considered for this study. With some researchers postulating acidification of the oceans as a result of climate change (Guinotte and Fabry, 2008; Wright and Davidson, 2007), with a resulting drop in shell production and potential increase in degradation, it is pertinent to consider a sensitivity analysis of what a reduction in shell might mean. Unfortunately, at this point of time, the issue of acidification and potential shell loss is unclear with some researchers convinced it will occur while others such as Carter (2010) argue that it will not.

The dunes at the northern end of the beach are of sufficient elevation that even a 0.9 m sea level rise is unlikely to result in losses due to overwash. However, at the southern end of the embayment, the relatively low relief of the area immediately behind the present-day beach means that overwash losses are likely to occur as the area behind the current beach builds up to the same relative level as exists today between the ocean and the land. That is, for the low-lying areas it could be expected these will potentially elevate by up to 0.9 m.

In summary the key issues to consider with climate change are (Figure 2.5.3*):

- Loss of sediment due to lagoon sequestration;
- Loss of sediment via overwash at the south end of the beach;
- Loss of sand through large scale "mega rips" during extreme storm events; and
- Potential shell degradation.

2.3 Cabarita Beach, NSW

Cudgen Headland is the northern point of the Cabarita (Casuarina-Salt) compartment. It is approximately 10 km south of the border between New South Wales and Queensland. The Cabarita compartment stretches 8 km south from Cudgen Headland to Norries Head in the village of Bogangar and includes in the central-north section, the recent developments of Casuarina and Salt (Figure 2.6). In this section an overview of the site, its geomorphology and its geological evolution (Figures 2.7 and 2.7.1) are presented. The sediment budget is also discussed in this section while an in-depth description of the relevant coastal processes (including wave and water level analysis) at the study site is presented in Appendix A.

2.3.1 Evolution

The Cabarita compartment contrasts to that of Avoca. During the Pleistocene high sea levels, significant quantities of sandy sediment were deposited to form an extensive coastal plain on the seaward side of the basalt hinterland (Figures 2.7 and 2.7.1). The Pleistocene deposits are up to 50 m thick (PWD, 1979) and today are recognisable in two different surface forms: slightly elevated (former) beach ridges, with crest levels at about 6 m AHD, between 1.5 and 4 km inland from the current beach; and a low level (1 m to 2 m above sea level), swampy, sand sheet to the east of the beach ridges, between the ridges and Cudgen Creek. This type of overall Pleistocene deposit is termed an Inner Barrier (Thom, 1965).

Unlike Avoca, the Pleistocene deposits of the Inner Barrier at Cabarita experienced only minor erosion, in set drainage paths, as the sea receded to its 17,000 years BP low of -130 m, approximately 25 km offshore of the present Cabarita shoreline. The proximity, and drainage paths, of the Tweed Valley to the north may have accounted for the lack of runoff scour of the Pleistocene deposits at Cabarita during the lower sea level phase, however, the disturbed agricultural land in the northern end of the compartment may disguise a Glacial Low drainage path.

The Holocene transgression transported sediments up from the continental shelf as the sea level rose from 17,000 years BP to 6,000 years BP (Roy and Thom, 1981). This led to the formation of the Outer Barrier which is about 0.5 km wide at its widest part, although it may have been wider when first formed. The post 6,000 years BP longshore redistribution of sediments due to the dominant northward littoral drift system, may mean that today's Outer Barrier shoreline also reflects a state of long-term coastal recession since the barrier formed.

Furthermore, although narrower than the Inner Barrier, the land surface is higher with dune crests up to 10 m to 15 m above sea level. The Outer Barrier has been heavily sand mined, hence much of today's surface relief is artificial. However, the pre-mining evidence suggests the original dunes were of the same general elevation as today's surface and miners were usually required to restore the mined areas to something approaching its pre-mined form.

Based on experience elsewhere, the Outer Barrier dunes are generally higher than would otherwise be expected from Holocene beach ridge formations. This may mean that at some time in the past the vegetation of the Outer Barrier was destabilised and the barrier subjected to wind driven landward transport processes that formed transgressive dunes; an indicator of a past inland sediment movement by wind.

Cudgen Lake and Cudgen Creek form a continuous estuary system that was created when the sand of the Outer Barrier stopped migrating landward. They are the low-lying swale trapped between the Outer and the Inner Barriers. Both the Lake and the Creek are on the Pleistocene deposit as a result of the Holocene barrier forming a shore-parallel berm along the full length of the compartment. The resulting relatively flat drainage slopes of the Creek bed cause it to meander northward from the Lake, through the wide swale between the Inner and Outer Barriers, until it exits to the north of Cudgen Headland. The Lake and Creek therefore play no part in the present day coastal processes of the Cabarita compartment and would only do so if the Outer Barrier was breached. Even with the high range sea level rise projections this outcome is highly unlikely within several centuries.

2.3.2 Site Description

The Cabarita–Casuarina-Salt compartment is a 8 km long relatively straight beach facing east, extending from Norries Head in the south to Cudgen Headland to the north (Figure 2.6). Cabarita Beach consists predominantly of medium grained sand across its width (typical grain size, D_{50} = 0.25 mm; carbonate content ~10%), of a consistent size throughout the compartment.

In this region of the NSW coast there is a strong net northward littoral drift system due to the obliquity of the net wave energy flux to the overall coastal alignment (Hoffman, 1979; PWD, 1982; WBM, 2001; Chapman *et al.*, 1982). Both Norries Head and Cudgen Headland locally anchor the overall coastal alignment but do not protrude sufficiently to present a significant impediment to the average net northward littoral drift that dominates the region. The reefs off both headlands are of low relief and hence they also have minimal impact on the average net drift.

There is a slight zeta shape to the shoreline, immediately north of Norries Head and north of Cudgen Headland, characteristic of a beach with a south to north net longshore transport in the nearshore zone and which is indicative of the role of the headlands as intermittent interrupters of the northward littoral drift.

The main dune system is extensive and relatively high at typically 6 to 10 m AHD, the higher dunes being in the central beach area. It has been re-contoured after extensive sand mining in the 1960-70s to a more or less even slope in most areas, sloping seawards from the Kingscliff-Bogangar road which runs along a back barrier dune ridge at an of elevation 10 m AHD at its western extremity, some 250 to 300 m from the beach. The dune barrier is today covered with casuarina trees (*casuarina cristata*) where not developed. Diagrams of representative beach profiles are presented in Figure 2.8.

A recreation reserve exists at Norries Head. This reserve extends north-west from the headland to cover the narrow strip of land between Cabarita township and the beach. It terminates at the northern end of the township. A similar reserve at the northern end of the beach unit extends some 1.5 km south from Cudgen Headland.

To the west of the road, the barrier dunes gently slope down to low lying wetlands and the Cudgen Lake/Cudgen Creek system. This system flows out of Cudgen Lake towards the north behind the barrier dunes and discharges through minor rock training walls at Kingscliff, adjacent to the northern side of Cudgen Headland.

Development in the 2000s established new residential and commercial centres known as Salt and Casuarina Beach along the central portion of the beach. This development occupies a substantial part of the previously mined dune barrier commencing about 2 km north of Norries Head and is planned to extend northward eventually for a distance of about 5 km.

Erosion reportedly in 1974, although possibly in 1967, created a distinct scarp in the main dune which persists today. In the central beach area, the top of this scarp is some 10 to 12 m AHD, while to the north and south it reaches to a height of about 5 to 6 m. A well- developed foredune exists seaward of the toe of the scarp in the main dune (WBM 2001).

Inspections and surveys over the past 20 years show that this foredune extends up to 50 m wide, is typically well vegetated with sand binding spinifex grass, and is wind formed to a peak height of about 4 to 5 m AHD. At some locations, this foredune is separated from the main dune erosion scarp by a swale in which thick vegetation, both native and exotic, is prevalent.

A complicating feature of the Cabarita compartment is the shape of the offshore profile. While the normally expected concave-up shape of the profile extends offshore to approximately 35 m of water depth, around 2 km offshore, the profile then becomes convex up, out to 50 m of depth, approximately 7 km offshore. Insufficient information is available to interpret this anomaly, however, Hoffman (1979) and PWD (1982) speculated that it could be evidence of an offshore sand lobe.

2.3.3 Sediment Budget Considerations Present Day

A vegetated dune backs Cabarita Beach, between the beach and the development, with the rest of the Holocene Outer Barrier either developed or well vegetated. There is no evidence of any significant, present day, wind driven sand losses into the dunes along the length of the compartment. Hence this potential sink can reasonably be eliminated from sediment budget considerations.

The Cudgen estuary (Lake and Creek) forms a shore parallel feature inland of the Outer Barrier deposit. The estuary exits to the ocean to the North of Cudgen Headland. Therefore, while technically the estuary is within the Cabarita compartment its interaction is not with the Cabarita compartment but rather with the Kingscliff compartment. That is, there are no losses or gains from, or to, the Cabarita coastal compartment from the Cudgen estuary.

Hoffman (1979) and PWD (1982) pointed to a long-term recessional trend of the shoreline resulting in a progressive retreat of the active beach into the back-of-beach Holocene dune formation. This on-going loss of sediment from the Holocene formation should be considered, in terms of the sediment budget, as a "source" of material to the coastal process system.

Based on the previous offshore sedimentology and geology studies (PWD 1982; Hoffman 1979) the offshore boundary of the Cabarita coastal compartment can reasonably be assumed to be the 35 m depth contour. The inshore limit of the lobe, postulated by Hoffman (1979) and PWD (1982) is at 35 m, which is also the likely outer limit of the active coastal profile movement. However, the possibility of sediment exchange from the offshore lobe back into the inshore coastal zone was considered in the compartment sediment budget and long-term coastal response (see Table 11).

The key to understanding the Cabarita sediment budget is the consideration of the differential littoral drift occurring within the compartment, i.e. the difference between the net littoral drift of sediment flowing into the compartment from the south around Norries Head and the net littoral drift flowing out of the compartment to the north around Cudgen Headland. An yearly average net is used because in any one year the drift may vary markedly as both the gross and the net drift will be dependent on the wave climate for the year and the availability of sand on the south side of Norries Head. Refer to the Glossary of Terms section for useful definitions of technical terms.

As previously described, the headlands at Norries and Cudgen both act like groynes protruding through the active surf zone. Sand tends to build up on their south (updrift) sides until bypassing occurs when the updrift areas are filled to capacity. During times of elevated wave action a pulse of sediment can be moved around the headland, often partially depleting the updrift area, which has to re-fill before bypassing is again fully established. Figure 2.9* shows aerial photographs of a 'sand pulse' bypassing Cudgen Headland into Kingscliff, north of the Cabarita compartment.

This behaviour must be taken into account both when analysing historical shoreline data and when postulating the inner workings of the coastal process system of the compartment. Hence, while it is important to recognise that the "sediment pulse effect" can dictate shoreline and bar behaviour within the compartment, it is, however, the average net differential of inflow versus outflow, that determines whether the shoreline of the compartment is undergoing long-term recession.

Hoffman (1979) and PWD (1982) assessed the net drift around Norries Head to be 240,000 m^3/year and the average net littoral drift differential for the Cabarita compartment to be 110,000 m^3/year. This implies an average recession rate of 0.9 m/year that, as Hoffman (1979) and PWD (1982) noted, agrees surprisingly closely to the average 1 m/year recession rate calculated from the analysis of aerial photography and survey data. That is, the littoral drift differential into and out of the compartment is made up by long-term shoreline recession. Figure 2.10* shows a conceptual model of littoral drift through the Cabarita compartment.

Figure 2.9* Photographs of Sediment Pulse Around Cudgen Headland: *Cudgen Headland and Cudgen Creek training wall during normal conditions (above) and with sand pulse bypassing into Kingscliff (below). (Source Google earth®)*

WBM (2001) postulated that the net littoral drift at Cape Byron is similar to that at the Southern Gold Coast, which was calculated by Delft (1970; 1992) to be in the vicinity of 500,000 m^3/year. Based on 7 years of wave record (1989 – 1995), during a period that WBM recognises as unusually calm, they calculated the littoral drift at Tallow Beach, south of Cape Byron, to be 455,000 m^3/year and 464,000 m^3/year at Hastings Point resulting in a differential of 56,000 m^3/year over the 50 km between Cape Byron and the Tweed. Hence according to WBM (2001), there is only a modest differential mechanism for long-term coastal recession of any part of the coast between Byron and Tweed.

WBM (2001) proposed a differential figure of between 10,000 m^3/year and 15,000m^3/year along Cabarita, which they estimated equates to a long-term recession rate of 0.1 m/year. The Hoffman (1979), PWD (1982) and WBM (2001) estimates of littoral drift through the Cabarita compartment are summarised in Figure 2.10* and Table 7.

Table 7: Littoral Drift Through Cabarita Compartment

Previous Studies	Norries Head	Cudgen Headland	Differential Drift	Recession Rate
	(m3/year)	(m3/year)	(m3/year)	(m/year)
Hoffman (1979), PWD (1982)	240,000	350,000	110,000	0.9
WBM (2001)	~470,000	~480,000	10 - 15,000	0.1

Gordon (2011) indicated that the wave energy flux necessary to transport approximately 500,000 m^3/year around Cape Byron may exist, using the wave data employed by WBM (2001), however, there are other mechanisms that limit the availability of sand supply to achieve the wave energy flux potential. Therefore, the littoral drift of sand around Cape Byron is likely to be significantly less than at the Tweed with the differential having to be made up by long-term shoreline recession of the coastal compartments between Cape Byron and the Tweed. Interestingly, while the numerical model used by Gordon *et al.*, (1978) and relied on by Hoffman (1979) and PWD (1982) was calibrated against the survey/air photogrammetric record of build-up of a sand impoundment against the Brunswick Breakwaters following their construction in the 1960s, the WBM (2001) model was not.

While it can be argued that the Gordon *et al.*, (1978) study, subsequently relied on by Hoffman (1979) and PWD (1982), used data much of which reflected a stormy cycle of 30 years, the WBM calculations were based on wave data for a 7 year period during a relatively quiescent period, with a non-representative wave energy flux condition. Additionally, the WBM model assumed the drift rate at the Tweed to be in the vicinity of 500,000 m^3/year and so adjusted the calculated rates to achieve this figure, which required a substantial by-passing of Cape Byron and very little differential drift. Possibly, this is a direct artefact of the wave data WBM used.

Supporting this argument is WBM's calculated average recession rate for the region of 0.06 m/year that they rounded up to an "estimate" of 0.1 m/year. However, they appear to have not given consideration to potential recession due to historical sea level rise. That is, even if the differential were only 10,000 m^3/year to 15,000 m^3/year, as WBM (2001) calculate, the recession rate should most likely have been 0.3 m/year not 0.1 m/year.

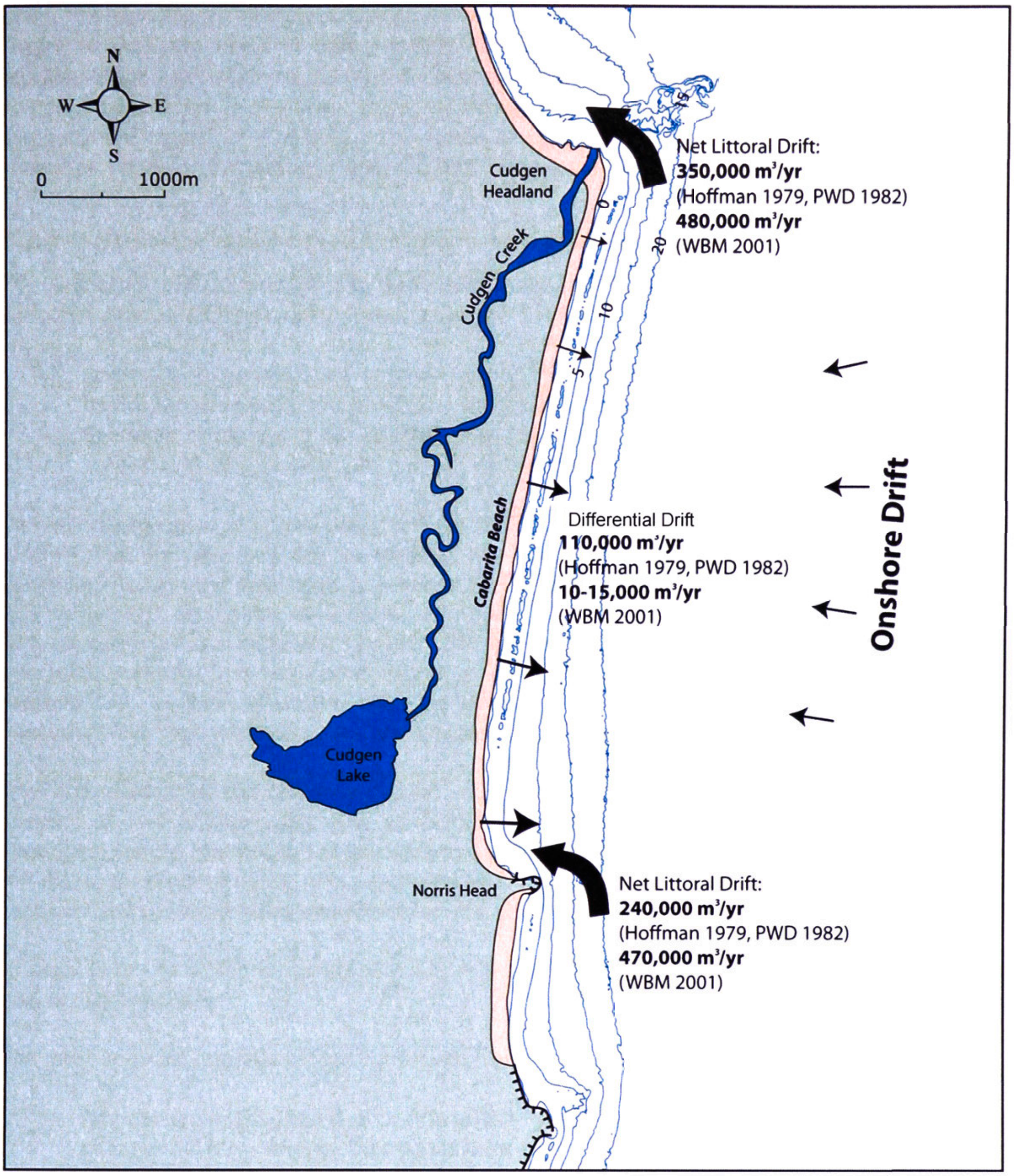


Figure 2.10* Cabarita Bathymetry and Conceptual Sediment Budget Model: *Different studies (Hoffman, 1979; PWD, 1982 and WBM, 2001) estimated different values for net littoral drift; potential sediment loss to the compartment is through differential drift, potential source is via onshore drift from the continental shelf.*

Given the significant differences (up to an order of magnitude) in the existing study results in regard to both the net drift and the drift differential, and the very real question about how representative each study is over a full Inter-decadal Pacific Oscillation (IPO) cycle of 60 to 80 years, it would be prudent to adopt a sensitivity approach when setting up the coastal compartment model for Cabarita. The lower and upper bounds of net littoral drift differential should be set to 10,000 m^3/year and 120,000 m^3/year, respectively.

2.3.4 Sediment Budget Considerations with Climate Change

The following components of the sediment budget within the Cabarita compartment were considered in the perspective of climate change:

- Sediment exchanges (loss or gain) from the beach to the dune system;
- In situ biogenic sediment production/degradation;
- Sediment exchange at the offshore boundary (onshore drift); and
- Littoral drift of sediment into and out of the coastal compartment.

Climate change may alter the wind and rainfall regimes in the Cabarita region, however, it is unlikely that the changes will de-stabilise the dunes and vegetation, given the intensity of development, and the incentives to manage the dune vegetation. Therefore, as for the present, it is considered reasonable to assume that it is not likely that the dunes will become a future sink, in terms of the sediment budget. Further, the dunes have sufficient elevation that an overwash sediment loss into the dunes at a higher (0.9 m) sea level is unlikely. As with the present day situation, however, the long-term recession of the shoreline into the Holocene formation will mean that the dunes are a source of material for the overall sediment budget.

The shell content of the beach and dune systems is low (~10%) and there is only a modest amount of reef offshore, not just at Cabarita but also for the coastline well to the south. Therefore, should acidification of the oceans occur, there are only minor implications in terms of this being a potential cause of a significant change in the overall volume of either sand in the compartment, or sand being moved into or out of the compartment, in the future.

In regards to the offshore boundary, a rise in sea level is likely to reduce any onshore sediment drift at the boundary.

The most relevant potential issues to consider are:

- Any change in the littoral drift differential demand within the compartment as a result of changes to wave energy flux because of alterations in the location of weather systems (latitude shift in the weather systems);
- Changes in the net drift into or out of the compartment due to the greater outstand of the headlands from the coast, that, is their increasing "groyne effect" as a result of a raised sea level at the beach, and enhanced beach recession; and
- Changes to the sand supply to the compartment from the south because of changes to the availability of sand from the compartments to the south.

A review of the projected wave climate change scenarios and a qualitative assessment of the sensitivity to potential changes in wave climate are reported in Appendix D.

2.4 Conclusions on Site Characterisation

The two sites present constraining geological settings and process regimes that are representative of coastal sediment compartments and beach types located within the NSW coast. At both sites, the geological settings define how sediment is exchanged between and on compartments. The main points to consider in the assessment of coastal response are presented below.

At Avoca Beach:

1. The dominant sediment transport process within the compartment is cross-shore with the extensive offshore reefs and large headlands isolating it from the adjacent compartments.

2. Avoca is currently in a state of dynamic equilibrium, however, it is potentially vulnerable to changes in sea level and/or net wave energy flux because of the limited volume of sediment contained within the compartment. In particular the main issues to consider are:

- Direct impact of SLR on shoreline recession;
- Alteration in shell production or shell degradation rates;
- Lagoon and lagoon barrier sediment sequestration;
- Sediment loss through dune overtopping and overwash; and
- Sediment loss through "mega rips" during major storms.

At Cabarita Beach:

1. The dominant sediment transport is a net northward littoral drift due to the obliquity of the net wave energy flux to the overall coastal alignment. The headlands at the northern and southern end of the beach do not present a significant impediment to the northward net littoral drift.

2. Cabarita Beach is in a state of long-term recession caused by sediment imbalance within the compartment. It is expected that sea level rise will exacerbate recession. The main issues to consider in the assessment of future coastal response are:

- Direct impact of SLR on shoreline recession;
- Changes in differential littoral drift caused by changes in wave energy flux;
- Alteration in sediment exchanges at the offshore boundary; and
- Changes in sediment supply from the south due to increased capacity of headlands to impound sediment with SLR and/or decreased sediment availability from compartments to the south.

3. Coastal Response to Short-term Processes

3.1 Storm Erosion

Coastal response to short-term processes refers to the rapid response of a beach to changing wave and water level conditions during or following ocean storms. During a storm, the beach will respond to wave attack by eroding. Beach erosion is defined as the removal by waves of sand from above mean sea level by a single extreme storm event, or from several storm events in close succession. Therefore, the timeframe considered for the assessment of coastal response is of the order of days to weeks to months i.e. the duration of a single or multiple closely spaced storm events.

During storms sand is eroded from the beachface and transported offshore to the nearshore bars and shoreface. As the bars build up, wave energy dissipation within the surf zone increases and eventually wave attack at the beachface reduces if storm conditions were to persist.

If the volume of sand available within the beach berm is not sufficient to meet the requirements for offshore transport and bar formation then erosion continues into the foredunes and ultimately in the backbeach area resulting in a threat to any infrastructure located there. Therefore, evaluation of beach erosion is crucial in the estimation of the potential hazard by storm events to coastal developments.

The beach response to a storm is generally manifested in a "storm bite" from the sub-aerial beach moving sediment offshore during the storm. The amount of sand (typically above 0 m AHD) transported offshore by wave action is referred to as "storm demand" and typically expressed as a volume of sand per metre length of beach *(m^3/m)*. This volume estimate can be converted to a horizontal "storm bite" setback distance for hazard zone mapping, and coastal planning and management purposes. In engineering practice, an allowance for geotechnical slope instability is also considered for the determination of the horizontal setback distance (Figure 3.1).

3.2 Evaluation of Storm Erosion

In current engineering practice, the storm demand is usually determined for a representative length of beach, and can consequently be related to a horizontal setback based on site-specific beach profiles.

Three approaches were considered in the estimation of the storm demand at the two study sites considered here:

1. Deterministic;
2. Semi-probabilistic; and
3. Fully probabilistic.

The deterministic approach widely used by practitioners is based on the analysis of historical beach survey records (when available) and photogrammetry data. Photogrammetry allows elevation data to be derived from historical aerial photographs. Historical beach profiles along the beach can therefore be obtained from the analysis of historical beach profile and volumes fluctuations. Gordon (1987) analysed 40 years of photogrammetry data at 19 coastal locations in NSW and derived empirical formulations relating storm demand to storm annual exceedance probabilities (AEP) or storm average recurrence intervals (ARI).

Following the approach utilising process-based models introduced in Carley and Cox (2003), Shand *et al.,* (2010; 2011) derived Synthetic Design Storm (SDS) from detailed statistical analysis of extreme storm characteristics including wave heights, periods and cumulative storm energy from available wave buoy data for a range of return periods. With a semi-probabilistic approach, SDS time series relative to different return periods can be used as inputs to a beach erosion model to provide estimates of beach profile fluctuations and storm demand for a range of probability of occurrence (Carley and Cox, 2003; Mariani *et al.,* 2012).

Callaghan *et al.*, (2008; 2009) and Ranasinghe *et al.,* (2011) implemented a fully probabilistic approach (Joint Probabilistic Method - Probabilistic Coastline Recession, JPM-PCR) to the data rich site of Narrabeen Beach NSW in order to obtain estimates of storm demand and long-term shoreline recession. The method was based on the derivation of joint probability distributions for extreme storm characteristics from wave buoy data, random generation of time series of storm sequences (clustering) and implementation of a simple dune erosion model to provide estimates of beach volume changes.

3.2.1 Historical Beach Profile Variations – Deterministic Approach

Estimates of extreme storm demands can be obtained from the analysis of historical beach profile variations due to large storms. Ideally, field data sets would incorporate pre- and post-storm beach profile and nearshore bathymetry. However, these data sets are often scarce and limited to selected key locations where beach surveys have been undertaken regularly and in concomitance with significant storm events. Narrabeen Beach and Bengello/South Broulee/Moruya Beach in NSW, and the Gold Coast in QLD are examples of data rich sites.

In the usual absence of such survey records, photogrammetry data is important in identifying historical profile variations and deriving estimates of storm demand. The main limitations of photogrammetry data are that: it provides no information on the underwater bathymetry, and analysis is restricted to the dates for which aerial photography exists (usually 2 to 10 years apart) which does not necessarily coincide with pre- and post-storm conditions.

As stated above, Gordon (1987) presented representative storm bite statistics for the New South Wales coast between Sydney and the Queensland border. Due to the limitations of photogrammetry, only eroded volumes above mean sea level were given. A distinction was made between volumes for "low demand, open beaches" and "high demand, rip heads" with the following equation presented:

- $V_L = 5 + 30 \ln(ARI)$ (1)
- $V_H = 40 + 40 \ln(ARI)$

Where:

- V_L and V_H are eroded volumes above AHD for "low demand, open beaches" and "high demand, rip heads", respectively (m^3/m);
- ln is the natural (base e) logarithm;
- ARI is average recurrence interval (years);

Due to the nature of the timing of the aerial photography, the eroded volumes may not have resulted from a single storm event, but rather the cumulative effect of a sequence of several storm events. Thus the ARIs presented refer to "erosion event" eroded volumes rather than erosion arising from single storm events of a particular ARI.

Gordon (1987) suggested that the erosion that occurs on the NSW coast for a 100 year ARI event falls between 140-220 m^3/m for low and high demand beaches, respectively. It was cautioned by Gordon (1990) that the indicated equations are suggested relationships only and that the database behind them is limited. The findings, however, provide a useful order of magnitude for the erosion volumes expected for the NSW coast and has been widely used by practitioners for the past 25 years.

3.2.2 Synthetic Design Storms - Semi-probabilistic Approach

Synthetic design storms (SDS) time-series were derived from relatively long-term records (in excess of 30 years) of wave measurements from nine wave buoys Australia-wide by Shand *et al.,* (2011). The methodology for the SDS derivation was introduced by Carley and Cox, (2003) and was implemented on a larger scale of wave buoy network by Shand *et al.*, (2011). The derivation of SDS for a range of return periods (ARI) is based on extreme storm statistics analysis including the following parameters: wave height, wave period, storm duration, storm shape and cumulative storm energy. Examples of 100 year ARI SDS are presented in Figure 3.2. Shand *et al.*, (2011) recommended that SDS derived within their study should be adopted for use in engineering design studies, hazard assessment and climate change adaptation studies.

As presented in Carley and Cox, (2003) SDS can be used as input to a process-based erosion model to generate estimates of beach profile fluctuations and storm demand under a range of storm events with different probability of occurrence. The methodology was recently applied to generate estimates of storm erosion at 50 locations around Australia (Mariani *et al.,* 2012).

For the purpose of this study, the SBEACH model (Larson and Kraus, 1989; Kraus and Byrnes, 1990) was implemented at Avoca Beach and Cabarita Beach. SBEACH has been developed and extensively verified with field and laboratory data collected during major American field experiments (Duck and Super Duck experiments, Larson and Kraus, 1989). In Australia, SBEACH was successfully calibrated and verified for a number of beaches including Warilla, Collaroy, Narrabeen, Wamberal and the Gold Coast (Carley *et al.*, 1998; Carley and Cox, 2003). At these sites, SBEACH was able to model measured storm erosion events. SBEACH is suggested in many state policies for the numerical modelling of beach erosion (Mariani *et al.*, 2012).

3.2.3 Probabilistic Approach - JPM-PCR

Ranasinghe *et al.*, (2011) presented a probabilistic semi-process based model (the Probabilistic Coastline Recession model, PCR). This model couples simplified erosion and accretion models with temporal forcing conditions (sequences of storm conditions followed by recovery periods) to provide estimates of storm erosion based on full temporal simulation of erosional and accretion events (Woodroofe *et al.*, 2012; Callaghan *et al.*, 2008). By including mean sea level changes in the temporal simulation, probabilistic estimates of shoreline position at a future date can be generated. A random process is implemented in PCR to generate sequences of storms sampled from joint probability distributions of storm characteristics (wave height, period, duration, etc.) derived from wave buoy data analysis (the Joint Probability Method, JPM, Callaghan *et al.*, 2008). For computational efficiency, simplified erosion models (Larson *et al.,* 2004; Kriebel and Dean, 1993) are used rather than more complete profile response models (although the authors note that such models could be incorporated).
The approach was successfully applied to Narrabeen Beach where the exceptionally rich, long-term beach survey record (32 years of monthly beach survey, (Short and Trembanis, 2004))

allowed model calibration (Ranasinghe *et al.*, 2011) and validation of model storm demand predictions. Callaghan *et al.*, (2009) compared JPM storm demand predictions at Narrabeen Beach to values predicted using the SDS method and observed that for return periods:

- Less than 3 years: SDS and JPM provided similar estimates;
- Less than 10 years: SDS predictions were non-conservative and JPM compared well with measured values; and
- More than 10 years: accuracy of predictions could not be evaluated for sampling error due to the "limited" 30 years record length.

Callaghan concluded that for higher return periods (>10 years), the validity of SDS and JPM predictions could not be compared and both were feasible methods. The key identified weakness of the SDS method under-predicting known erosion statistics when SDS is applied with a single storm, can be overcome with the use of multiple sequential storms as recommended in Carley and Cox (2003) and WA State Policy. That is, a 10 year ARI erosion event will involve more erosion than that caused by a single 10 year ARI storm event, but will be comparable to the combined impact of a sequence of two or three (10 year ARI) storm events.

While the JPM-PCR method presents a powerful framework for assessing short-term and long-term shoreline response, the reliance of the erosion and accretion models on site-specific calibration limits its application to the study sites considered here.

3.3 Avoca Beach

3.3.1 Previous Studies – Deterministic Approach

There have been a limited number of previous coastal hazard studies undertaken for this section of coastline, including PWD (1985), WRL (1988), PWD (1994), WBM (1995). These studies have all investigated the coastal erosion hazards caused by storm demand based on photogrammetric analysis of aerial photography. It should be noted that the more recent WBM (1995) study used results of the PWD (1994) storm demand analysis but re-contextualised them in a coastal management plan.

The storm bite analysis on Avoca Beach as performed by WRL and PWD, was based on the volume changes between 22/4/72 and 19/6/74; 9/1/77 and 2/8/78; and 23/8/84 and 18/8/86 measured above 0 m AHD and 2 m AHD. These sets of photographs separated the major storm events in June 1974, June 1978 and August 1986.

The PWD (1994) study reported that volume changes during storms were the largest in the central and northern parts of the beach. Maximum storm bite was measured between 22/4/72 and 19/6/74 just north of Avoca lagoon entrance. Here volume change of around 200 m^3/m above 0 m AHD was measured. The calculated storm bite in the southern section of Avoca was found to be significantly lower (around 50 m^3/m) due to its orientation offering natural protection for storm events originating from the south-east.

Table 8: Design Storm Demands from Previous Studies

Representative Profile Location	Volume of Storm Demand (m^3/m)		
	Previous Studies		
	PWD (1985)	PWD (1994)	WBM (1995)(1)
Avoca North	200	120-160	205
Avoca Central North	200	150-200	205
Avoca Central South	50	50-170	100-200
Avoca South	50	0-60	50-100

Notes:

(1) WBM (1995) study provides design storm erosion demand based on the results of the PWD (1994) study.

It should be noted that the design volumes of storm demand given in the WBM (1995) study were significantly higher than PWD (1994) on the northern section of the beach as they allowed for additional storm erosion due to formation of rips during the storm. Moreover, while all the photogrammetric analysis was based on the volume changes in the beach system due to predominantly south-east wave attack, it is important to consider the potential risk of storm erosion at the southern end by east to north-east waves and adopt conservative erosion extents on this section of beach.

3.3.2 Synthetic Design Storms

SBEACH modelling for storm demand was carried out for a range of storm events with probabilities ranging from 1 to 100 year ARI and for single and a sequence of two and three storms. Detailed reporting of model setup, calibration and results are presented in Appendix B. The 100 year ARI synthetic design storms used as input to the SBEACH model for Avoca and Cabarita Beach are shown in Figure 3.3. Predicted storm demands for the 1, 10 and 100 year ARI storm events are presented for three representative locations (Figure 2.4) along Avoca Beach in Figure 3.4. Storm demand predictions using the Gordon (1987) empirical formulations are also plotted. A summary of the values is shown in Table 9.

Table 9: Storm Demand Predictions for Avoca Beach

	Storm Demand (m^3/m)		
	Avoca South	Avoca Central North	Avoca North
Previous Studies	50-100	150-205	120-205
Gordon (1987) 100 yr ARI	140-220	140-220	140-220
3×100 yr ARI SDS	90	140	140

For the lower range return periods (less than 10 years), the SDS predictions were in reasonably good agreement with the Gordon statistics and historical photogrammetry evidence (Figure 3.4). That is, they are representative at the three modelled locations along Avoca Beach and for both single and clustering of storms, with the sequencing of three storms yielding, as expected, the higher range of storm demands.

For the higher return periods (more than 10 years), the single and sequencing of two storms significantly under-estimated storm demand in comparison to both Gordon predictions and site-specific photogrammetry analysis. The clustering of three storms, yielded predictions in reasonable agreement with the lower range of Gordon and predictions from previous studies in the northern, more exposed section of the beach. While in the southern, more sheltered part of the beach, SDS predictions (for 3 consecutive storms) also significantly underestimated historical photogrammetry evidence. Being a 1D model, SBEACH does not model 2D effects such a longshore sediment transport and rip currents, which could account for erosion under-estimations.

3.4 Cabarita Beach

3.4.1 Previous Studies – Deterministic Approach

There have been a number of previous coastal hazards studies undertaken for this section of coastline, including PWD (1982), WBM (1988), WBM (2001), Carley and Mole (2010).

The PWD (1982) and WBM (2001) studies investigated the coastal erosion hazards caused by storm demand based on photogrammetric analysis of aerial photography.

The storm bite analysis on Cabarita Beach performed by PWD (1982) was based on the volume changes between 1962 and 1975. From this analysis, the anticipated storm demand was adopted as approximately 200 m^3/m above AHD (Hoffman 1979; PWD 1982) and this is usually taken as a regional recommended design storm demand volume in coastal erosion assessment.

In their 2001 photogrammetric analysis of Cabarita Beach, WBM (2001) reported that the existing beach/foredune (1999/2000 photogrammetry) was partially eroded in the central to northern sections of the compartment as part of short-term cross-shore fluctuations (i.e. 1996 and 1999 storms). On that basis, the 200 m^3/m storm bite provision in the 1982 assessment was found to be potentially conservative and they adopted a reduced storm demand on exposed parts of the beach. On the other hand, the southern section of the beach unit was found to have exhibited substantial accretion since the 1960s and on that basis the full 200 m^3/m above AHD was used in the storm bite calculations. As discussed above, the central and northern sections having experienced recent erosion and taking this into consideration a reduced storm bite quantity of 160 m^3/m above AHD was adopted by WBM (2001) in these areas relative to the 1999-2000 profiles in determining the immediate hazard zone.

3.4.2 Synthetic Design Storms

SBEACH modelling for storm demand was carried out for a range of storm events with probabilities ranging from 1 to 100 year ARI and for single to a sequence of three storms. As described previously, detailed reporting of model setup, calibration and results are presented in Appendix B. The 100 year ARI synthetic design storm used as input to the SBEACH model is shown in Figure 3.3. Predicted storm demands for the 1, 10 and 100 year ARI storm events are presented for three representative locations (Figure 2.6) along Cabarita Beach in Figure 3.5. Storm demand predictions using the Gordon (1987) empirical formulations are also plotted. A summary of the predicted values is shown in Table 10.

Table 10: Storm Demand Predictions for Cabarita Beach

	Cabarita Storm Demand (m^3/m)		
	South	**Central**	**North**
Previous Studies	160	160	160
Gordon (1987) 100 yr ARI	140-220	140-220	140-220
3×100 yr ARI SDS	170	120	170

For the lower range return periods (less than 10 years), the SDS predictions were found to be within the range predicted using Gordon empirical formulations and historical photogrammetry evidence. At the three representative locations along Cabarita Beach, the single storm and the sequencing of two and three storms produced results within the lower, medium and higher range of Gordon's envelope.

For the higher return periods (more than 10 years), the single and sequencing of two storms significantly under-estimated storm demand in comparison to both Gordon predictions and site-specific photogrammetry analysis. The clustering of three storms, yielded predictions in reasonable agreement with the mid-lower range of Gordon predictions while they matched the storm demand predictions from previous studies in the southern and northern segment of the beach.

3.5 Summary of Coastal Response to Short-term Processes

While a fully probabilistic method (Callaghan *et al.*, 2008; 2009) presents a potentially powerful framework for assessing short-term shoreline response, site-specific calibration limits its application to a small number of data rich sites. Moreover, the extrapolation of storm demand predictions from stochastic simulations to high return periods (100 year ARI or 1% AEP) is limited, for sampling error, by the data record length.

Given that the actual annual probabilistic exceedance level selected in coastal erosion assessments is of the order of 1% AEP, i.e. 100 year ARI, the selection of a fully probabilistic method such as the JPM-PCR over a semi-probabilistic method such as the SDS approach is not presently feasible at the great majority of locations where data is generally limited.

The use of Synthetic Design Storms derived from long-term wave buoy records to drive refined process-based erosion models (Mariani *et al.,* 2012) offers a reliable alternative (Carley and Cox, 2003) to estimate storm erosion for different probabilistic scenarios at typical "data poor" locations. The erosion model's dependence on a limited number of calibration coefficients is a key factor in the applicability and transferability of the models at different locations where pre- and post-storm survey data record are limited or not available.

Results at the two case study sites show that the sequencing (clustering) of two or more storms is necessary to produce estimates of storm demand that match historical measurements. The application of the SDS approach to Avoca Beach showed that underestimation in prediction of storm demand for higher return periods is not uncommon. Or, the deterministic storm demand estimates by Gordon (1987) are overly conservative. Figure 3.6* summarises storm demand predictions using SDS at Avoca and Cabarita Beach.

A key limitation is that two-dimensional effects such as rip currents, sediment loss due to longshore currents and overwash which have been observed to occur at Avoca Beach during large storms, are not modelled in SBEACH, and are plausible reasons for the underestimation of predictions. Long-term coastal planning and hazard definition also requires a consideration of other processes apart from storm erosion.

The accuracy of the surfzone and nearshore bathymetry was found to be an important factor in the modelling of short-term erosion processes with under-prediction common when interpolation from offshore to the nearshore data is undertaken to compensate for lack of detailed nearshore surveys (Mariani *et al.*, 2012). Consequently, high quality nearshore survey data is a necessary input for erosion modelling reliability.

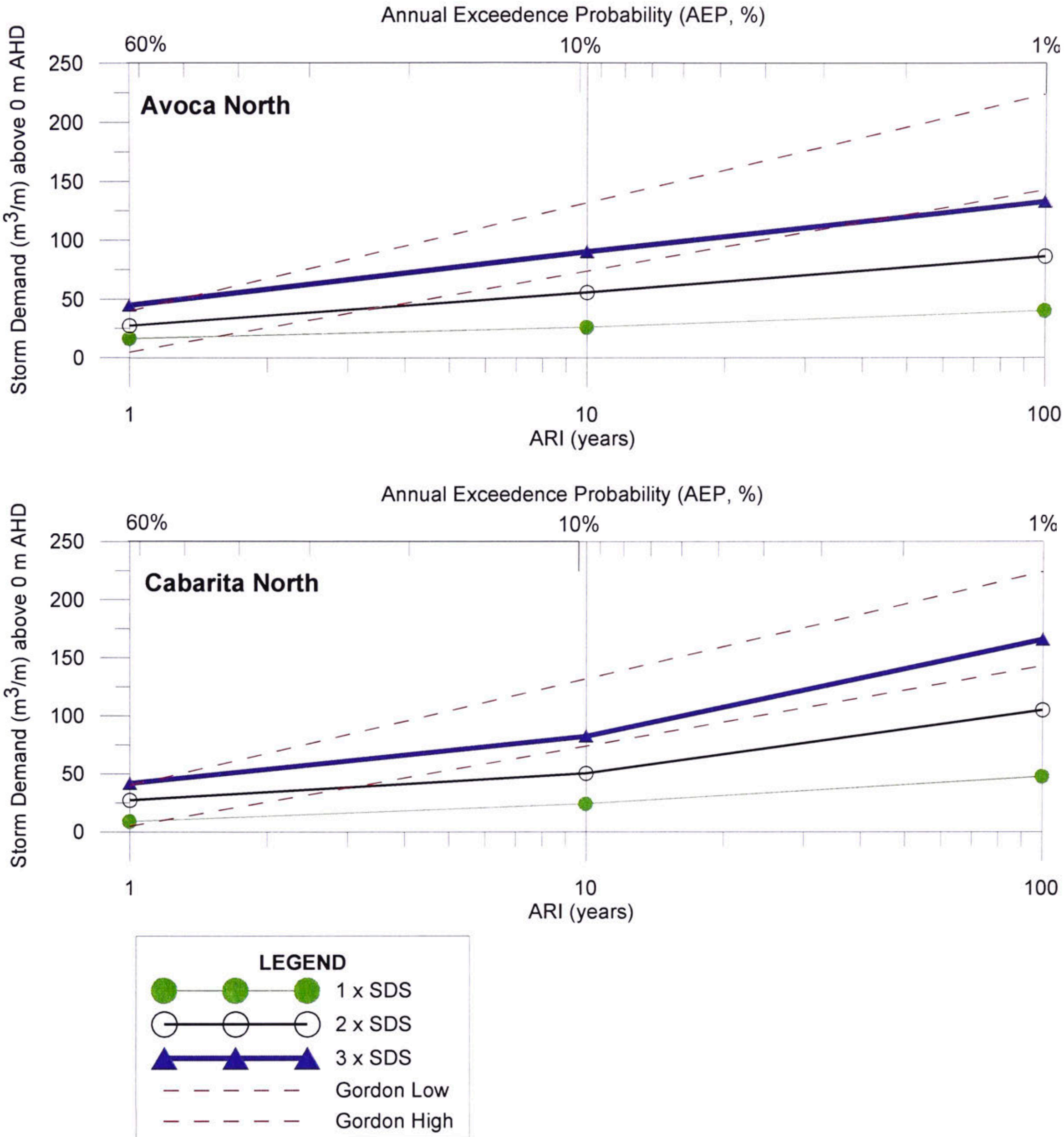


Figure 3.6* Summary of SDS Short-term Predictions: *Clustering of 3 consecutive storms (3×SDS) was necessary to produce erosion estimates within the range predicted using Gordon (1987) statistical method.*

The Marine LiDAR data made available by OEH for the two study sites proved adequate for the purpose of the modelling. However, the bathymetric data used in the modelling is only representative of a single morphodynamic beach state corresponding to when the survey was undertaken. The initial state of the beach is an important factor to consider. The contribution of the surfzone gradient and morphological features, such as sand bars, to the final erosion estimates are as important as the choice of the hydrodynamic input. Differing beach types occur in a spatial and temporal continuum with storm events and accretionary periods driving a transformation in beach type due to the co-adjustment of beach and surf zone morphology to re-establish dynamic equilibrium with the higher (lower) wave power.

As such, a more dissipative surfzone profile (at the time of the bathymetric survey) would lead to lower estimates in the prediction of storm demands. When detailed nearshore bathymetry data is available for different dates, the analysis and the modelling of the corresponding beach states is recommended.

3.6 General Conclusions on Short-term Response

1. Fully probabilistic methods (Callaghan *et al.*, 2008; 2009) present powerful frameworks for assessing short-term shoreline response. However, site-specific calibration limits its application to sites where extensive data record exists for both beach response, and wave and water level conditions.

2. The use of Synthetic Design Storms derived from long-term wave buoy records to drive refined process-based erosion models (Mariani *et al.*, 2012) offers a reliable alternative (Carley and Cox, 2003) to estimate storm erosion for different probabilistic scenarios at typical "data poor" locations.

3. To provide realistic predictions of beach erosion during storm events, storm clustering needs to be taken into consideration as well as two-dimensional effects such as rip currents, sediment loss due to longshore currents and overwash.

4. Surfzone and nearshore bathymetric data is crucial for the modelling of beach erosion processes.

4. Coastal Response to Long-term Processes

4.1 Shoreline Recession

Shoreline recession refers to the long-term trend of a shoreline to move landward in response to a net loss in the sediment budget. Additional shoreline recession is also predicted to result from future sea level rise.

Beaches undergo long-term fluctuations which may involve either the addition or removal of sediment. Those beaches receiving a net addition of sediment, are called accreting or prograding beaches. While still experiencing short-term erosion events, these beaches generally display a seaward movement or progradation of the beach-foredune system over time. Beaches undergoing longer term removal of sand are called receding beaches and experience a landward migration of the beach/ dune system. They are generally characterised by a prominent back beach escarpment which moves landward during major storm events.

The timeframe related to long-term processes is of the order of decades to centuries and millennia. However, for engineering assessments and coastal planning purposes, the timeframe considered is typically of the order of 50 to 100 years. For the purpose of this study, the 2100 future scenario was considered.

Current engineering practice considers separately:

- Ongoing underlying shoreline recession; and
- SLR shoreline recession.

Both are expressed in terms of change over years in volume of sand within the active beach system *(m^3/m/year)* and/or corresponding landward shoreline movement *(m/year)*.

4.1.1 Ongoing Underlying Shoreline Recession

Shoreline recession may result from increasing water levels and/or sediment loss due to imbalance in longshore/cross-shore sediment transport, aeolian sand transport or irregularities in longshore alignment due to beach rotation.

Long-term trends of underlying shoreline recession are typically estimated from the analysis of long-term data records of beach surveys or historical photogrammetry data by:

- Assessing the change over years in volume of sand within the beach and the dune system; and
- Assessing the shoreline evolution. Typically in NSW, the upper dune face (between +3 and +6 m AHD contours) would be used as the morphological indicator of the shoreline as it lies above the seasonal fluctuations of beaches.

As an example, Figure 4.1 shows the +4 m AHD contour position in 1967, 1987 and 2010 for Belongil Beach, Byron Bay, NSW.

4.1.2 Shoreline Recession due to Sea Level Rise

While it is a commonly applied theory that an elevation in sea level will result in recession of the coastline (Bruun, 1962; 1983; Cowell *et al.*, 1992; Komar *et al.*, 1997), much controversy remains in regard to the methods for quantifying the future recession due to SLR.

A number of methods for estimating coastal response to changes in sea level have been developed over the past 50 years. These methods include approaches based on basic geometric principles to more complex process-based assessment. While some methods are used more widely than others, none have been proved categorically correct nor adopted universally.

Mariani *et al.*, (2012) provided a general overview of methods to estimate SLR recession including the Bruun model (1962), the Shoreface Translation Model (Cowell *et al.*, 1992; 1995), the Komar *et al.*, (1997) Geometric Model of Foredune Erosion, the Probabilistic Coastline Recession model (Ranasinghe *et al.*, 2011), Shoreline Response Model (Huxley, 2009), etc.

The most widely known and applied model for beach response is that of Bruun (1962). The Bruun model assumes that as sea level is raised, the equilibrium profile is moved upward and landward conserving mass and original shape. This occurs by the following assumptions (SCOR, 1991):

1. The upper beach is eroded due to the landward translation of the profile;
2. The material eroded from the upper beach is transported immediately offshore and deposited, such that the volume eroded is equal to the volume deposited; and
3. The rise in the nearshore profile as a result of this deposition is equal to the rise in sea level.

Validations, limitations and critical reviews of the Bruun model application are provided within SCOR (1991); Cooper and Pilkey (2004); Cowell *et al.*, (2006) and Ranasinghe *et al.*, (2007). However, in general, while the overall principles of the Bruun model (i.e. an increase in sea level results in an upward and landward shift in the profile) can be verified for particular geomorphic and geologic circumstances, the quantitative accuracy of the Bruun Rule has not been verified.

4.2 Coastal Compartments - Sediment Budget Approach

In order to evaluate the applicability and relative merits of a deterministic versus a probabilistic approach in the perspective of a coastal compartment classification, a sediment budget approach was adopted for the present study.

A sediment budget approach provides a logical methodology for defining the boundaries and boundary conditions of coastal compartments. A sediment budget approach also provides the natural framework for evaluating long-term shoreline response to climate change.

For a given sea level, if more sand enters than leaves over/through the longshore, offshore and onshore boundaries of a compartment, then it accretes/progrades. Conversely, if more sand leaves than enters, it erodes/recedes. A sediment budget approach provides the methodology for examining "sources" and "sinks" of sediment associated with a coastal compartment thereby enabling determination as to whether there is a net gain (accretion) or a net loss (erosion), and hence the shoreline reaction.

Furthermore, if the sea level alters, as a consequence of climate change, then the sediment budget may also alter as the flow of sediment across the boundaries may change. The availability of sediment within the compartment to adjust to a sea level change may become limited. Similarly, the amount of sand entering or leaving a coastal compartment may alter if the net wave energy flux, or the net wind energy flux alters. The sensitivity of the overall budget, hence of the shoreline behaviour, to climate change impacts can be usefully tested using this approach.

4.2.1 Model Development

A simple two-dimensional model was developed for this study to be used as a platform to provide deterministic predictions and to simulate probabilistic variations of future coastal response. The model was based on a long-term sediment budget approach and a two-dimensional profile geometric transformation (Woodroffe *et al.*, 2012; Cowell *et al.*, 2006). The adopted approach is diagrammatically presented in Figure 4.2.

The model's simplicity was essential to allow the large number of iterations associated with the stochastic simulations required in this study. The choice of the model and its level of complexity and accuracy in the description of the coastal processes was not, per se, relevant in the perspective of this study, as this study aimed to provide a qualitative evaluation of deterministic versus probabilistic approaches at two contrasting coastal sites.

The model rationale is that any change in time of beach profile elevation (h) is constrained by the principle of sediment mass continuity which in simple terms translates to:

$$dh/dt \propto dQ/dt \qquad (2)$$

where Q is the net rate of sediment supply (loss) and depends on sediment exchanges at offshore/onshore/longshore boundaries and in situ production/degradation.

Horizontal translations of the beach profile, R (m), are driven by changes in:

- Sea level, S (m);
- Sediment budget; and
- Beach profile geometry.

A number of assumptions were adopted in order to simplify the recession model. A description of the model setup is presented in Appendix C. In particular:

- Embayments were reduced to representative two-dimensional beach profiles extracted from (OEH) Marine LiDAR data analysis;
- While the model is time-dependent, it is driven only by changes in sea level and gains or losses in the sediment budget rather than any hydrodynamic forcing. A single time step, present day to 2100 scenario, was implemented for the purpose of this analysis;
- A simple geometric translation was implemented in the model to provide analytical solutions to equation (2). The geometric transformation did not accommodate variations in sediment properties across the profile or profile control by hard structures such as substrate geology or adjacent headlands or engineered structures. However, this simplification was considered reasonable for this study due to the beach and shoreface profile characteristics at the two study sites.

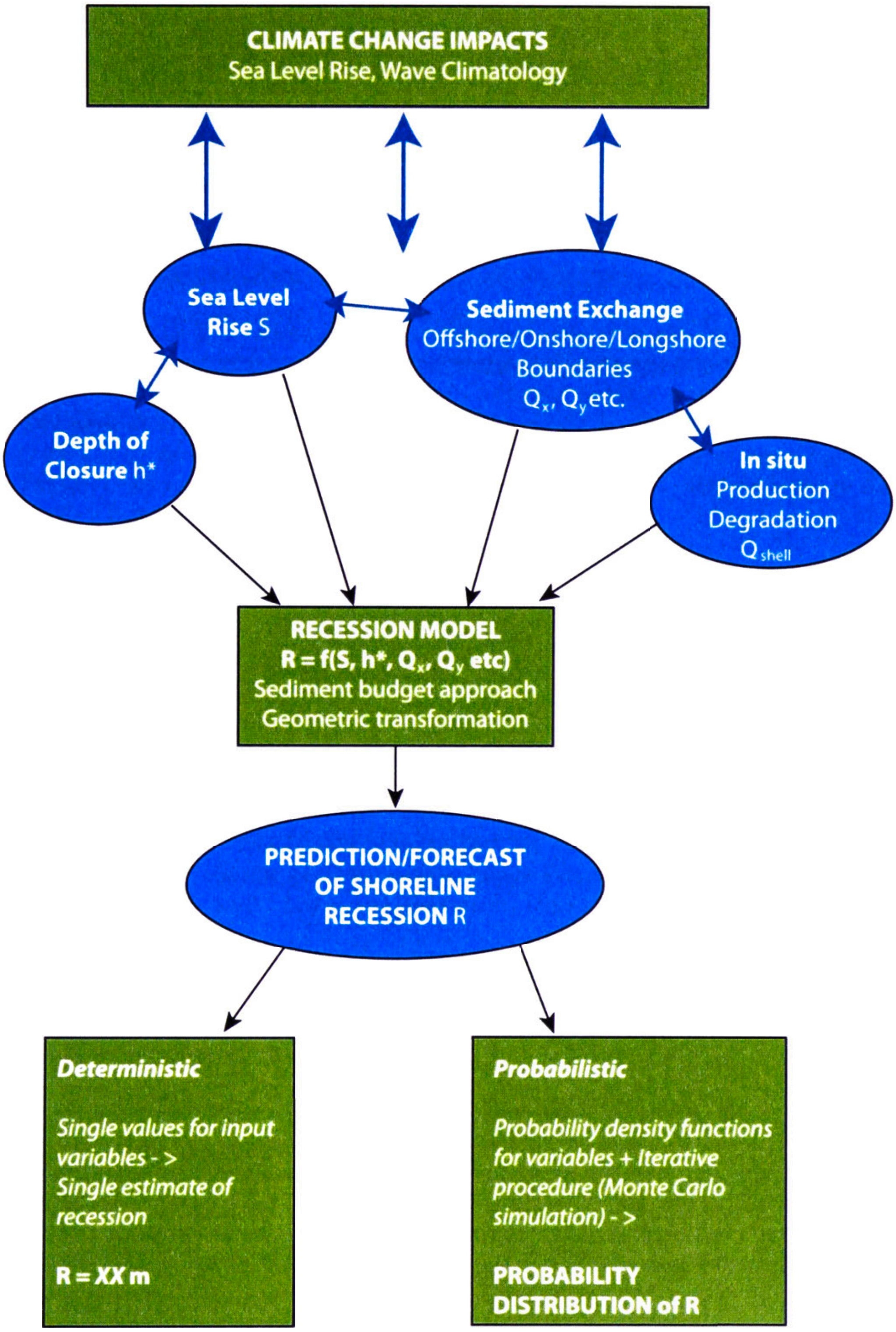


Figure 4.2* Flow Diagram of Probabilistic and Deterministic Approach: *Climate change will potentially impact coastal response by altering sea level and compartment sediment budget; these are used as input variables to a recession model to provide estimates of future coastal recession; a deterministic approach provides a single value estimate of recession, while a probabilistic approach provides a probability distribution of recession.*

4.2.2 *Model Input Variables*

The model variables defined the initial state of the coastal compartment and determined, through the application of the recession model, the predicted future (2100) shoreline behaviour (Figure 4.2*).

The analysis of recent LiDAR bathymetric data and the sediment budget considerations described in Section 2 allowed the identification of:

- Geometric variables related to beach profiles representative of two study sites; and
- Sediment budget variables relevant at the two study sites.

As described in Section 2, in defining the coastal compartment it was convenient to define the longshore boundaries as being headlands. The onshore boundary was established as being the landward limit of the active coastal zone, which included actively transgressive, wind driven, dunes. For ease of analysis, the offshore boundary was set as the limit of on shore/off shore sediment movement of the seabed profile. Detailed studies of a number of open coast locations in the Greater Metropolitan Sydney region showed that this is achieved by a depth of approximately 40 m (Gordon, 1990b; 2009).

The following geometric variables were determined for each representative beach profile at the two study sites:

- Depth of closure;
- Distance of closure;
- Dune height; and
- Total length of embayment;

The depth of closure is defined as the depth corresponding to the offshore limit of active sediment transport. Its determination is subject to large uncertainty, with practitioners generally relying on site specific geology/sedimentology evidence or empirical methods (Bruun, 1988; Hallermeier, 1978; 1981; 1983; and Birkemeier, 1985).

The sediment budget variables considered losses or gains through:

- Sediment exchange across or through onshore, offshore and longshore boundaries; and
- In situ sediment production or degradation.

A coastal compartment may be classified as "open" when there is sand flow across the boundaries, including the onshore landward boundary. Losses across the landward boundary may include wind driven transport across or losses into an onshore sink, such as an estuary. Sand gains across onshore boundaries can be due to terrestrial sands reaching the coastal compartment from river or creek transport, or when there is long-term recession into the Holocene or Pleistocene sandy deposits. Depending on the quantum of flow across boundaries a compartment may be fully open (for example, the longshore drift in around one headland is equal to the longshore drift out around the other headland), or partially open where the drift in is greater than the drift out. Where a coastal compartment is considered "closed" there is no flow of sandy sediments across any of the boundaries.

At Avoca Beach, the site characterisation (Section 2) identified the following potentially relevant sediment budget components:

- Lagoon and lagoon berm sequestration;
- Dune overwash;
- Loss through "mega rips"; and
- In situ, biogenic net sediment production or degradation.

At Cabarita Beach, the following relevant sediment budget components were identified:

- Littoral drift; and
- Exchanges with the inner continental shelf or onshore drift.

4.2.3 Probabilistic Approach

In a deterministic approach, each of the input variables is assigned a single value and a single estimate (prediction) of recession is produced. In a probabilistic approach, each input variable is allowed to (randomly) vary over a range of values pre-defined through probability distribution functions (pdf). By implementing a stochastic method to the recession model (Monte Carlo simulations) a probabilistic range of estimates (forecasts) of future recession is produced.

Table 11: Probability Density Functions of Input Variables

Parameter	Units	Distribution	Min	Mode	Max
Avoca					
S - Sea Level Rise (by 2100 and relative to 1990)	m	Triangular	0.1	0.5	1.1
h_* - Depth of closure	m	Triangular	12	20	35
(1)V_{Lagoon} – Loss to Lagoon (assuming 1.1 m SLR in 2100)	$\frac{m^3}{yr}$	Triangular	0	250	500
Q_{shells} – Biogenic production/degradation	$\frac{m^3}{m \cdot yr}$	Triangular	-1.8	-0.9	0.2
$V_{mega\text{-}rips}$	$\frac{m^3}{yr}$	Triangular	0	3000	6000
(1)$V_{overwash}$ – Dune overwash (assuming 1.1 m SLR in 2100)	$\frac{m^3}{yr}$	Triangular	0	250	500
Q_x – onshore drift	$\frac{m^3}{m \cdot yr}$	Triangular	0	0	0
Cabarita					
S - Sea Level Rise (by 2100 and relative to 1990)	m	Triangular	0.1	0.5	1.1
h_* - Depth of closure	m	Triangular	12	20	35
Q_y – Differential longshore transport	$\frac{m^3}{yr}$	Triangular	10,000	50,000	120,000
Q_x – onshore drift	$\frac{m^3}{m \cdot yr}$	Triangular	0	1	4

Notes:

(1) Dependent on SLR; values presented assume S = 1.1 m in 2100

The assignment of pdfs to each of the input variable is essentially an heuristic process based on site specific knowledge and expert judgement. For the purpose of this exploratory study and in the absence of additional information, simplified triangular pdfs were assigned to each input variables through the definition of:

- More frequent expected value (mode); and
- Lower and upper bounds (minimum and maximum).

Numerous alternative probability distributions are available, however, these are beyond the scope of this study. Such alternatives could easily be incorporated into the framework presented in this study.

Table 11 summarises the input parameters for the two study cases and Figure 4.2.1 shows plots of input parameter pdfs for Avoca and Cabarita Beach. While the results presented were derived from 10,000,000 simulations, convergence tests showed that by 100,000 simulations, differences between stochastic outputs were negligible. In both cases, computing time was of the order of few minutes. Plots of convergence tests are shown in Appendix C.

4.3 Avoca Beach Results

For the purpose of this analysis, the Avoca embayment was subdivided into two representative sections north and south of the lagoon entrance. Using Marine LiDAR bathymetric data, two beach and shoreface profiles were selected as representative of North and South Avoca. Profile locations are shown in Figure 2.4 and profile plots are presented in Figure 4.3. The south section of Avoca is characterised by lower foredunes (approximately 4 m AHD) and flatter gradient (slope) compared with the north profile (approximately 6 m AHD).

Estimates of projected recession by 2100 derived from 10,000,000 stochastic simulations are presented in Figure 4.4 for North Avoca and Figure 4.5 for South Avoca. Both simulated probability distribution and corresponding cumulative probability functions of recession are presented. A comparison of recession estimates in terms of cumulative probability distribution at North and South Avoca are presented in Figure 4.6.

In order to evaluate the sensitivity of the shoreline behaviour to the various input variables, simulations were run by, in turn, zeroing the contribution of each variable and re-calculating distributions for the simulated recession. As an example, contributions of each input variable to total recession are presented for Avoca South through plots of probability distributions (Figure 4.7*) and mean recession plus or minus one standard deviation. Median, 10^{th} and 90^{th} percentile of simulated recession estimates are plotted against sea level rise values in Figure 4.8 for Avoca North and South. Tabulated values of probabilistic estimates of recession at Avoca Beach are summarised in Table 12.

Table 12: Summary of 2100 Probabilistic Recession Estimates for Avoca Beach

Total Recession	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Avoca North									
R [m]	26.1	25.5	1.9	56.6	8.1	37.1	15.8	0.27	2.69
R [m3/m/yr]	8.8	8.3	0.5	26.7	3.4	13.4	4.9	0.79	3.60
Avoca South									
R [m]	30.4	29.9	1.9	61.4	9.4	43.3	18.4	0.17	2.53
R [m3/m/yr]	9.2	8.8	0.6	26.6	3.4	13.8	5.2	0.65	3.32

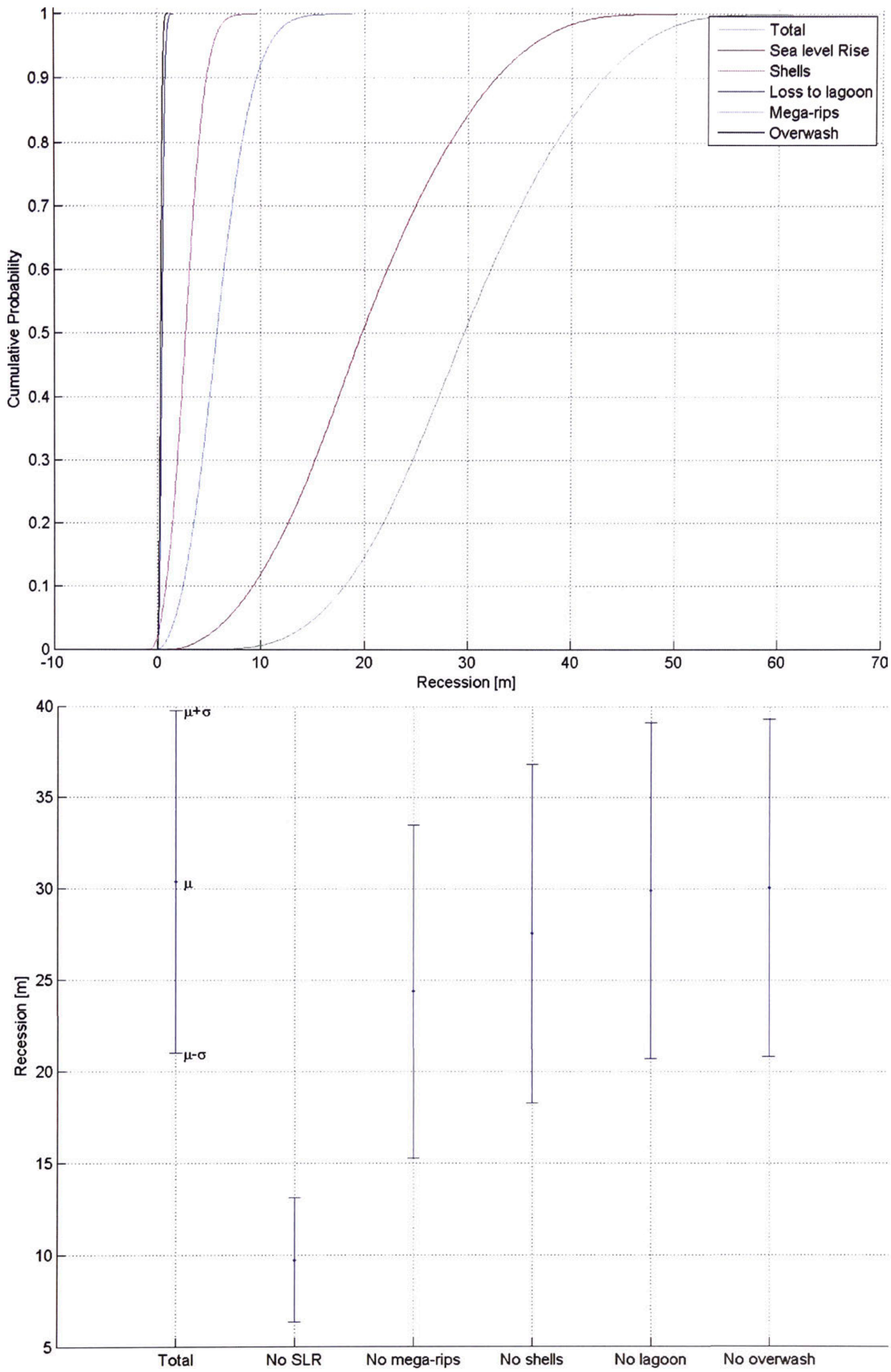


Figure 4.7* Avoca South Contributions to Recession: *SLR is the major factor contributing to potential shoreline recession followed by loss of sediment through mega-rips and shell degradation.*

4.4 Cabarita Beach, Results

For the purpose of this analysis, the Cabarita (Casuarina/Salt) compartment was subdivided into three representative sections north, centre and south. Using Marine LiDAR bathymetric data, representative beach and shoreface profiles were selected. Profile locations are shown in Figure 2.6 and profile plots are presented in Figure 4.9. For brevity only the results relative to the centre section are presented in this section, with the complete results shown in Appendix E.

Estimates of predicted recession by 2100 derived from 10,000,000 stochastic simulations are presented in Figures 4.10 for Cabarita Beach (centre section). Both simulated probability distribution and corresponding cumulative probability functions of recession are shown. A comparison of recession estimates in terms of cumulative probability distribution at the different sections along Cabarita Beach are presented in Figure 4.11.

In order to evaluate the sensitivity of the shoreline behaviour to the various input variables, simulations were run by, in turn, zeroing the contribution of each variable and re-calculating distributions for the simulated recession. As an example, contributions of each input variable to total recession are presented for Cabarita Centre through plots of probability distributions and mean recession plus or minus one standard deviation (Figure 4.12*).

Median, 10^{th} and 90^{th} percentile of simulated recession estimates are plotted against sea level rise values in Figure 4.13 for Cabarita Centre representative beach profile. Table 13 summarises the 2100 probabilistic recession estimates for Cabarita Beach.

Table 13: Summary of 2100 Probabilistic Recession Estimates for Cabarita Beach

Total Recession	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Cabarita Centre									
R [m]	28.4	27.8	-3.9	84.0	10.0	41.6	16.0	0.40	3.19
R [m3/m/yr]	13.6	12.8	-1.7	51.5	5.6	20.9	7.1	0.89	4.30
Cabarita North									
R [m]	29.5	28.6	-4.7	101.8	10.9	43.5	16.4	0.61	3.87
R [m3/m/yr]	12.5	11.6	-1.6	57.0	5.7	19.6	6.4	1.26	5.74
Cabarita South									
R [m]	37.9	37.4	-4.4	93.8	12.6	54.6	21.9	0.19	2.74
R [m3/m/yr]	15.0	14.4	-1.5	49.9	5.7	22.6	8.2	0.65	3.66

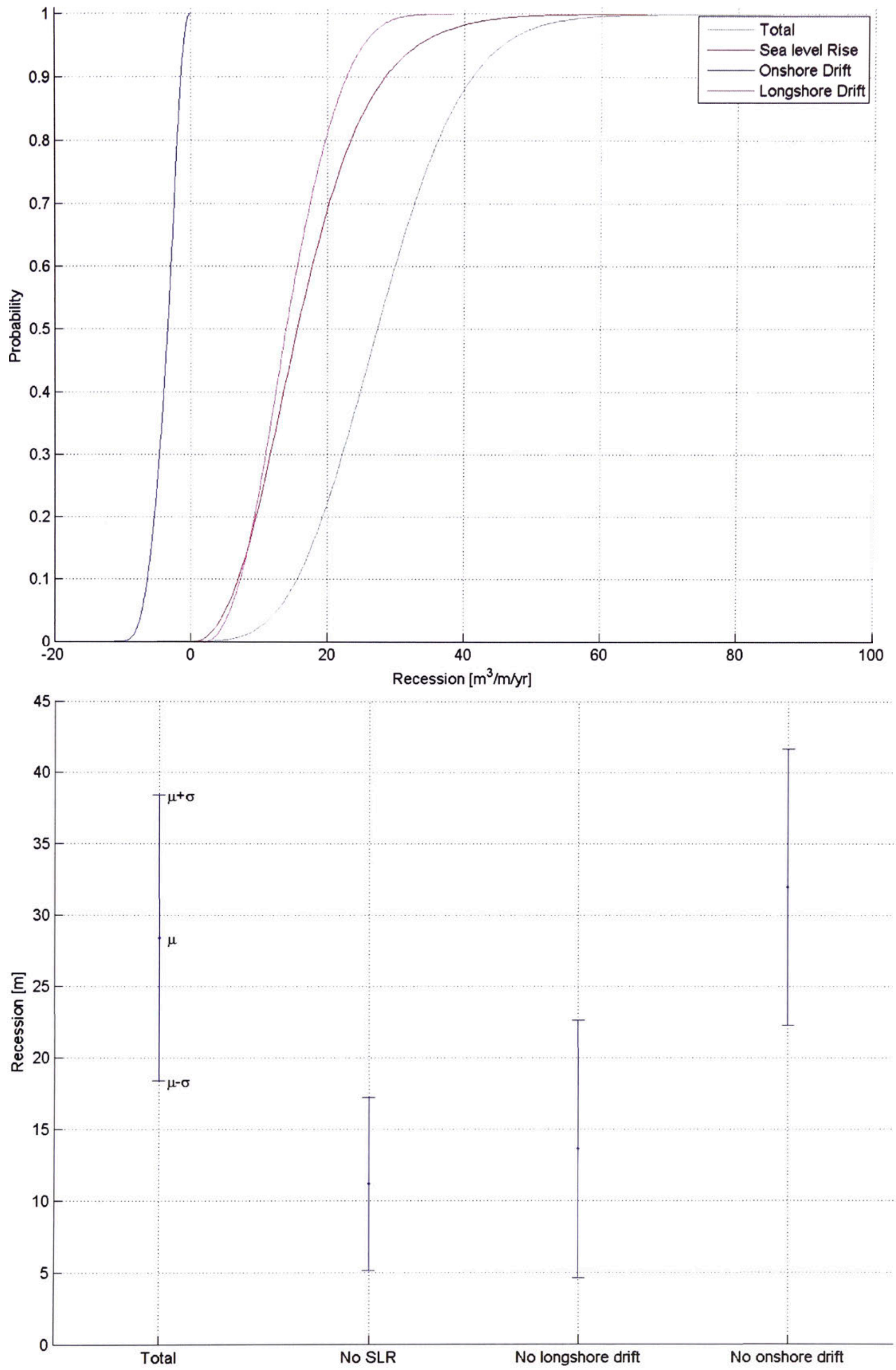


Figure 4.12* Cabarita Centre Contributions to Recession: *SLR and longshore drift variability have comparable impacts on shoreline recession while sediment contribution from onshore drift from the continental shelf would be responsible for potential accretion.*

4.5 Discussion of Probabilistic Results

Based on the probabilistic results, the southern section of Avoca Beach will be more vulnerable to long-term recession (taking into account SLR) with the mean predicted recession for 2100 of 30 m (9.2 m^3/m/yr) compared to 26 m (8.8 m^3/m/yr) in the northern section. The 90th percentile recession estimates were 43 and 37 m (13.4 and 13.8 m^3/m/yr), respectively for South and North Avoca.

At Cabarita, recession estimates for 2100 are similar for the central and northern sections of the compartment with average recession estimates of approximately 28 m (13 m^3/m/yr) and 90th percentile of approximately 42 m (20 m^3/m/yr). However, higher recession rates were estimated in the southern section of Cabarita Beach with estimates ranging from an average of 38 m (15 m^3/m/yr) in 2100 to 55 m (22.6 m^3/m/yr) for the 90th percentile.

Based on the probabilistic results, the main driving factor of recession in both the Avoca and Cabarita compartments by 2100 (assuming stationary wave climate conditions) is sea level rise. In Avoca, the loss of sediment to the compartment through mega-rips and through shell degradation have similar contributions to future shoreline recession. In particular the inclusion of loss via mega-rips and shell degradation increased mean recession estimates by approximately 29% and 11% respectively, while sediment loss to the lagoon and through dune overwash were found to have minimal impact (less than 3% increase) on projected shoreline recession (Figure 4.7*).

At Cabarita, the contribution to long-term recession by littoral drift differentials was found to be similar magnitude to the SLR contribution, while the inclusion of the sediment gain via onshore drift from the continental shelf caused a reduction in recession on average of approximately 18% (Figure 4.12*).

Based on the probabilistic results, Cabarita Beach was found to be more vulnerable to long-term recession due to sediment imbalance and sea level rise. Moreover, recession estimates for 2100 were found to span over a wider range of possible values due to the high variability in net littoral drift differential (10,000 to 120,000 m^3/yr). Figure 4.14 shows plots of projected recession against sea level rise scenarios (ranging from 0.1 to 1.1 m in 2100) for both Avoca and Cabarita. While the lower bound (10th percentile) of the envelope of predictions coincides at the two sites, the median (50th percentile) and higher bound (90th percentile) at Cabarita exceeds by approximately 50% the ones at Avoca for all SLR scenarios.

Future changes in wave climate (Appendix D) could result in changes in the net differential littoral drift, however, it is expected that these changes would be within the range (10,000 to 120,000 m^3/yr) considered in the probabilistic approach.

4.6 Comparison of Probabilistic and Deterministic

In order to qualitatively evaluate relative merits of deterministic versus probabilistic approach, the probabilistic estimates of recession obtained from the Monte Carlo simulations were compared to the deterministic estimates from Section 3 and previous assessments at the two contrasting study sites.

Detailed deterministic analysis of long-term recession due to ongoing recession and SLR at the two study sites is presented in Appendix A. Table 14 shows values of ongoing recession and Bruun factors adopted in this study to calculate deterministic estimates of 2100 recession. For the deterministic application of the Bruun rule, depths of closure needed to be determined at each representative profile. Different methods are available for the estimation of the depth of closure. For comparison with the probabilistic estimates, conservative estimates were adopted between closure depths obtained via the application of Hallermeier (1978; 1981 and 1983) and Birkemeier (1985) inner and outer closure depths and the offshore limit of storm profile response as determined by the beach response modelling described in Section 3 and Appendix B.

Table 14: Deterministic Estimates of Recession

	Avoca		Cabarita		
	North	South	North	Centre	South
On-going Recession [m/yr]	0.2	0.2	0.1	0.1	0.1
Adopted Closure Depth [m AHD]	-15	-10	-15	-14	-14
Adopted Bruun Factor [-]	32	37	26	30	46

Figure 4.15* shows recession estimates for Avoca Beach in terms of median, 10^{th} and 90^{th} for sea level rise scenarios ranging from 0.1 to 1.1 m in 2100, using a probabilistic and a deterministic approach. For both North and South Avoca, the deterministic estimates are generally within the upper bound of the probabilistic estimates envelope, i.e. equal or higher than the 90^{th} percentile. However, for the higher range of SLR scenarios (higher than 0.6 m by 2100) in South Avoca particularly, the deterministic estimates converge to the median of the probabilistic estimates.

On the other hand, in Cabarita, deterministic estimates tended to match the lower bound of probabilistic estimates as shown in Figures 4.16 and 4.17. The tendency to lie between the median and the 10^{th} percentile of the probabilistic estimates was observed over the whole range of SLR scenarios and beach length.

4.7 General Conclusions on Long-term Response

1. A sediment budget approach provides the natural framework for evaluating long-term shoreline response to climate change. It provides the methodology for examining "sources" and "sinks" of sediment associated with a coastal compartment thereby enabling determination of the shoreline response in the long-term.

2. Where large uncertainty remains in the determination of the sediment budget and likely climate change impacts, the probabilistic approach is useful to manage the uncertainty and relate it to future shoreline behaviour. In such cases, deterministic estimates can lead to gross under or over estimation of shoreline response.

3. The sensitivity of the overall sediment budget, hence of the shoreline behaviour, to climate change impacts can be usefully tested using a probabilistic approach.

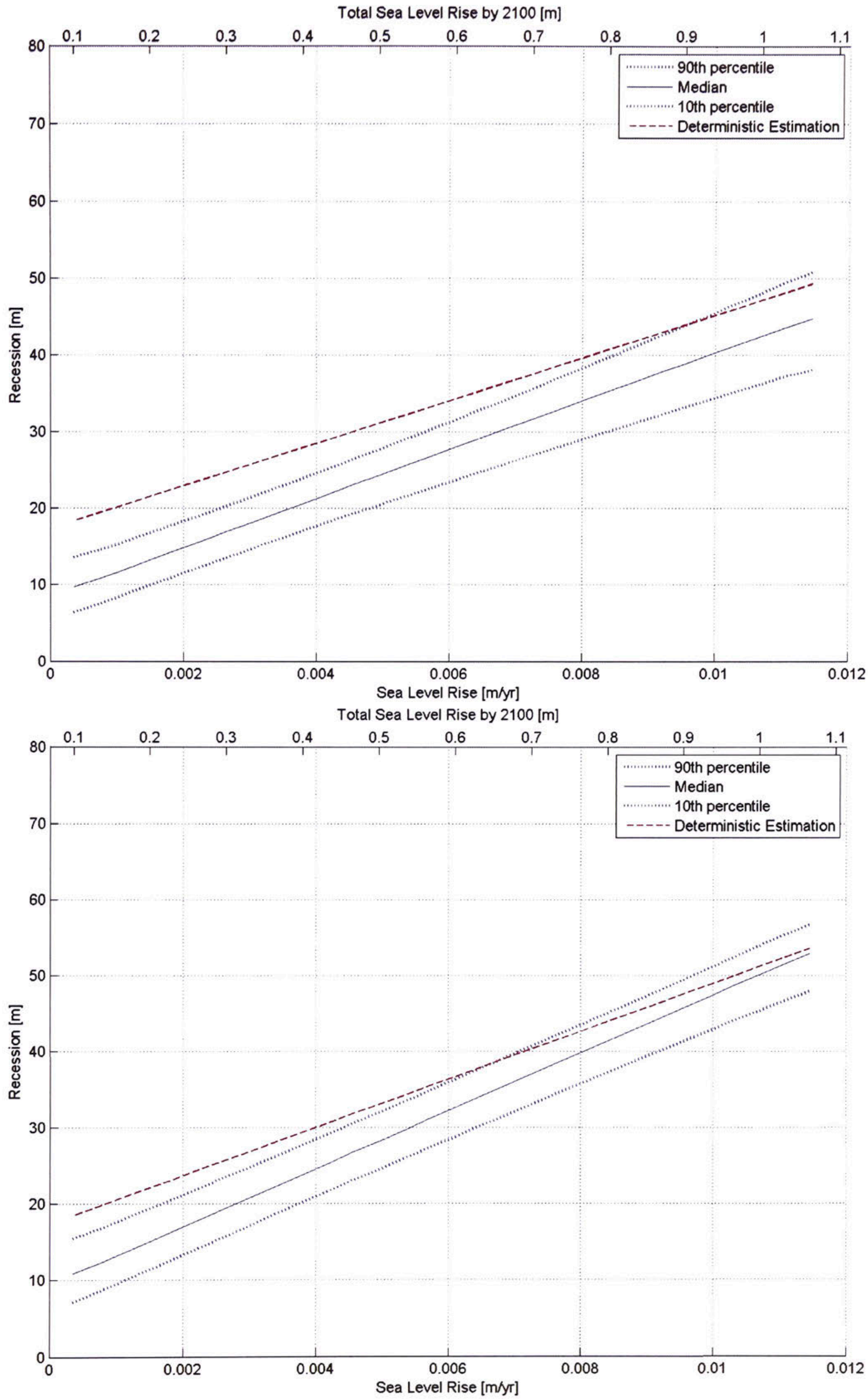


Figure 4.15* North and South (upper and lower plot) Avoca Deterministic and Probabilistic Comparison: *Deterministic predictions are within the higher range of probabilistic forecasts (≥90th percentile); except for high SLR scenarios where deterministic predictions converge to the median of the probabilistic forecasts.*

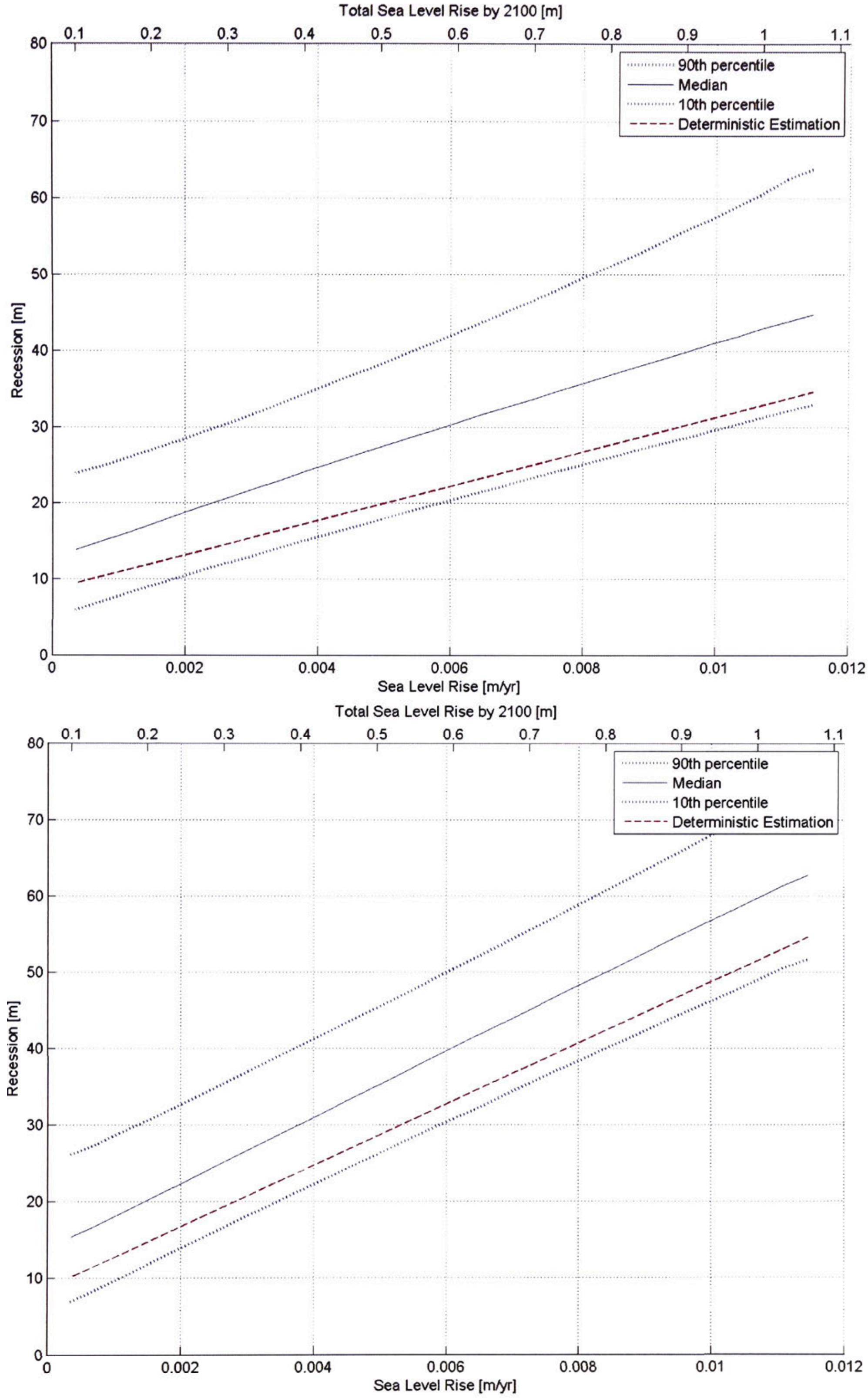


Figure 4.17* North and South (upper and lower plot) Cabarita Deterministic and Probabilistic Comparison: *Deterministic predictions are within the lower range of probabilistic forecasts and consistently below the median probabilistic forecasts for all SLR scenarios.*

5. Conclusions

The assessment of coastal response was undertaken at two study sites along the NSW coast. Avoca Beach on the NSW Central Coast and Cabarita-Casuarina-Salt Beach on the northern NSW Coast were selected as representative in terms of differing regional geological setting and sediment processes.

The assessment was undertaken considering short-term and long-term processes, deterministic and probabilistic approaches. Short-term processes included beach erosion in response to one or a sequence of storm events over the timeframe of days or weeks. Long-term processes included shoreline recession in response to sediment imbalance and changes in mean sea level, which are both potential impacts of climate change. Analysis of coastal response to long-term processes was undertaken for the 2100 timeframe.

For the assessment of (short-term) erosion due to storm events, the applicability of fully probabilistic, semi-probabilistic and deterministic methods was investigated. The applicability of fully probabilistic methods such as JPM-PCR (Callaghan *et al.*, 2008; Ranasinghe *et al.*, 2011) was limited by data availability at the two representative study sites. The use of Synthetic Design Storms derived from long-term wave buoy records to drive refined process based erosion models (Carley and Cox, 2003; Shand *et al.*, 2011; Mariani *et al.*, 2012) offered a reliable alternative to estimate storm erosion for different probabilistic scenarios at "data poor" locations.

Results at the two study cases show that the sequencing (clustering) of two or more storms is necessary to produce realistic estimates of storm demand that match historical measurements. The accuracy of the surfzone and nearshore bathymetry was found to be an important factor in the modelling of short-term erosion processes, with high quality and frequent nearshore survey data necessary for the erosion modelling to be representative of different morphodynamic beach states.

For the assessment of long-term processes, a probabilistic approach based on Monte Carlo stochastic simulations, and coastal compartment sediment budget coupled to simple two-dimensional geometric transformation, was applied to the two study sites. Deterministic estimates of 2100 shoreline recession were compared with probabilistic projections in the perspective of the two coastal sediment cell cases investigated.

In a relatively closed compartment such as Avoca, deterministic estimates were found to provide conservative estimates of recession matching the upper bound of probabilistic predictions. However, in the Cabarita compartment, deterministic estimates under-estimated the median of probabilistic predictions. At this location, the probabilistic approach allowed investigation of the sensitivity of the shoreline behaviour due to the large variability (one order of magnitude) in littoral drift differential.

The probabilistic approach was found to provide a powerful tool for the analysis of the sensitivity of shoreline behaviour to future variability in sediment budget components. The probabilistic approach also indirectly accounted for future changes in wave climate as these are likely to result in sediment budget changes. Within those coastal compartments where large uncertainty remains in the quantification of the sediment budget, a probabilistic approach is useful to manage the uncertainty and relate it to future shoreline behaviour.

The following points are provided for consideration for future coastal erosion/recession and risk assessments:

1. The continuous improvement of beach monitoring data quality and frequency is a key factor in the improvement of reliability and feasibility of both deterministic and probabilistic approaches:

- Long-term, high quality and frequent beach and surfzone bathymetric surveys, possibly in concomitance with storm events, will allow validation of erosion (and accretion) models and shoreline recession estimates; and
- Beach and surfzone surveys will increase the feasibility of approaches based on stochastic methods by increasing the sampling population for the derivation of probabilistic forecasts;

2. The use of synthetic design storms (SDS) derived from the analysis of long-term wave buoy data is a practical and reliable method to estimate coastal response to extreme storm events at data poor locations:

- Upgrading and maintenance of the current wave buoy and tide gauge networks will allow improved reliability of storm characteristics predictions;
- The inclusion of the effects of wave direction (when information is available) is recommended; and
- The analysis of joint occurrence of extreme wave heights and water levels is recommended when information/data exists.

3. Storm sequencing and two-dimensional (2D) effects need to be considered in the analysis of coastal response to extreme storm events:

- The use of storm sequences to drive erosion models is recommended together with the comparison with historical (if available) measurements of storm erosion; and
- Two-dimensional effects (such as rip currents) have the potential to significantly increase localised erosion. Erosion estimates from one-dimensional models are therefore prone to underestimation at those locations where 2D effects are relevant. Allowances for 2D effects need to be included in the erosion estimates.

4. A sediment budget approach based on a probabilistic approach provides a powerful framework for the evaluation of long-term shoreline response to climate changes, including sea level rise and wave climate changes:

- It provides the methodology for examining "sources" and "sinks" of sediment within a coastal compartment thereby enabling determination as to whether there is a net gain (accretion) or a net loss (recession); and
- Changes in both mean sea level and wave energy flux will alter the sediment processes within the coastal compartment. If large uncertainty remains in the definition of the sediment budget components, a probabilistic approach provides a useful tool to evaluate the sensitivity of the overall budget, hence the shoreline reaction, to changes in budget components.

6. References and Bibliography

Birkemeier, W.A., (1985) "Field Data on Seaward Limit of Profile Change" *J. Waterway, Port, Coastal and Ocean Division*, v. III, n. 3, ASCE,p. 598-602

Booij, N., Ris, R.C. and Holthuijsen, L.H. (1999a) "A Third-generation Wave Model for Coastal Regions, Part II, Verification", *Journal of Geophysical Research* C4, 104, 7667-7681

Booij, N., Ris, R.C. and Holthuijsen, L.H. (1999b) "A Third-generation Wave Model for Coastal Regions, Part I, Model Description and Validation", *Journal of Geophysical Research* C4, 104, 7649-7666

Bruun, P. (1962) "Sea-level Rise as a Cause of Shore Erosion" *Journal of Waterways and Harbours Division*, 88:117-130

Bruun, P. (1988) "The Bruun Rule of Erosion by Sea Level Rise: A Discussion on Large-scale Two- and Three-dimensional Usages" *Journal of Coastal Research*, 4, 627–648

Bruun, P. and Schwartz, M. (1985) "Analytical Predictions of Beach Profile Change in Response to a Sea-level Rise", *Z. Germorph.*, Suppl-Bd 57 pp33-50

Callaghan J. and Helman P. (2008) *"Severe Storms on the East Coast of Australia 1770–2008"* Griffith Centre for Coastal Management, Griffith University

Callaghan, D.P., Nielsen, P., Short, A.D. and Ranasinghe, R. (2008) "Statistical Simulation of Wave Climate and Extreme Beach Erosion" *Coastal Engineering*, 55(5), 375-390

Callaghan, D.P., Ranasinghe, R. and Short, A. (2009) "Quantifying the Storm Erosion Hazard for Coastal Planning". *Coastal Engineering* 56 1: 90-93

Carley, J.T., Couriel, E.D. and Cox, R.J. (1998) "Numerical Modelling Sand Nourishment Profiles/Quantities and Beach Erosion due to Storms and Sea Level Rise", *WRL Technical Report 1998/04*. Water Research Laboratory, University of NSW, Sydney

Carley, J.T. and Cox, R.J. (2003) "A Methodology for Utilising Time-Dependent Beach Erosion Models for Design Events", *Proceedings of 16th Australasian Coasts and Ports Conference*, Auckland, New Zealand

Carley, J.T. and Mole, M.A. (2010) "Update of Tweed Shire Coastal Hazard Lines" *WRL Technical Report 2010/11*, Water Research Laboratory, University of NSW, Sydney

Carter, R.M. (2010) *"Climate: the Counter Consensus"*. Stacey international, ISBN: 978-1-906768-29-4, 315pp

Chapman, D., Geary, M., Roy, P.S. and Thom, B.G. (1982) "Coastal Evolution and Coastal Erosion in New South Wales", Coastal Council of NSW, Sydney

Chief Scientist and Engineer (2012) "Assessment of the Science Behind the NSW Government's Sea Level Rise Planning Benchmarks", NSW Government

Cardno Lawson Treloar (2010) "Gosford Coastal Lagoons Processes Study", Volume 1 July 2010

Coghlan I.R., Carley J.T., Shand T.D., Blacka M.J., Cox R.J., Davey E.K. and Blumberg G.P. (in prep.), "Kingscliff Beach Foreshore Protection Works Part A - Alternative Terminal Seawall Designs and Beach Nourishment and Beach Nourishment", *WRL Technical Report 2011/25.* Water Research Laboratory, University of NSW, Sydney

Cooper, J.A.G. and Pilkey, O.H. (2004) "Sea-level Rise and Shoreline Retreat: Time to Abandon the Bruun Rule" *Global and Planetary Change* Vol. 43 Issue 3 p157-171

Dean, R.G. and Dalrymple, R.A. (2002) "Coastal Processes with Engineering Applications" Cambridge University Press

Drummond, C.D. (2011) "The Implications of Climate Change for the Beaches of the Central Coast", B. Eng thesis, University of NSW, Sydney

Cowell, P.J., Roy, P.S. and Jones, R.A. (1992) "Shoreface Translation Model: Computer Simulation of Coastal Sand Body Response to Sea Level Rise" *Mathematics and Computers in Simulation* 33 (1992) 603-608

Cowell, P.J., Roy, P.S., and Jones, R.A. (1995) "Simulation of Large Scale Coastal Change Using a Morphological Behaviour Model" *Marine Geology,* 126, 45–61

Cowell, P.J., Thom, B.G., Jones, R.A., Everts, C.H. and Simanovic, D. (2006) "Management of Uncertainty in Predicting Climate-Change Impacts on Beaches" *Journal of Coastal Research* 221: 232-245

Dallas M. and Tuck D., (2008) "Aboriginal and European Cultural Heritage Assessment Casuarina Town Centre Kingscliff South, NSW", *Mary Dallas Consulting Archaeologists*, Report to Kings Beach No. 2 Pty Ltd

DEFRA UK (2006) "Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities – Climate Change Impacts October 2006" UK Department for Environment, Food and Rural Affairs

Delft Hydraulics Laboratory, (1970) "Gold Coast Queensland Australia – Coastal Erosion and Related Problems" Report 257. Prepared for the Queensland Government. 1970

Delft Hydraulics, (1992) "Gold Coast Queensland Australia - Southern Gold Coast Littoral Sand Supply", Final Report Volume II Full Report. Prepared for the Queensland Government. October 1992

DCC (2009) *"Climate Change Risks to Australia's Coast, A First Pass National Assessment"* Australian Government Department of Climate Change, ISBN: 978-1-921298-71-4

Department of Environment, Climate Change and Water (2009) "Sea Level Rise Policy", NSW Government

Department of Environment, Climate Change and Water (2010) "Coastal Risk Management Guide: Incorporating Sea Level Rise Benchmarks in Coastal Risk Assessments", NSW Government

Duke, A., (2012) "Cabarita Beach/Bogangar Community Project Plans Report", Report for the Cabarita Beach Bogangar Community Economic Development Committee

Evans, P., Hanslow, D., Coutts-Smith, A. and You, Z.J. (2000) "Nearshore-Inner Shelf Sediment Exchange on the NSW Central Coast". *27 th Int. Conf. on Coastal Eng.*, ASCE, 3151–3164

Engineers Australia (2012) "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering", *Engineers Australia National Committee on Coastal and Ocean Engineering,* 3rd ed., ISBN: 9780858259195.

Engineers Australia (2012a) "Climate Change Adaptation Guidelines in Coastal Management and Planning", *Engineers Australia National Committee on Coastal and Ocean Engineering*, ISBN: 9780858259515.

Garber, S., Treloar, D. and Beadle, C., (2010) "Wollongong LGA Coastal Hazards Study, Some Unique Aspects", *The 19th NSW Coastal Conference, Batemans Bay, NSW,* Australia

Goda Y. (2000), "Random Seas and design of Maritime Structures." *World Scientific*

Gordon, A.D., Lord, D.B. and Nolan, M.W. (1978) "Byron Bay – Hastings Point Erosion Study" NSW Department of Public Works, *Coastal Engineering Branch, Report No 78026*, November 1978

Gordon, A.D. (1987) "Beach Fluctuations and Shoreline Change: NSW", *8th Australasian Conference on Coastal and Ocean Engineering*, pp 104-108

Gordon, A.D., (1990a) "Coastal Lagoon Entrance Dynamics" Proceedings 22nd International Conference on Coastal Engineering, American Society of Civil Engineers, Delft, The Netherlands 1990: 2880-2893

Gordon. A.D., (1990b) "Beach Fluctuations and Shoreline Change - N.S.W.", *Australian Civil Engineering Transactions*, Institution of Engineers, Australian Vol., CE32No. 1. 1990: 7-13

Gordon, A.D. (1992) "The Restoration of Bate Bay, Australia – Plugging the Sink" Proceedings *23rd International Conference on Coastal Engineering*, American Society of Civil Engineers, Venice, Italy, October 1992, 3319-3330

Gordon, A.D. (2009) "The Potential for Offshore Sand Sources to Offset Climate Change Impacts on Sydney's Beaches" *Proceedings 19th Australasian Conference on Coastal and Ocean Engineering* as included in Coast and Ports 2009, Engineers Australia in conjunction with the New Zealand Coastal Society, Wellington September 2009

Gordon, A.D. (2011) "Anchoring Coastlines – Natural and Artificial Headlands" Proceedings *Coasts and Ports Conference 2011*. Engineers Australia

Guinotte, J.M. and Fabry, V.J. (2008) "Ocean Acidification and its Potential Effects on Marine Ecosystems" Ann. NY Academy of Science 1134:320-342

Hallermeier, R.J. (1978) "Uses for a Calculated Limit Depth to Beach Erosion" *Proc. Coastal Eng. Conf. 16th*, Hamburg, Germany, pp 1493 – 1512.Eng. Conf., 16th, Hamburg, Germany, pp. 1493--1512

Hallermeier, R.J. (1981) "A Profile Zonation for Seasonal Sand Beaches from Wave Climate" *Coastal Engineering* 4, 253-277

Hallermeier R.J. (1983) "Sand Transport Limits in Coastal Structure Designs". *Proceedings of a Specialty Conference on Design, Construction, Maintenance and Performance of Coastal Structures*. ASCE, Arlington, pp 703–716

Harley M.D., Turner I.L., Short A.D. and Ranasinghe, R. (2009) "Interannual Variability and Controls of the Sydney Wave Climate", *International Journal of Climatology*, Royal Meteorological Society

Helman, P. (2007) "Two Hundred years of Coastline Change and Future Change, Fraser Island to Coffs Harbour, East Coast Australia", PhD Thesis, Southern Cross University

Hemer, M.A., McInnes, K.L. and Ranasinghe, R. (2012) "Projections of Climate Change-driven Variations in the Offshore Wave Climate off South Eastern Australia", *International Journal of Climatology* 2012

Higgs, K.B. and Nittim, R. (1988) "Coastal Storms in N.S.W. in August and November 1986 and their Effect on the Coast". *WRL Technical Report 1988/06,* Prepared for Public Works Department. Water Research Laboratory, University of NSW, Sydney

Hoffman, J.G, Evans, H.G. and Messner, J.P. (1979) "Bogangar-Kingscliff Coastal Engineering Advice", Department of Public Works, Coastal Engineering Branch, Sydney

Huxley, C. (2009) "Shoreline Response Modelling – Assessing the Impacts of Climate Change" *Proceedings of the 18th NSW Coastal Conference*, Ballina, 3–6 November

Institute of Engineers Australia (2004) National Committee on Coastal and Ocean Engineering. "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering 2004 Update." *ACT: The Institution of Engineers Australia*

IPCC (2001) *Technical Summary of the Working Group I Report and Summary for Policymakers,* The United Nations Intergovernmental Panel on Climate Change, Cambridge University Press, UK

IPCC (2007a) *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC (2007b), *Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback), [Solomon, S, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp

James Cook University of North Queensland (1977), "Numerical Simulation of Tropical Cyclone Surge Along the Queensland Coast", Part X, Gold Coast. Report Prepared for Beach Protection Authority of Queensland, November

Komar, P.D., McDougal, W.G., Marra, J.J. and Ruggiero, P. (1997) "The Rational Analysis of Setback Distances: Application to the Oregon Coast" *Shore and Beach Vol. 67 (1) 41-49*

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M. (2010), "Tropical Cyclones and Climate Change", *Nature Geoscience* 21 February 2010

Kraus, N., Larson, M., Rosati, J. and Wise, R. (1993), "SBEACH: Numerical Model for Simulating Storm-Induced Beach Change", User's Manual. *US Army Corps of Engineers*

Kriebel, D.L. and Dean, R.G. (1993) "Convolution Method for Time-dependent Beach-profile Response", *Journal of Waterway, Port, Coastal and Ocean Engineering, Vol 119 (2)*, pp 204-226

Laxton, J.H. and Laxton, E.S. (2009), The Effects of Climate Change on Beaches in Pittwater, Warringah and Manly Local Government Areas. Private Research Project by J.H. & E.S. Laxton - Environmental Consultants P/L, June 2009

Larson M., Erikson, L. and Hanson, H. (2004) "An Analytical Model to Predict Dune Erosion due to Wave Impact" *Coast Engineering* 51(8–9):675–696

Larson M. and Kraus N.C. (1989) "SBEACH: Numerical Model for Simulating Storm-Induced Beach Change, Report 1: Theory and Model Foundation", Technical Report CERC-89-9, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg USA

Lord D.B. and Kulmar M.A. (2000) "The 1974 Storms Revisited: 25 years. Experience in Ocean Wave Measurement Along the South-East Australian Coast", *Proceedings International Conference of Coastal Engineering*, pp 559-572, ASCE

Manly Hydraulics Laboratory (2010) NSW Ocean Water Levels, Draft MHL Report 1881, December

Mariani A., Shand T.D., Carley J.T., Goodwin I.D., Splinter K., Davey E.K., Flocard F .and Turner I.L. (2012) "Generic Design Coastal Erosion Volumes and Setbacks for Australia", *WRL Research Report 247,* Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania

Marshall, J.F. and Thom, B.G. (1976) "The Sea level in the Last Interglacial", *Nature* 263, 120–121

McInnes, K, Abbs, D, O'Farrell, S, Macadam, I, O'Grady, J and Ranasinghe, R (2007). *Projected Changes in Climatological Forcing for Coastal Erosion in NSW*, a project undertaken for the Department of Environment and Climate Change NSW, CSIRO Marine and Atmospheric Research, Victoria

McLean, R. and Shen, J-S. (2006), "From Foreshore to Foredune: Foredune Development Over the Last 30 Years at Moruya Beach, New South Wales, Australia", *Journal of Coastal Research*, Volume 22, Number 1, pp 28-36

MSQ (2011), Semidiurnal Tidal Planes. Queensland Tide Tables 2012, Marine Safety Queensland, September 2011

Nielsen, A.F. (1987) "Coastal Features of Gosford City Foreshores", Gosford Geographical Society February 1987

Nielsen, A.F. and Adamantidis, C.A. (2007) Defining the Storm Erosion Hazard for Beaches, *Australian Journal of Civil Engineering*, Volume 3, Number 1, pp. 39-50

Patterson Britton & Partners (1999) "Broken Bay Beaches Coastal Management Plan" Issue No 3 August 1999

Patterson Britton & Partners (2006) "Scoping Study on Byron Bay Sand Extraction" Final Report March 2006

Public Works Department, NSW (1978) "Byron Bay- Hastings Point Erosion Study", *Public Works Department*- Coastal Engineering Branch, Report No PWD 78026

Public Works Department, NSW (1982) "Bogangar Beach Coastal Engineering Advice", *Public Works Department*- Coast and Flood Division, Report No PWD 81022

Public Works Department, NSW (1985) "Gosford City Council Beach Management Strategies" *Public Works Department* May 1985

Public Works Department, NSW (1985) "Wamberal Beach and Avoca Beach Coastal Engineering Advice" *Public Works Department*- Civil Engineering Division, Report No PWD 85040

Public Works Department, NSW (1989) "Topographic Setting and Offshore Sediment Distribution Terrigal/Wamberal Beach", Survey taken 1984-1989

Public Works Department, NSW (1994) "Gosford Coastal Process Investigation", *Public Works Department*- Coast and Flood Division

Pugh, D.T. and Vassie, J.M. (1979) "Extreme Sea Levels from Tide and Surge Probability", pp.911-930 in Vol 1, *Proceedings of the Sixteenth Coastal Engineering Conference*, 1978, Hamburg, Germany. New York: American Society of Civil Engineers, 3060pp

Ranasinghe, R., Watson, P., Lord, D., Hanslow, D. and Cowell, P. (2007) "Sea Level Rise, Coastal Recession and the Bruun Rule" *Proceedings of Coasts and Ports '07*, Melbourne, Vic, Australia. On CD Rom produced by Engineers Australia

Ranasinghe, R., Callaghan, C. and Stive, M.J.F. (2011) "Estimating Coastal Recession due to Sea Level Rise: Beyond the Bruun Rule", *Climate Change* June 2010

Ris, R.C., Holthuijsen L.H. and Booij N. (1994) "A Spectral Model for Waves in the Near Shore Zone", *24th International Conference of Coastal Engineering, Kobe*, October 1994, pp 68-78

Ryan, D.A., Heap, A.D., Radke, L. and Heggie, D.T. (2003) "Conceptual Models of Australia's Estuaries and Coastal Waterways: Applications for Coastal Resource Management, Geoscience Australia, Record 2003/09, 136pp

Roy, P.S. (1973) "Coastal Geology of the Cudgen Area – North Coast of NSW", Geological Survey of NSW, Department of Mines Geological Survey Report No. GS 1973/286, September, 1973

Roy, P.S. and Crawford, E.A. (1980) "Quaternary Geology of Newcastle Bight Inner Continental Shelf, New South Wales, Australia" New South Wales Geological Survey Records, 19. 145-88

Roy, P.S. and Thom, B.G. (1981) "Coastal Quaternary Deposits of New South Wales: A Model for Development in the Late Quaternary" *Journal of Geol. Soc. Aust.*, 28, 471-489

SCOR Working Group 89 (1991) "The Response of Beaches to Sea-level Changes: A Review of Predictive Models" *Journal of Coastal Research*, 7(3), 895-921

Shand, T.D., Goodwin, I.D., Mole, M.A., Carley, J.T., Coghlan, I.R., Harley, M.D. and Peirson, W L. (2010) "NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves", prepared by the Water Research Laboratory and Macquarie University for the Department of Environment, Climate Change and Water. *WRL Technical Report 2010/16,* University of NSW, Sydney

Shand, T.D., Mole, M.A., Carley, J.T., Peirson, W.L. and Cox, R.J. (2011) "Coastal Storm Data Analysis: Provision of Extreme Wave Data for Adaptation Planning", *WRL Research Report 242,* Water Research Laboratory, University of NSW, Sydney

Short, A.D. (1985) "Rip-current Type, Spacing and Persistence, Narrabeen Beach, Australia." *Journal of Marine Geology*, 65 1985

Short, A.D. and Turner, I.L. (2000) *Beach Oscillation, Rotation and the Southern Oscillation, Narrabeen Beach, Australia,* Proceedings Coastal Engineering 2000, ASCE, 2439-2452

Short, A.D. and Trembanis, A.C. (2004) "Decadal Scale Patterns in Beach Oscillation and Rotation Narrabeen Beach, Australia-Time Series, PCA and Wavelet Analysis" *Journal of Coastal Research* 20(2): 523-532

Stephens, A.W., Roy, P.S. and Jones, M.R. (1981) "Model of Erosion on a Littoral Drift Coast", *Proceedings of the Fifth Australian Conference on Coastal and Ocean Engineering*, Perth. WA. pp. 171-6. Sydney: The Institute of Engineers. Australia

Thom, B.G. (1965) "Late Quaternary Coastal Morphology of the Port Stephens-Myall Lakes Area, NSW", J. Proc. R. Soc. NSW, 98, pp23-26, 1965

Thom, B.G. (1974) "Coastal Erosion in Eastern Australia", Search, 5, pp198-209

Thom, B.G. (1978) "Coastal Sand Deposition in Southeast Australia during the Holocene", *Landform Evolution in Australasia*, ed. J.L. Davies and M.A.G. Williams, pp. 197-214. Canberra: ANU Press

Thom, B.G. and Hall, W. (1991) "Behaviour of Beach Profiles During Accretion and Erosion Dominated Periods", *Earth Surface Processes and Landforms*, Volume 16, pp 113-127

Tweed Shire Council (2012d) *Ordinary Council Meeting Thursday 25 October 2012*, Council Minutes

Watson P.J and D.B Lord (2008). *"Fort Denison Sea Level Rise Vulnerability Study"*, a report prepared by the Coastal Unit, NSW Department of Environment and Climate Change, October

Watson, P.J., (2011) "Is There Evidence Yet of Acceleration in Mean Sea Level Rise Around Mainland Australia?", *Journal of Coastal Research*, 27(2), 368–377. West Palm Beach (Florida), ISSN 0749-0208

WBM (1995) "Coastal Management Study and Coast Management Plan- Gosford City Open Coast Beaches", *WBM Oceanics Australia*

WBM (1988) "Coastal Engineering Advice: Ocean Paradise Estates Bogangar Beach Tweed Shire, NSW", prepared for Lenen Developments Pty Ltd by Winders, Barlow and Morrison, QLD, Report Number 3869

WBM (2001) "Tweed Coastline Hazard Definition Study" - Final Report (Revision 3), R.B12876.002.03.doc, Brisbane, (Council has advised that the stated year of 2007 is a typographical error, with 2001 being the correct year of issue)

Woodroffe, C.D., Cowell, P.J., Callaghan, D.P., Ranasinghe, R., Jongejan R., Wainwright, D.J., Barry, S.J., Rogers, K., Dougherty, A.J. (2012) "Approaches to Risk Assessment on Australian Coasts: A Model Framework for Assessing Risk and Adaptation to Climate Change on Australian Coasts", National Climate Change Adaption Research Facility, Gold Coast pp.203

WorleyParsons (2009) "Ex-HMAS Adelaide Artificial Reef Coastal and Oceanographic Processes", Report prepared for NSW Land and Property Management Authority, Newcastle NSW

Wright, S. and Davidson, A. (2007) "Ocean Acidification: A Newly Recognised Threat", 10 *Australian Antarctic Magazine* 27 (2007)

You, Z.J. (2007) "Extrapolation of Extreme Wave Height with a Proper Probability Distribution Function", *Proceedings of the Australasian Coasts and Ports Conference*, Melbourne, The Institute of Engineers Australia

Young, I.R., Zieger, S. and Babanin, A.V. (2011) "Global Trends in Wind Speed and Wave Height", *Science*, 332 (6028), 451-455

7. Glossary of Terms and Abbreviations

Average Recurrence Interval (ARI): The average time between which a threshold is reached or exceeded (e.g. large wave height or high water level) of a given value. Also known as *Return Period.*

Annual Exceedance Probability (AEP): The probability (expressed as a percentage) of an exceedance (e.g. large wave height or high water level) in a given year.

Coastal Sediment Compartment: Structural features related to the geologic frameworks on the coast. The framework is responsible for the structural evolution of the planform of the coastline. Compartments are defined based on coastal aspect and land systems, as well as the large coastal geomorphology landforms.

Cross-shore Transport: Refers to the sediment moved in a cross-shore direction to the coastline induced by water motions due to waves and undertow.

Extreme Storm Event: Storm for which characteristics (wave height, period, water level etc.) were derived by statistical 'extreme value' analysis. Typically these are storms with ARIs ranging from 1 to 100 years.

JPM-PCR: Joint Probability Method – Probabilistic Coastline Recession model.

ICOLL: Intermittently closed or open lakes and lagoons.

Longshore Transport = Littoral Drift: Refers to the sediment moved along a coastline under the action of wave-induced longshore currents (Dean and Dalrymple, 2002). The *net drift* is the sum of the positive (conventionally northwards direction in NSW) and negative (southwards in NSW) direction. The *gross drift* is the sum of the drift magnitudes (absolute values). The *differential drift* is the difference between the net drift into and out of a coastal compartment. Both gross and net drift are typically averaged over a year and expressed in m^3/yr.

Pdf(s): probability density/distribution function.

SDS: Synthetic Design Storms.

SLR: Sea Level Rise.

2D: Two-dimensional.

3D: Three-dimensional.

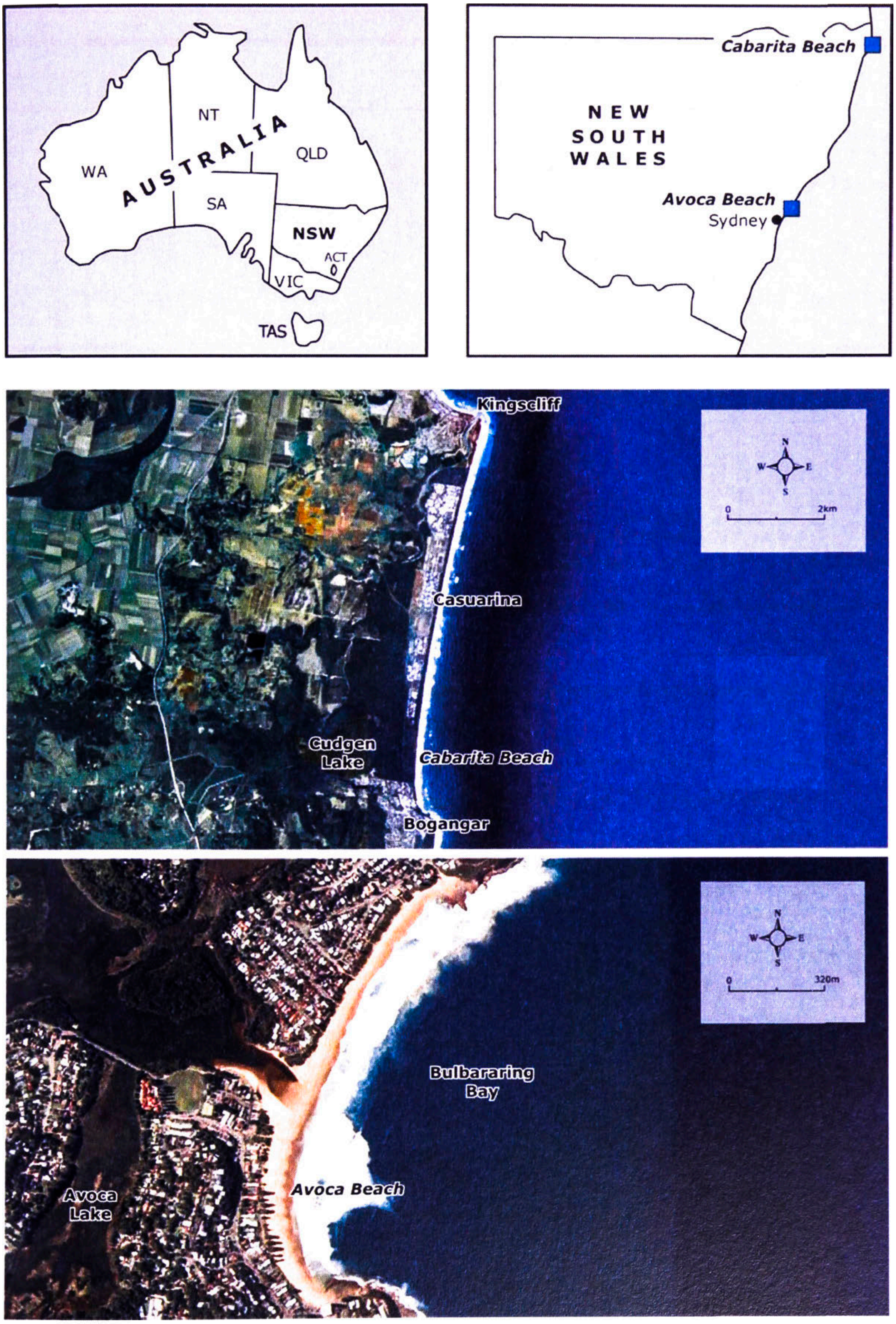
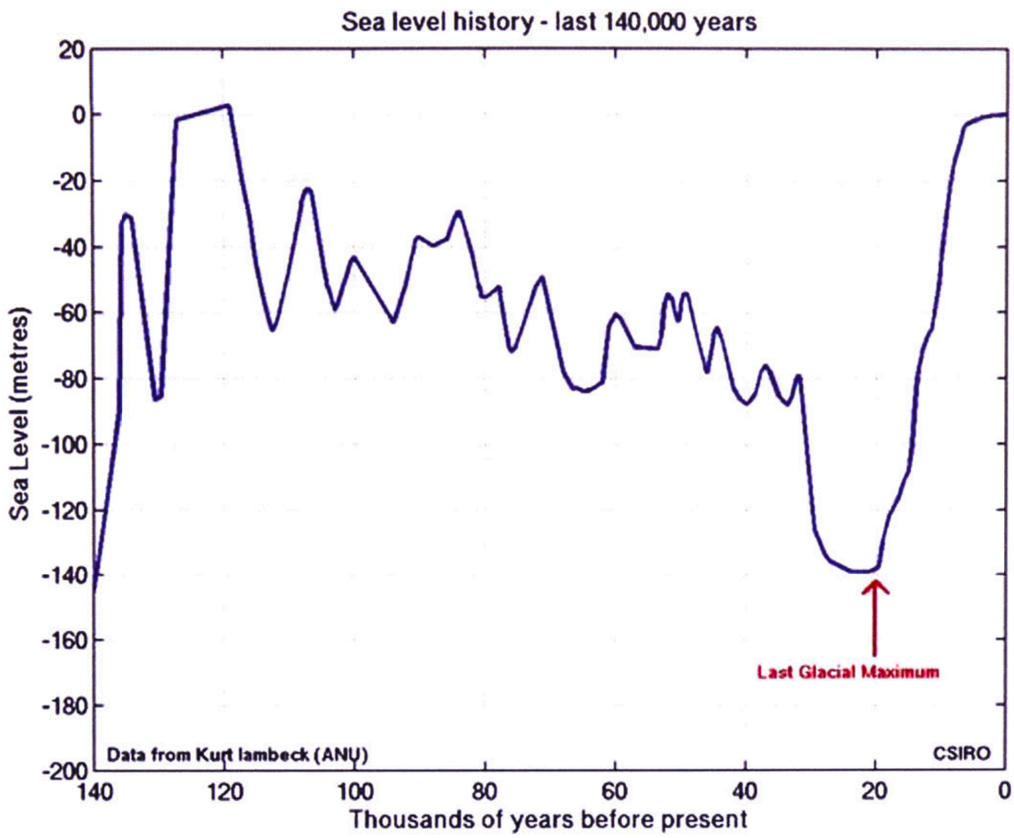


Figure 1.1 Study Sites Location



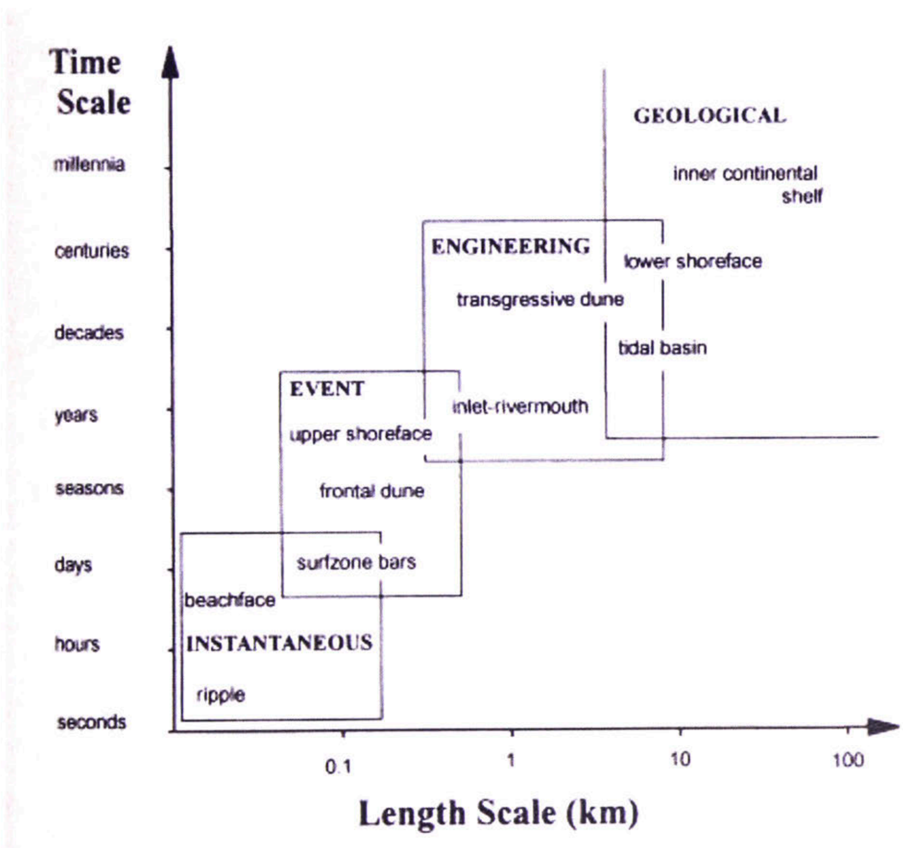


Figure 2.1 Sea Level Changes Over Time and Temporal and Spatial Scales (source coastalwiki.org)

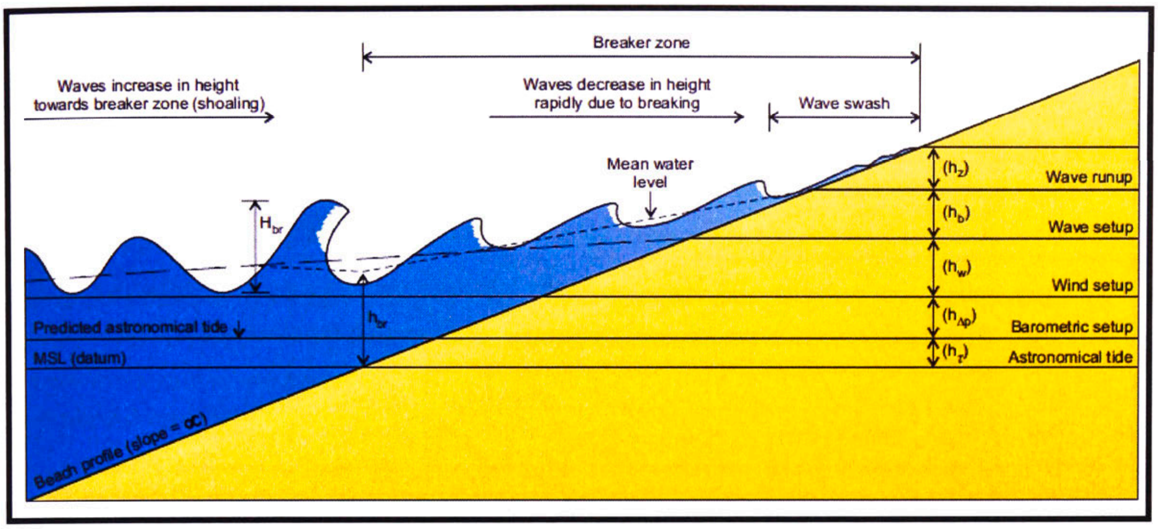


Figure 2.2 Elevated Water Levels

Jonson St, Byron Bay, 1973. Photograph: K. Dunstone c\ Byron Shire Council.

Figure 2.3 Coastal Inundation Byron Bay 1973

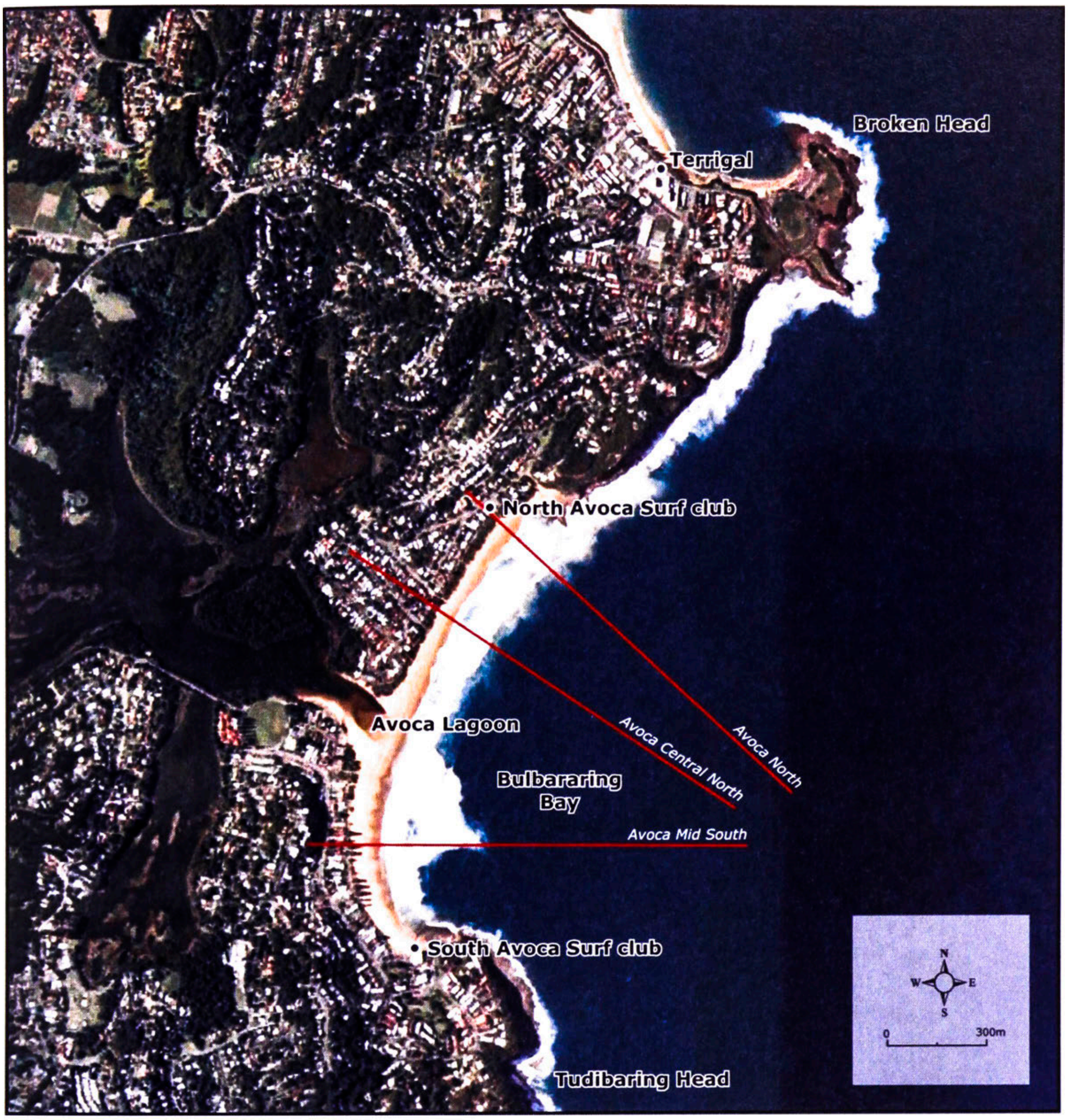


Figure 2.4 Avoca Beach Location

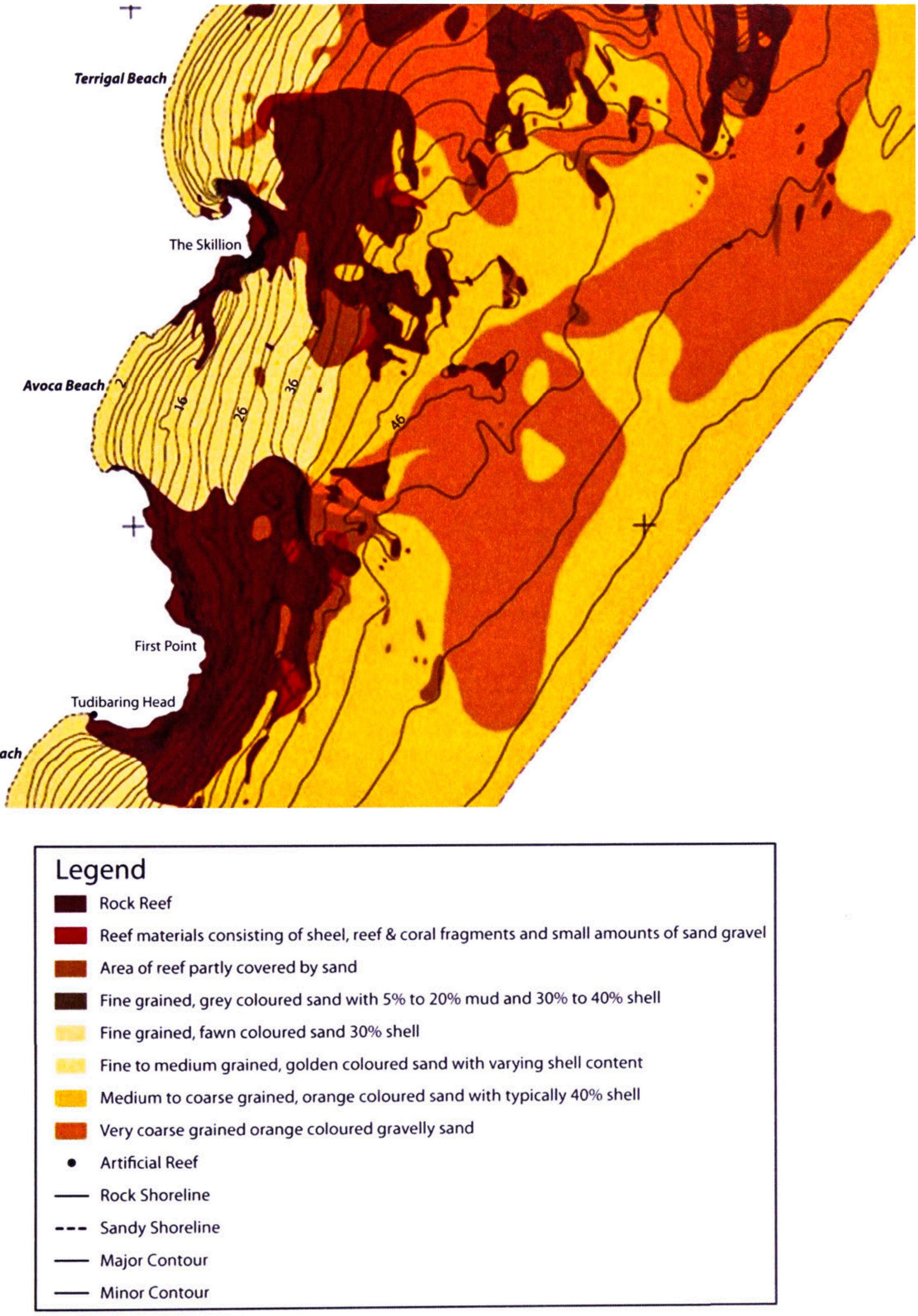
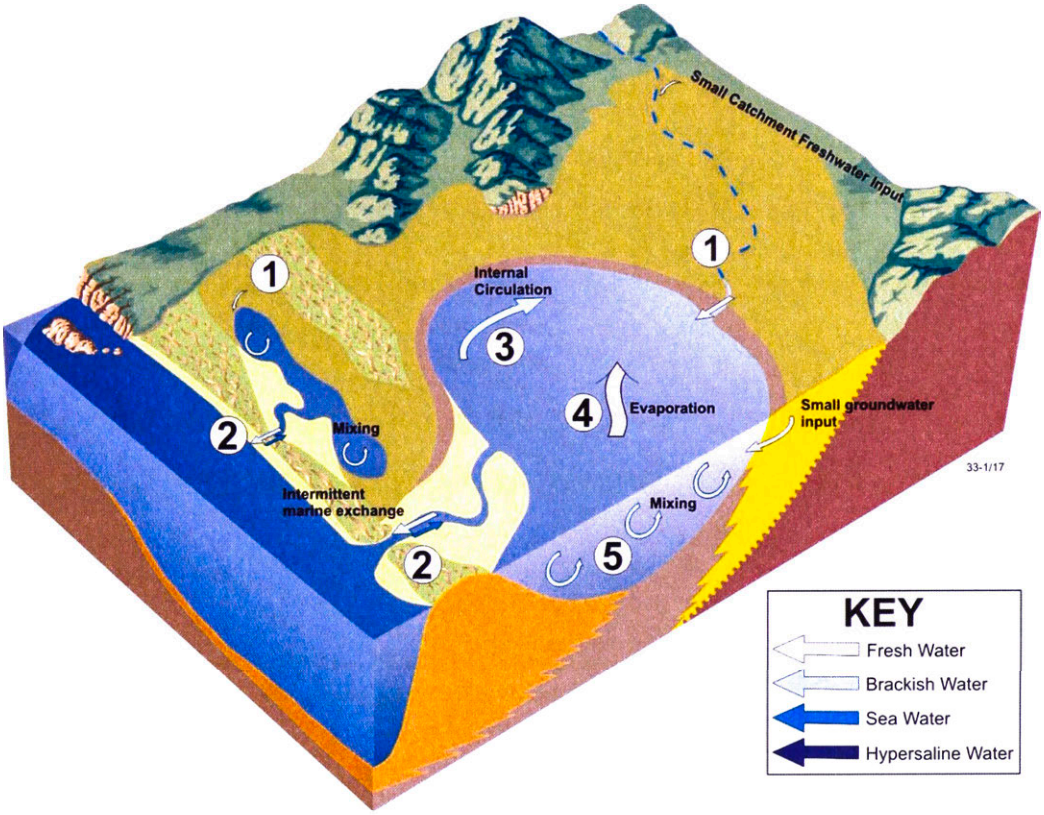


Figure 2.5 Avoca Beach Sedimentology (NSW Department of Commerce)



Saline Coastal Lake and ICOLLs

1. Very little freshwater enters from the catchment and the quantity of input can vary seasonally
2. Entrances tend to remain closed for long periods, only opening during floods
3. Internal circulation within coastal lagoons is driven by wind and ocean wave and tidal influence is negligible inside the basin
4. Evaporation may be significant in certain climatic regions, and can exceed freshwater input
5. Salinity can vary significantly from brackish to hypersaline, depending upon the amount of freshwater input, climate and the frequency and duration of entrance opening

Figure 2.5.1 Conceptual Model of Coastal Lagoon/ICOLL (source: Engineers Australia 2012a; modified from Ryan et al. 2003). © Commonwealth of Australia (Geoscience Australia) 2012.

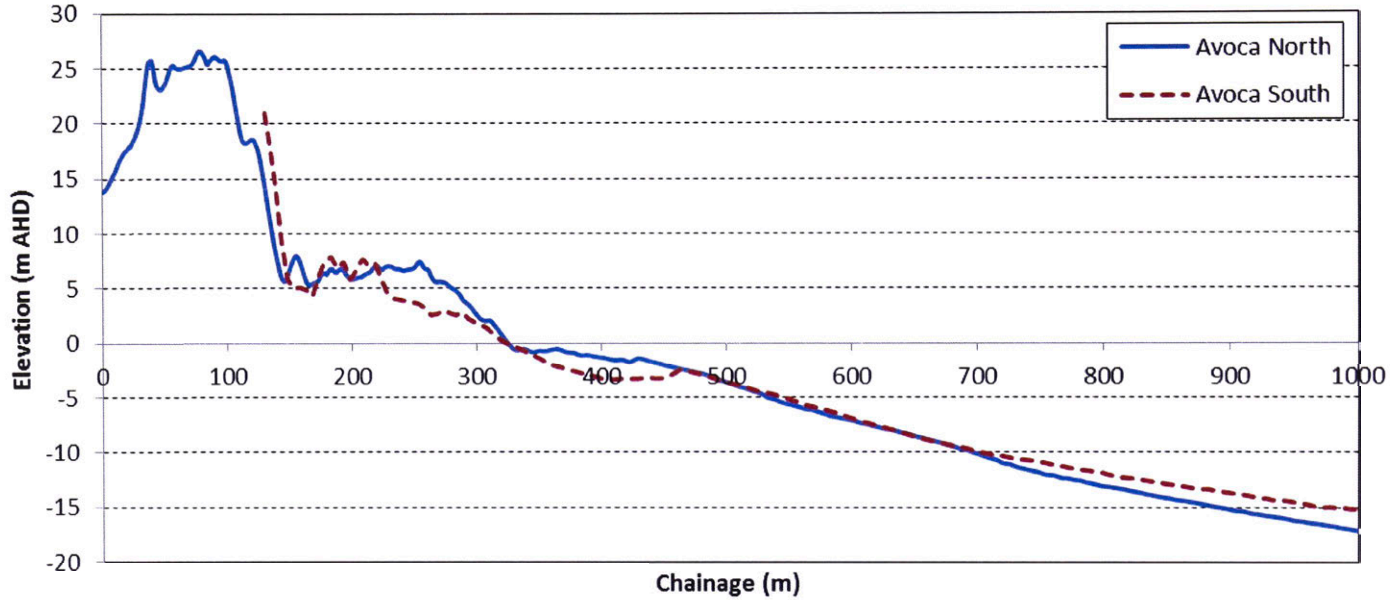


Figure 2.5.2 Representative Beach Profile at North and South Avoca

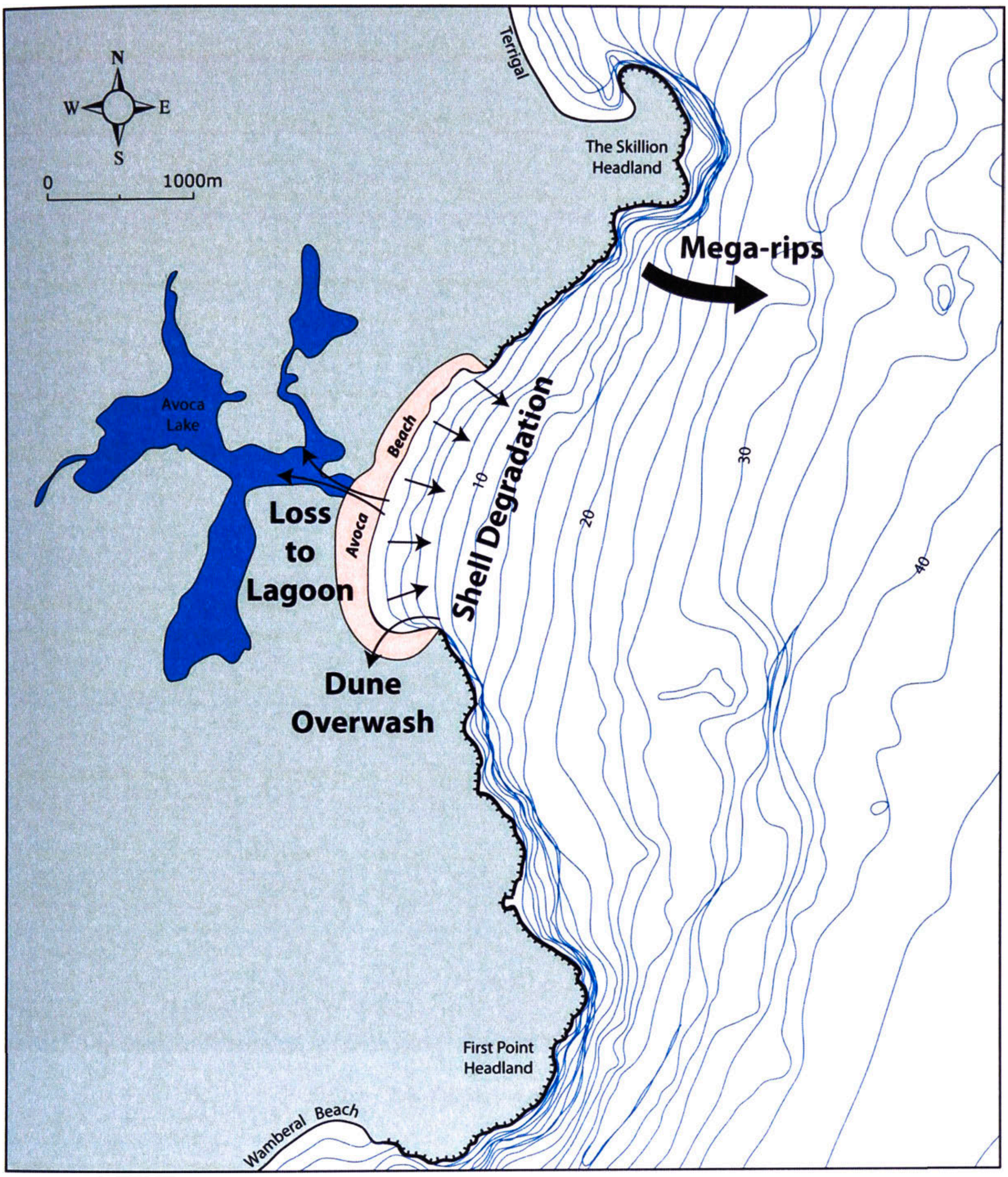


Figure 2.5.3 Avoca Bathymetry and Conceptual Sediment Budget

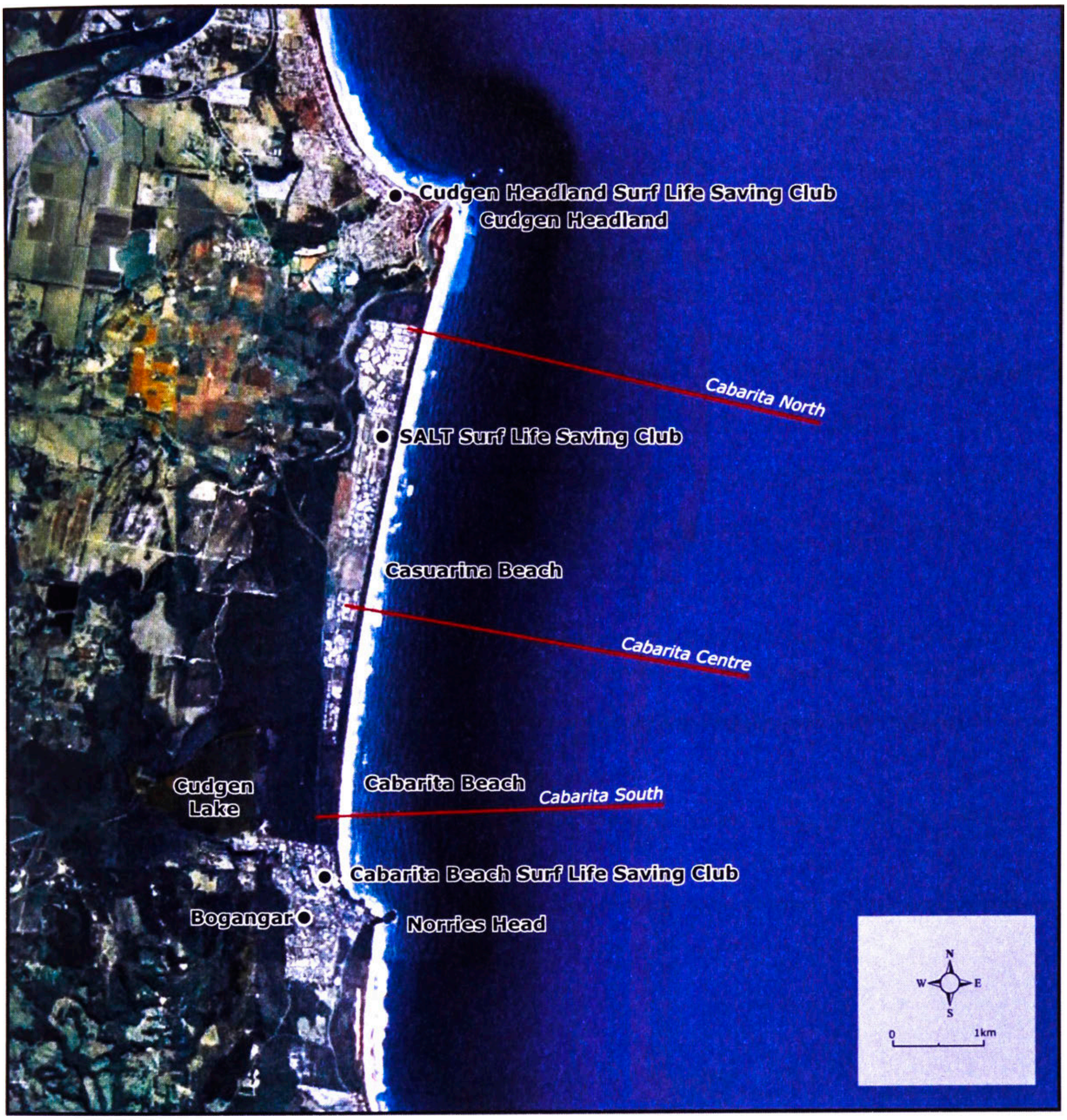


Figure 2.6 Cabarita Beach Location

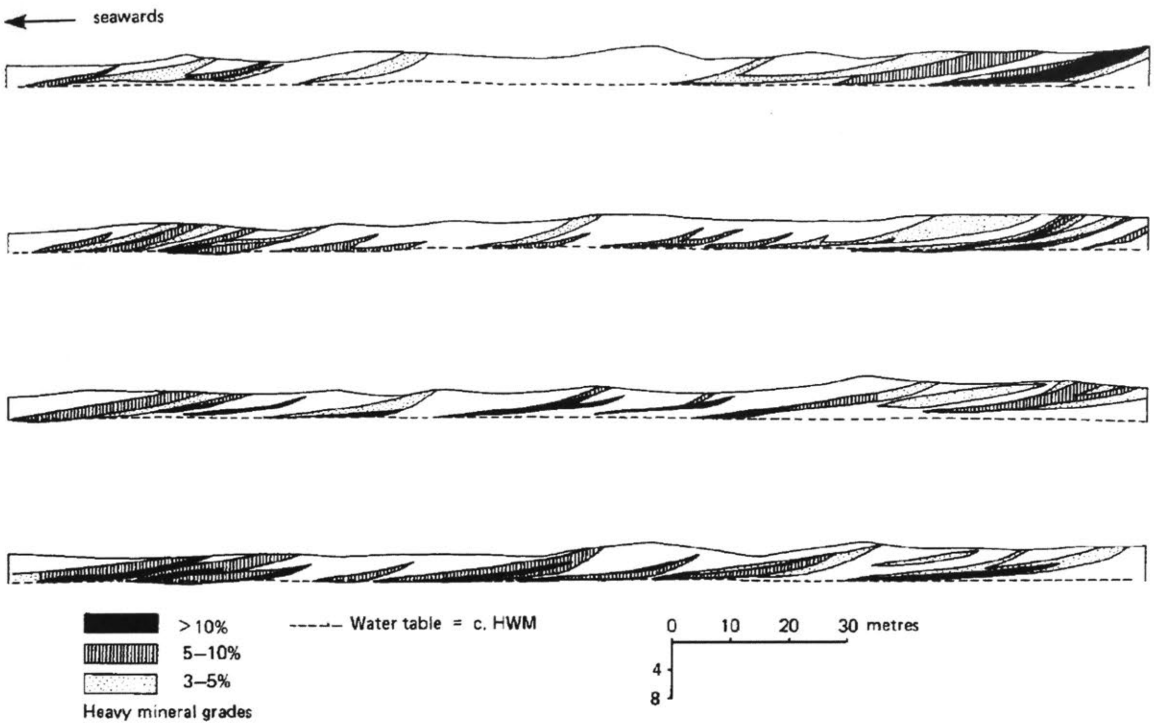


Figure 2.7 Prograded Barrier at Cabarita (source: Thom and Roy 1985)

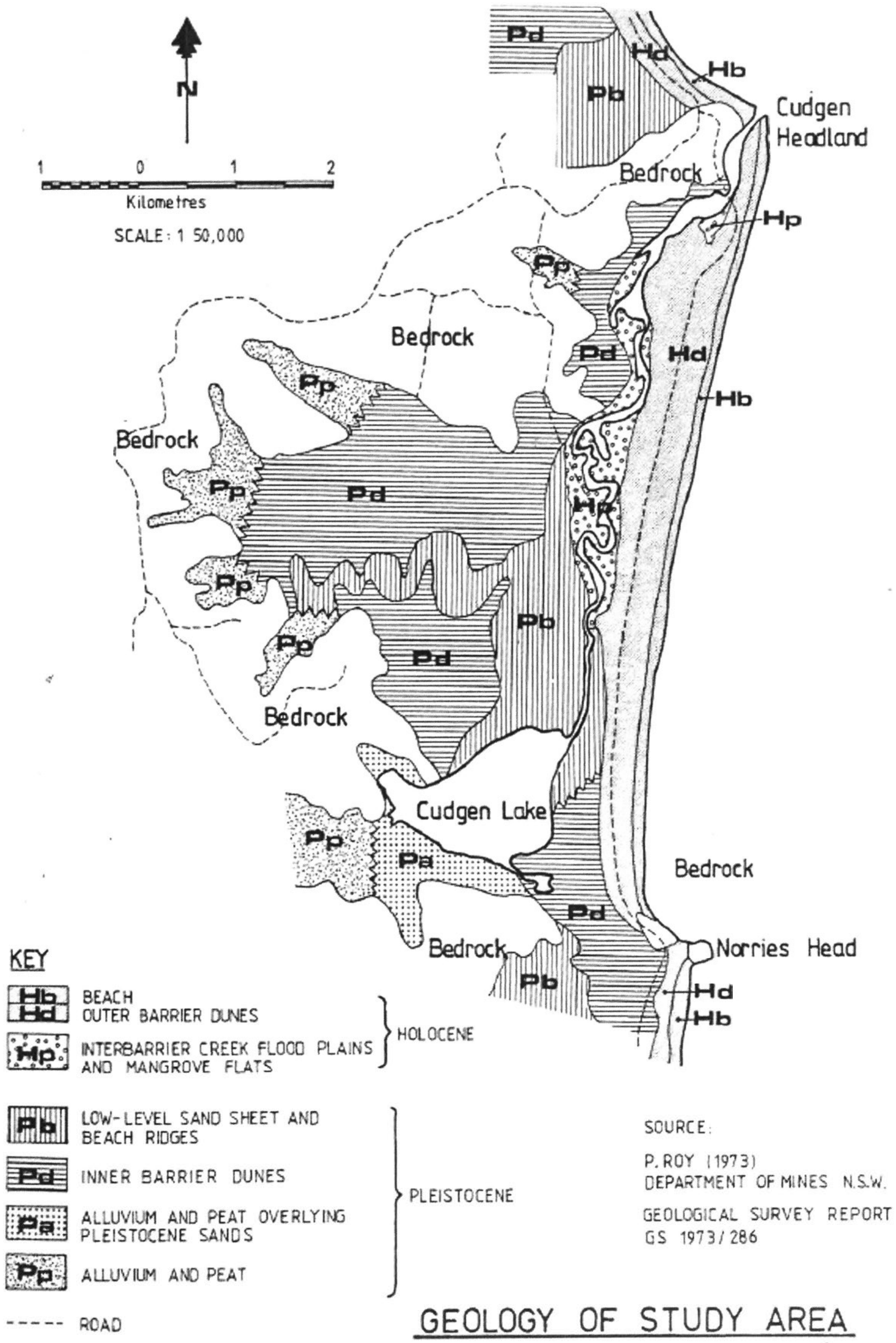


Figure 2.7.1 Geology of Cabarita Compartment (source: PWD 1982)

Figure 2.8 Cabarita Representative Beach Profiles

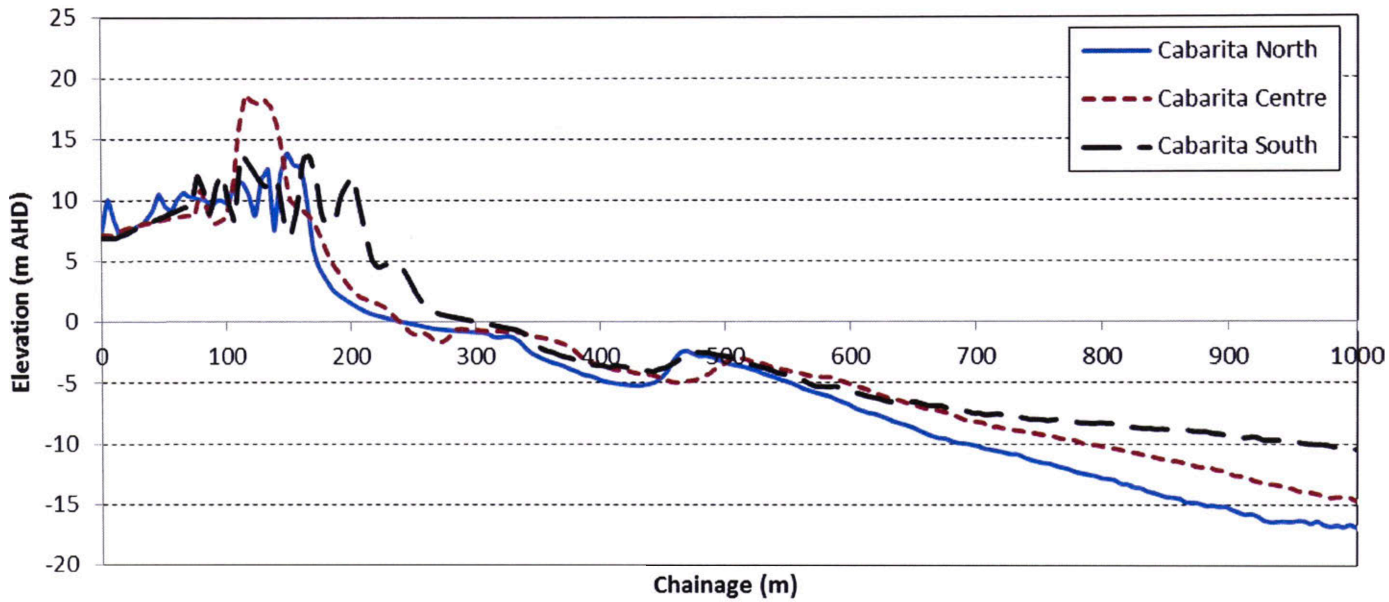


Figure 2.9 No Sand Bypassing Cudgen Headland into Kingscliff on 13/5/2010 (above) and 'Sand Pulse' Bypassing on 24/6/2011 (below)

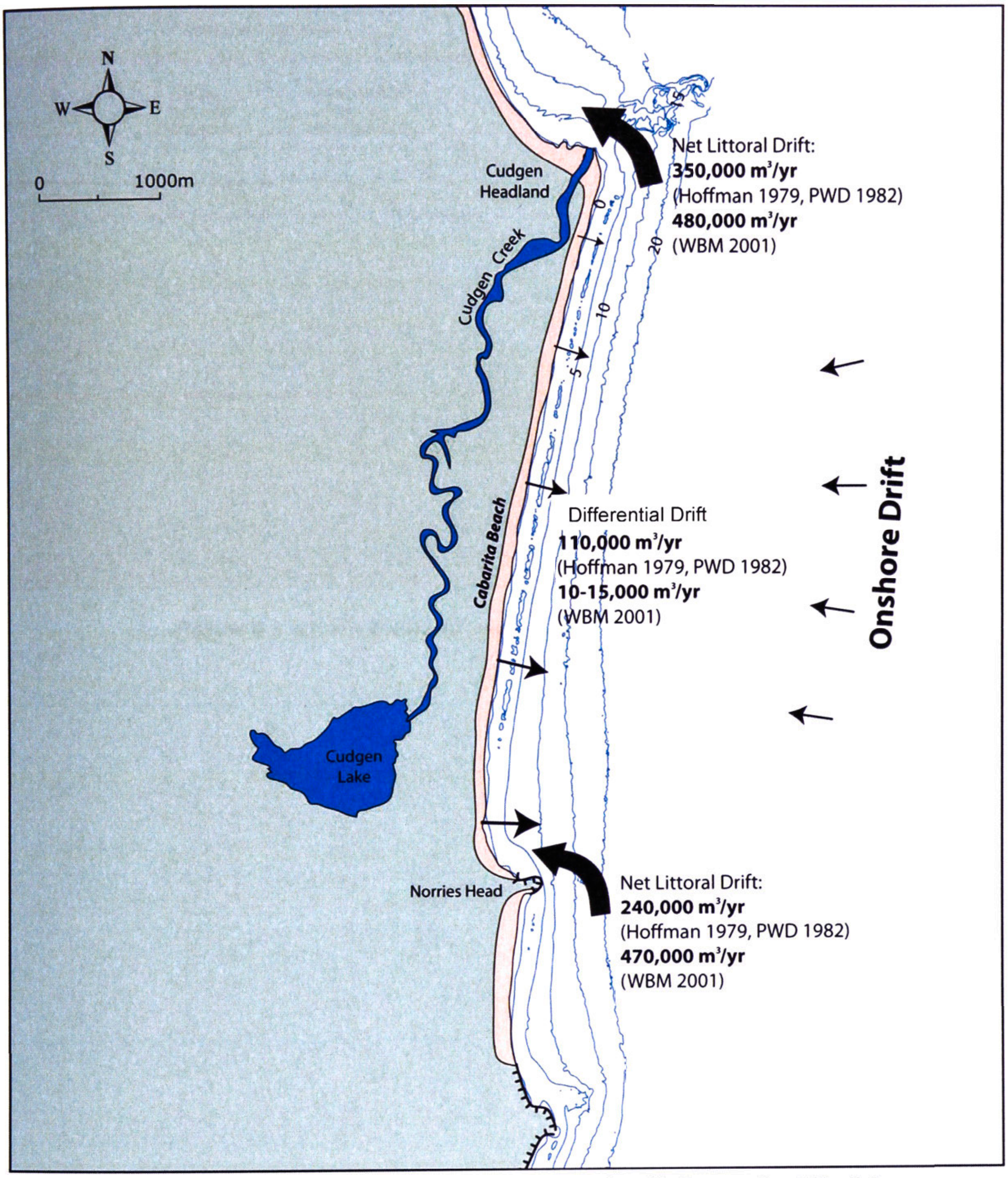


Figure 2.10 Cabarita Compartment Littoral Drift Conceptual Model

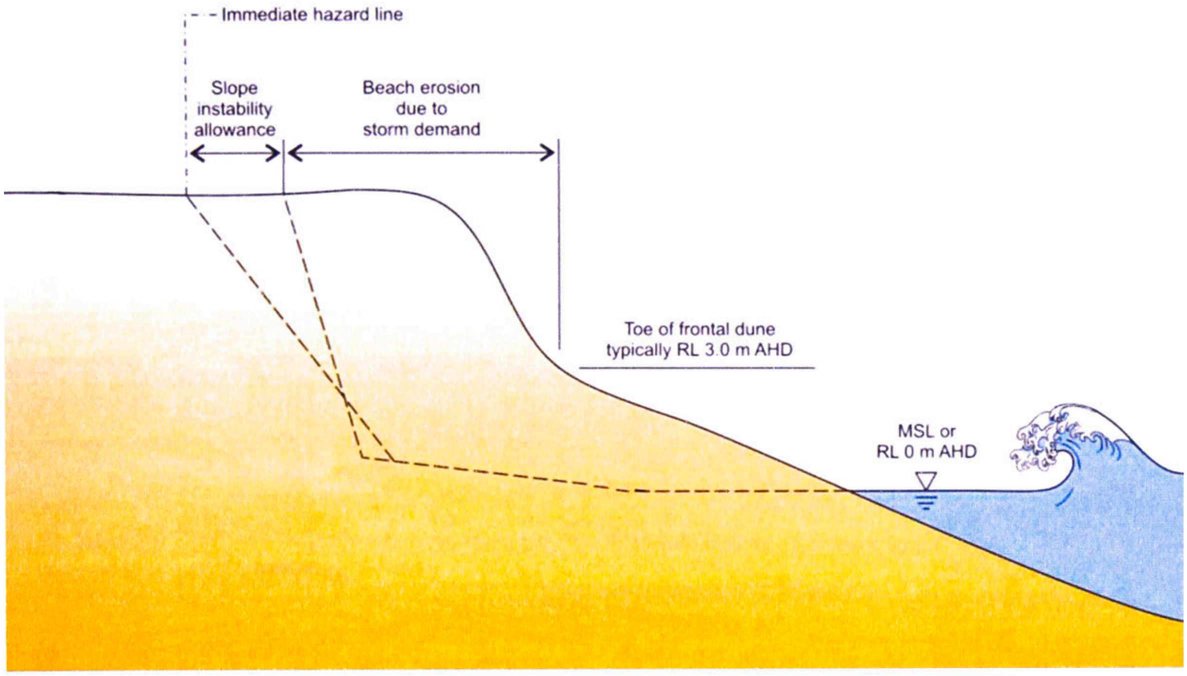


Figure 3.1 Storm Demand and Horizontal Setback Distance

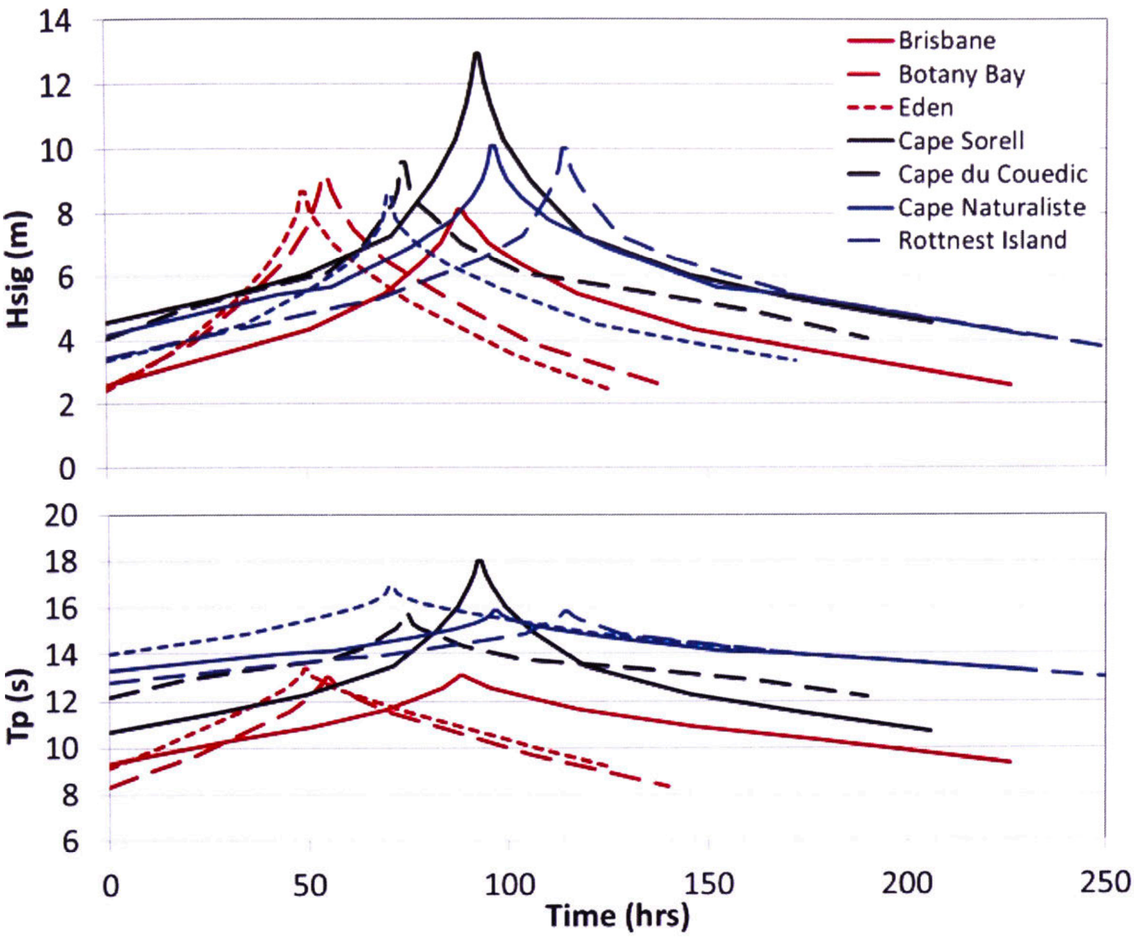


Figure 3.2 Examples of 100 year ARI Synthetic Design Storm Events for Each Assessed Buoy (Shand et al. 2011)

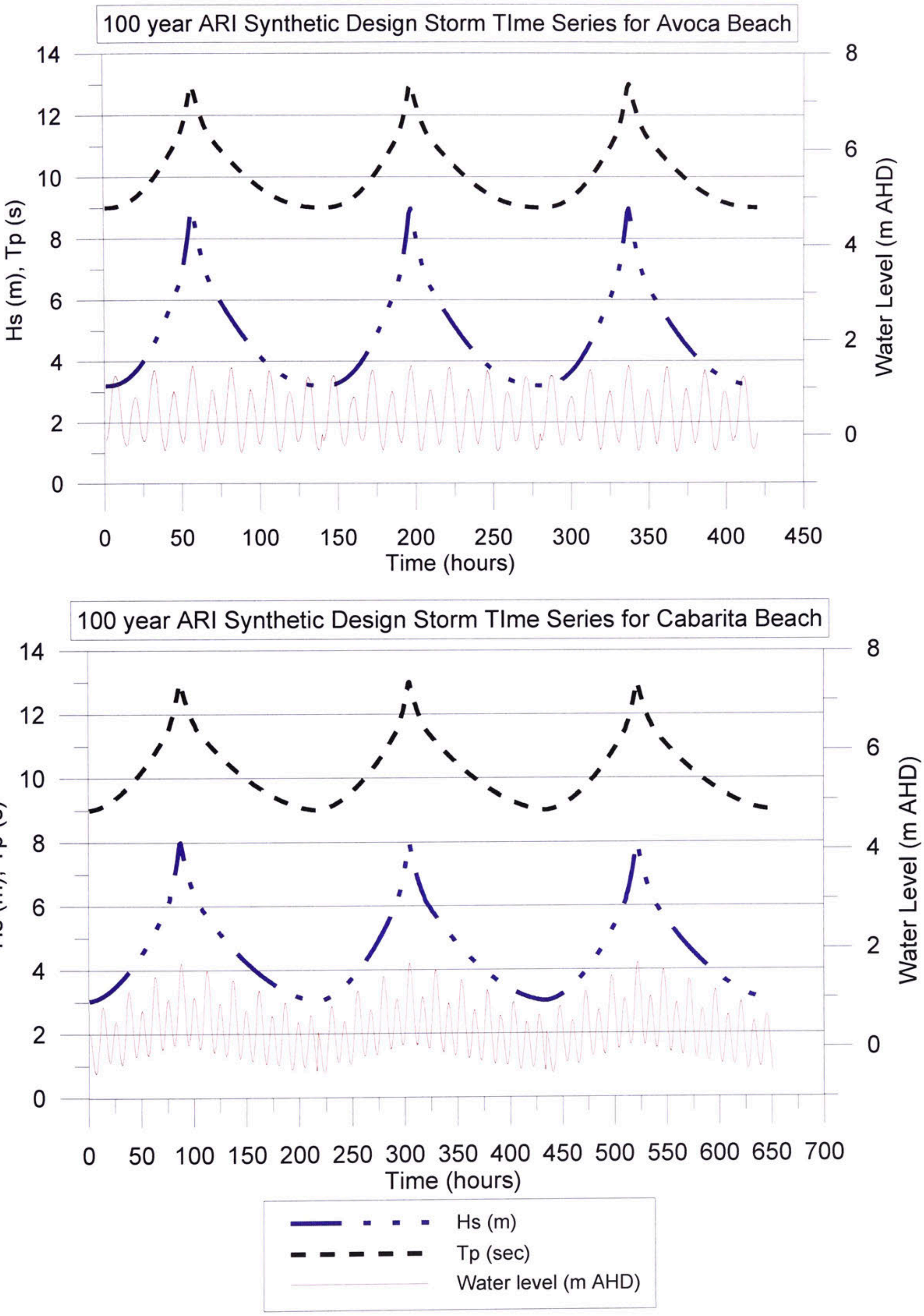


Figure 3.3: 100 year ARI Synthetic Design Storm (offshore) for Avoca and Cabarita Beach

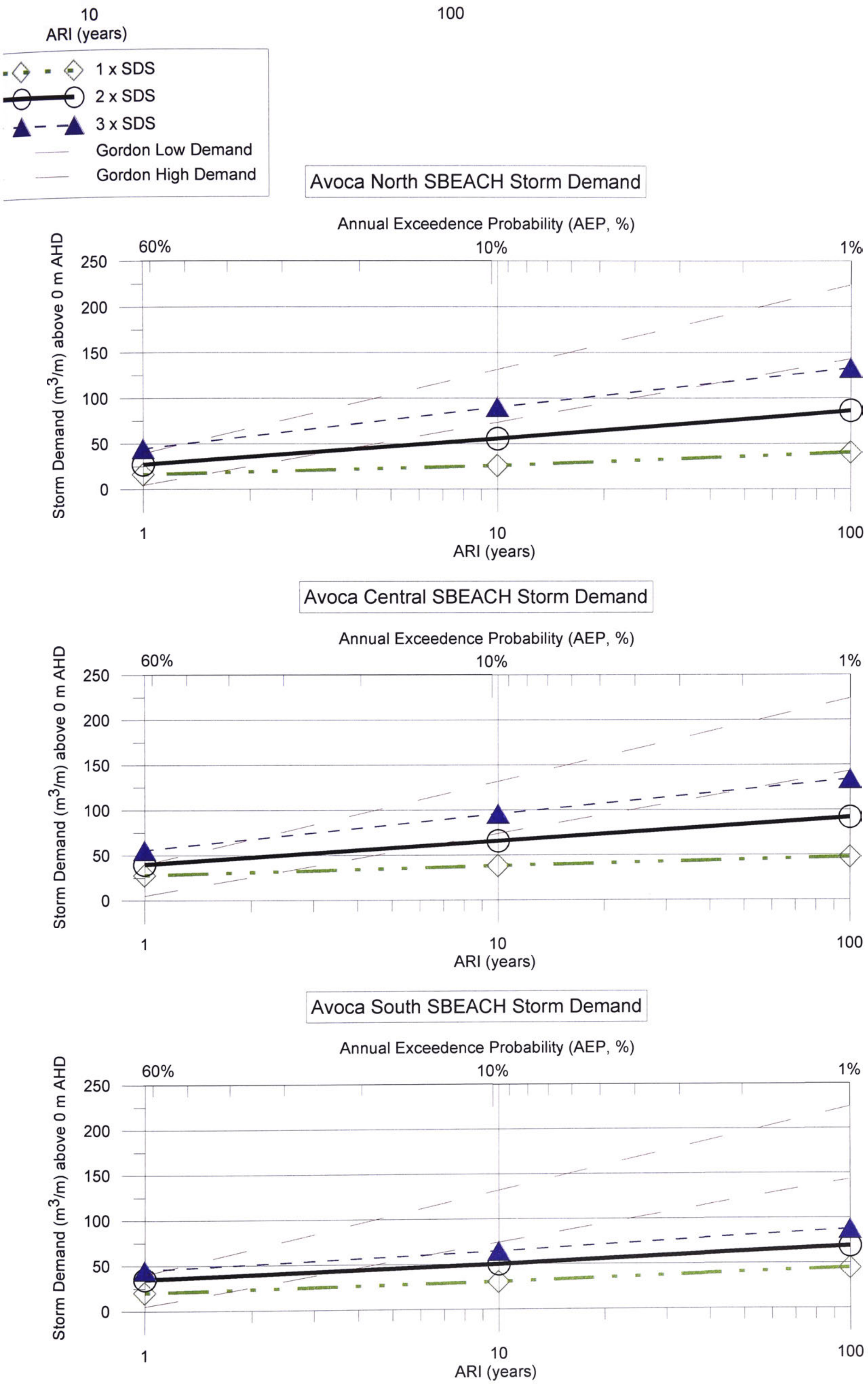


Figure 3.4: Estimates of Storm Demand for Avoca Beach

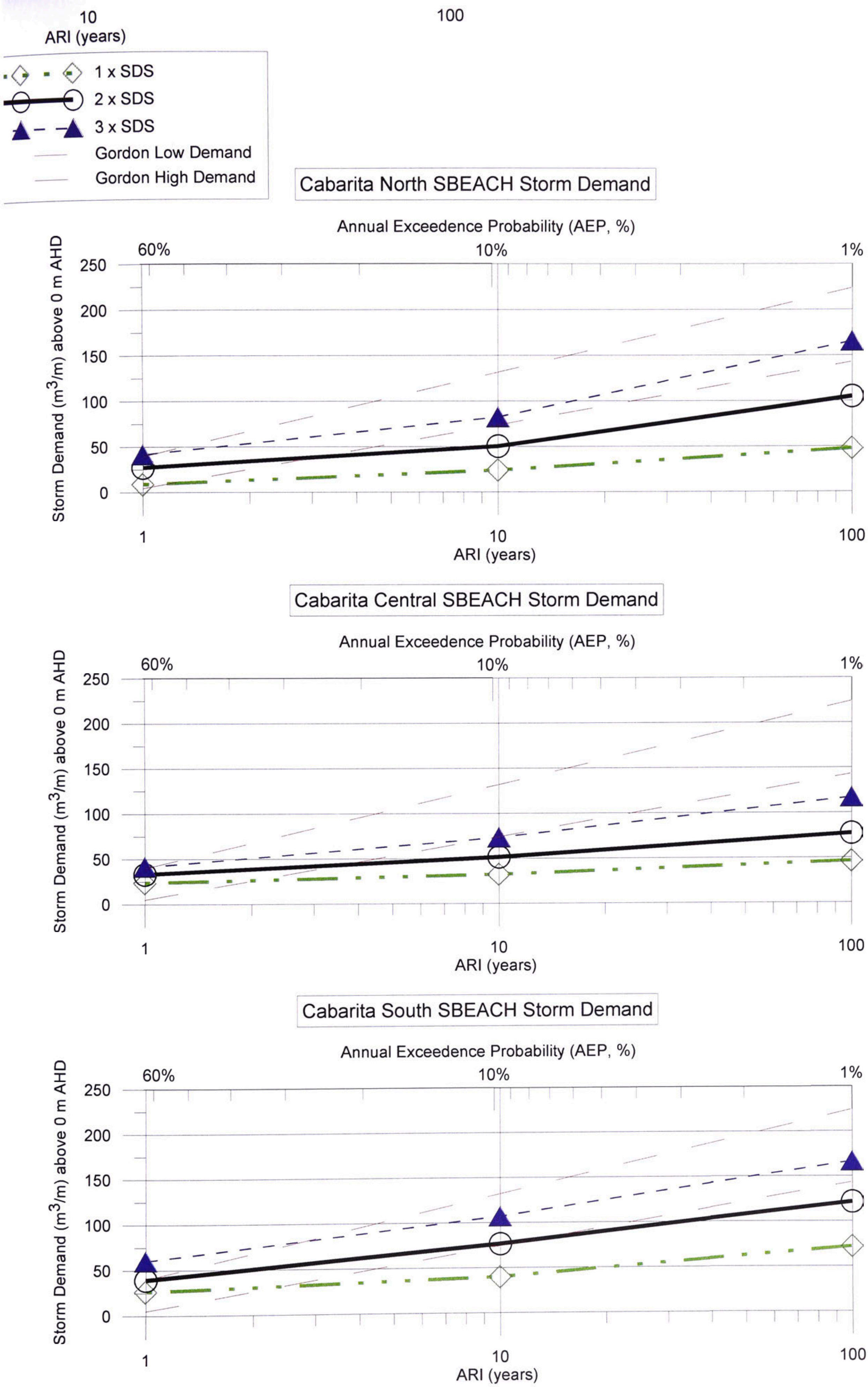


Figure 3.5: Estimates of Storm Demand for Cabarita Beach

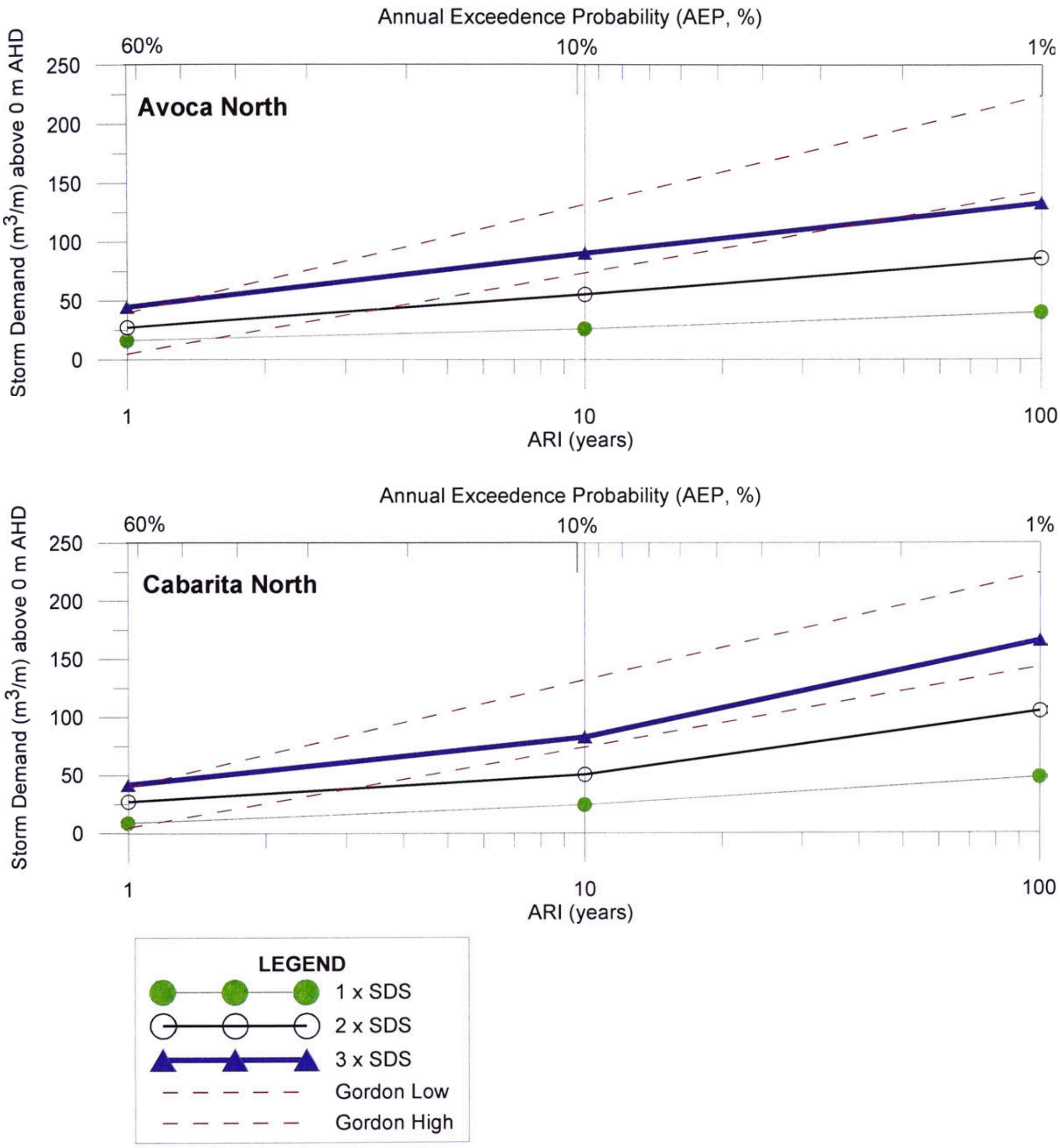


Figure 3.6 Summary of SDS Short-term predictions

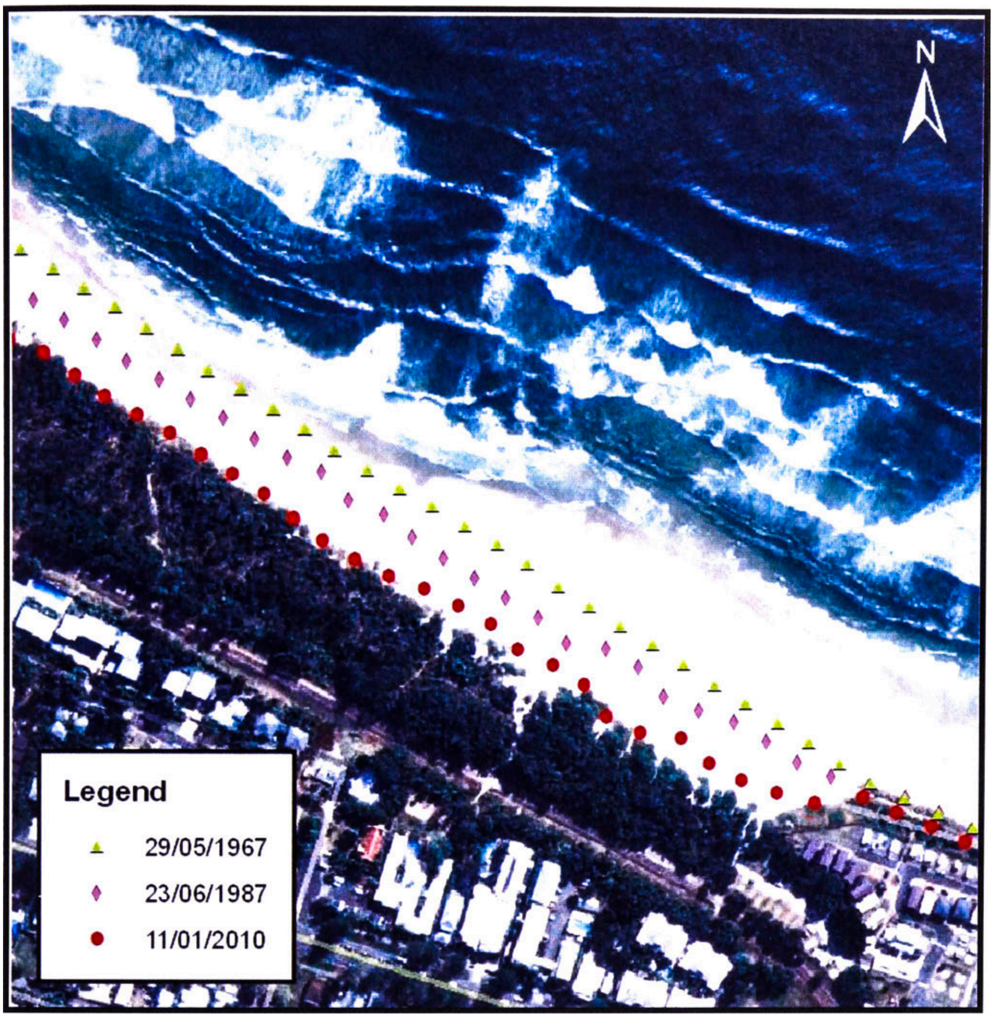


Figure 4.1 Belongil Beach +4 m AHD Contour Evolution from 1967 to 2010

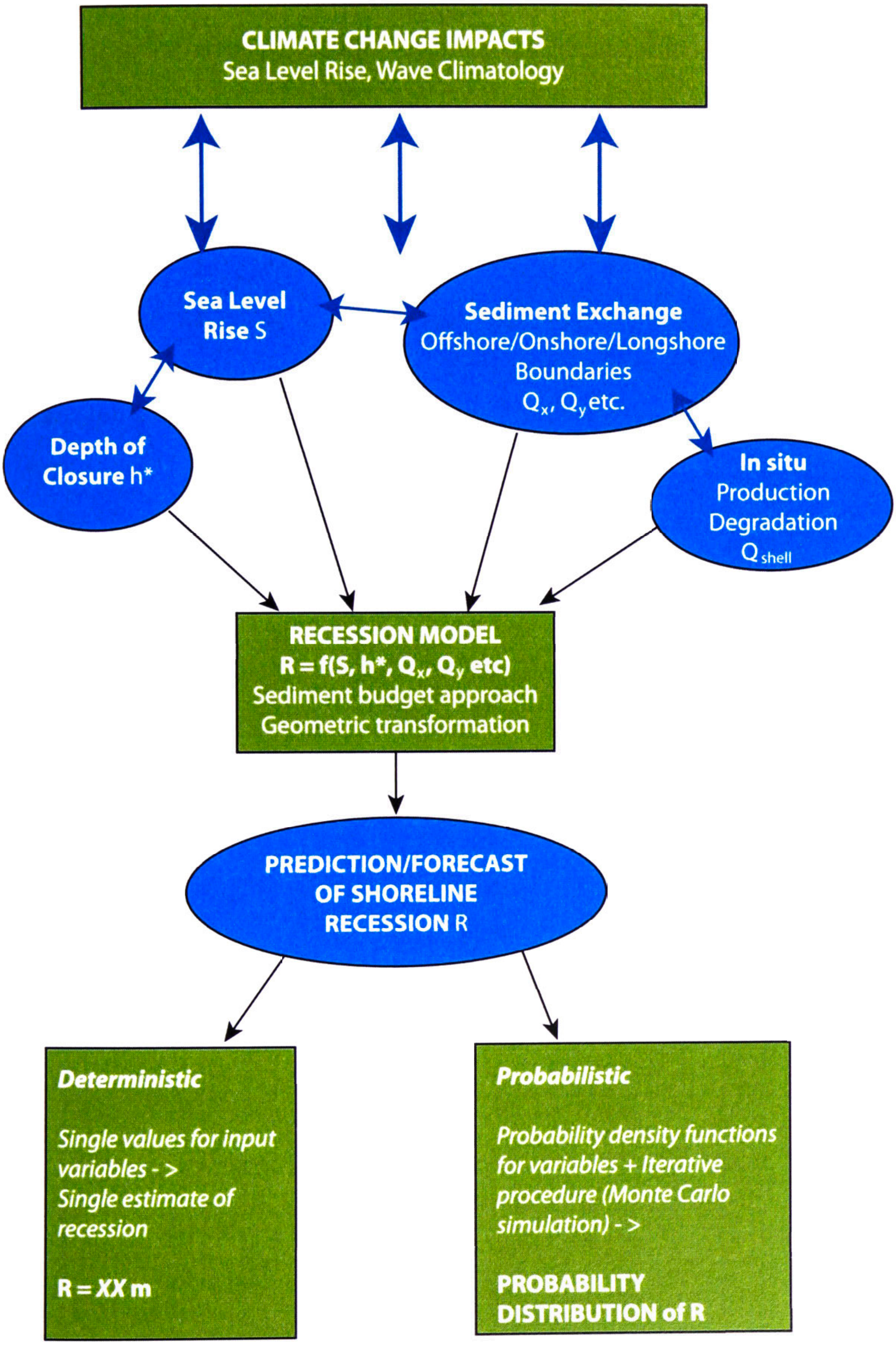


Figure 4.2 Flow Diagram of Probabilistic and Deterministic Approach

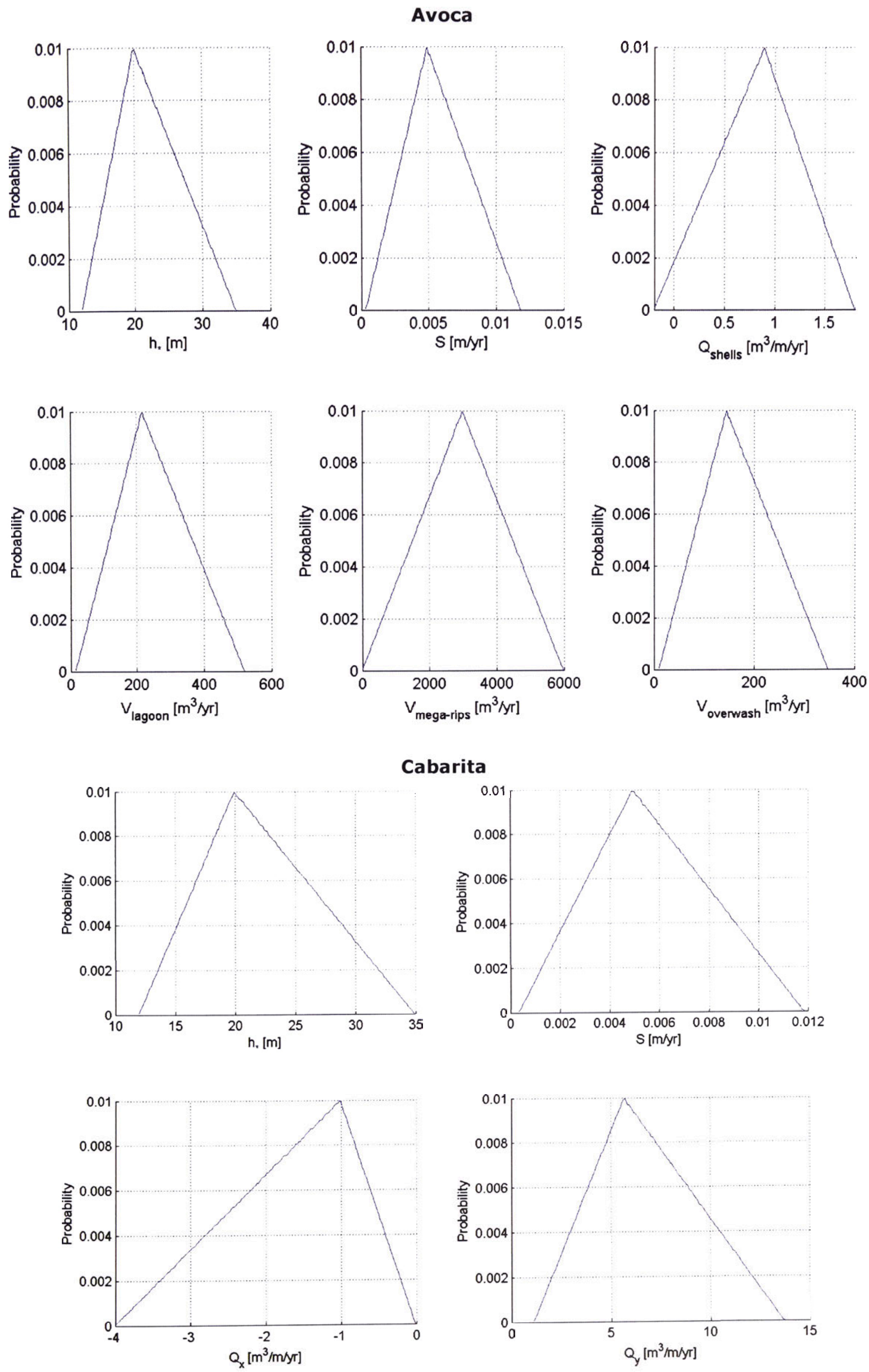


Figure 4.2.1 Avoca and Cabarita Input Variables Probability Distributions

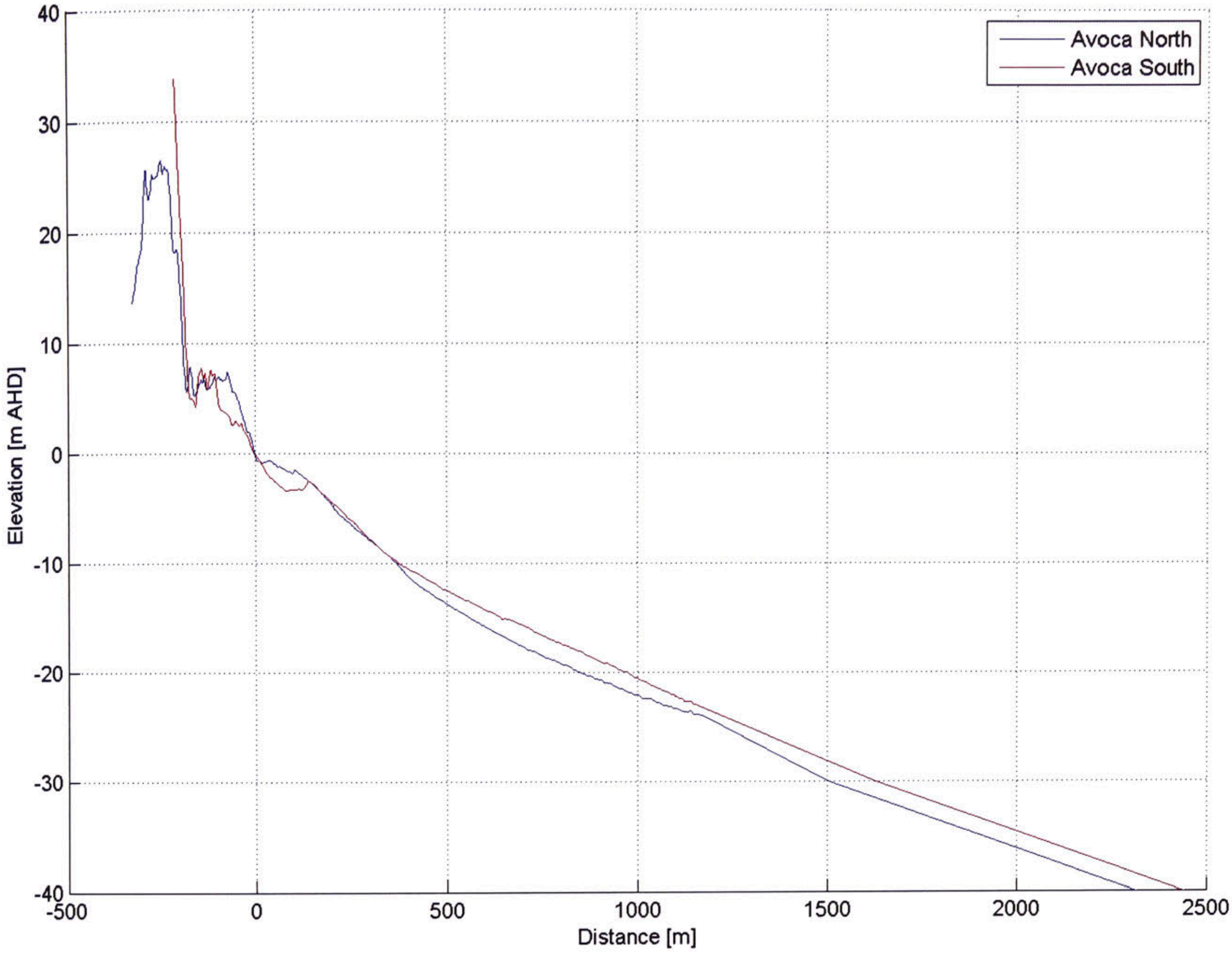
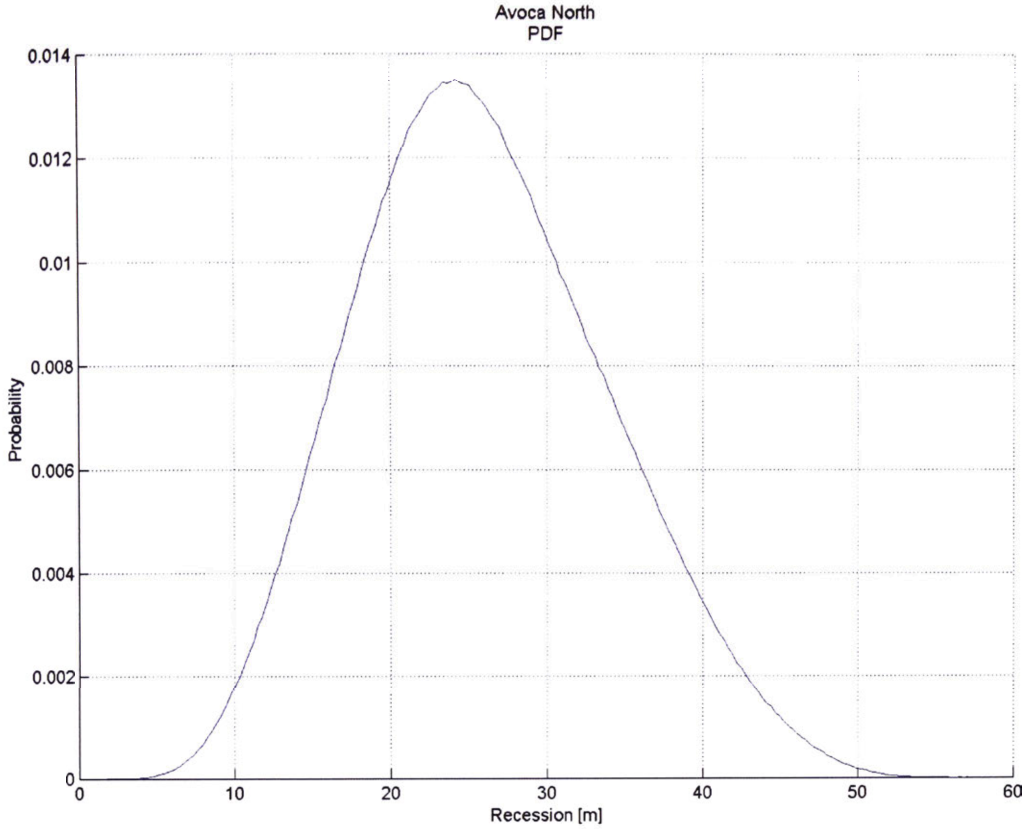


Figure 4.3 Avoca Beach Representative Beach Profiles



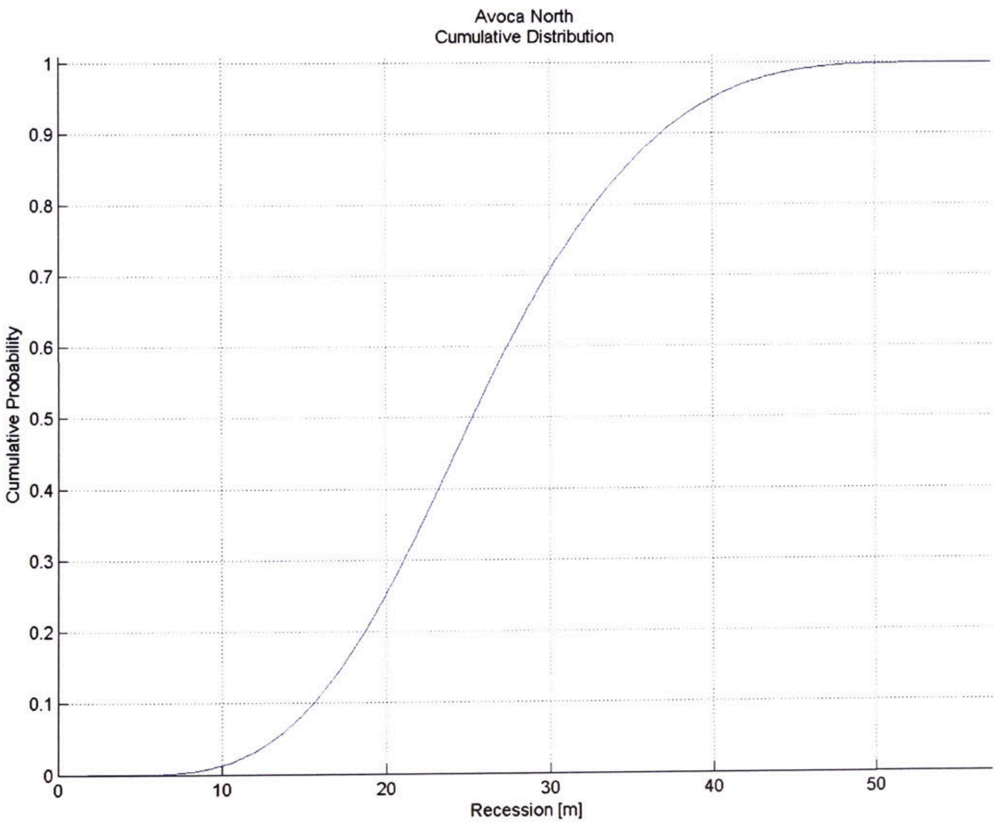
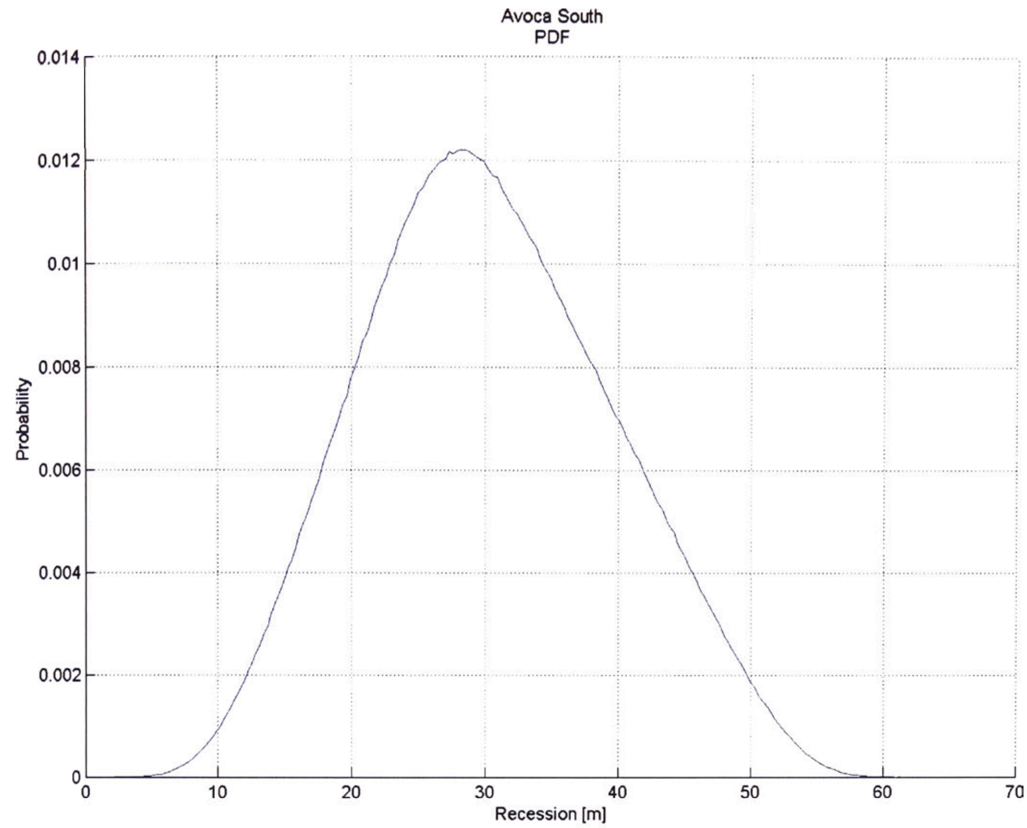


Figure 4.4 Avoca North 2100 Recession Estimates



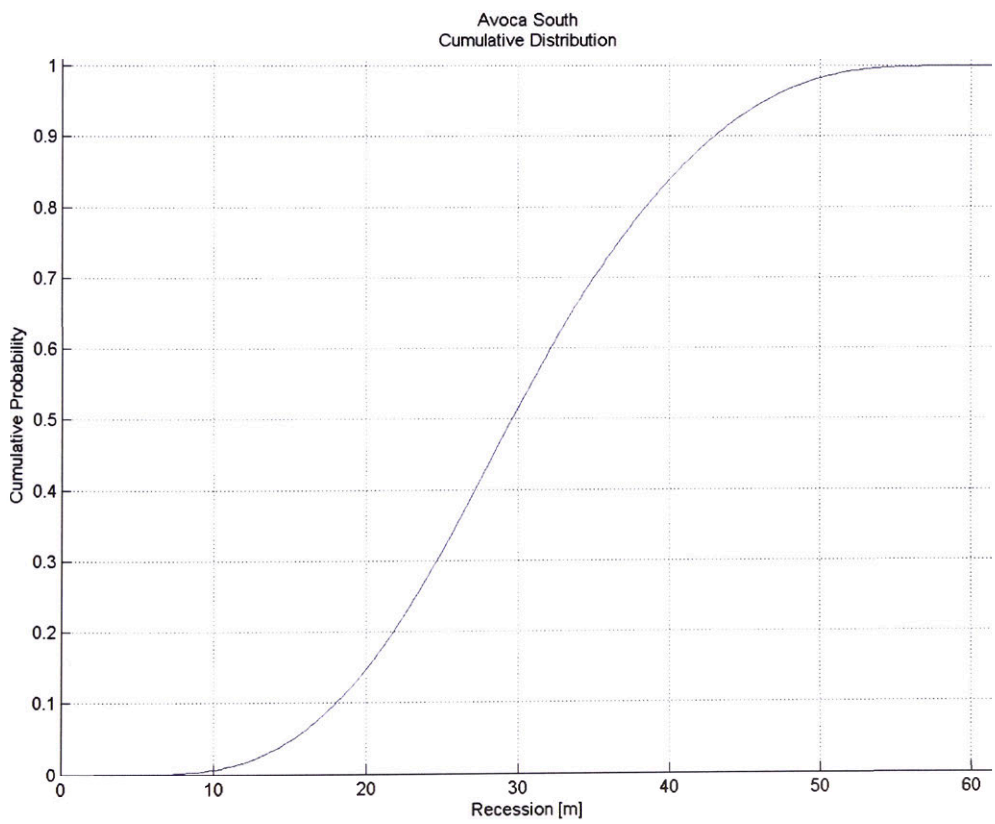


Figure 4.5 Avoca South 2100 Recession Estimates

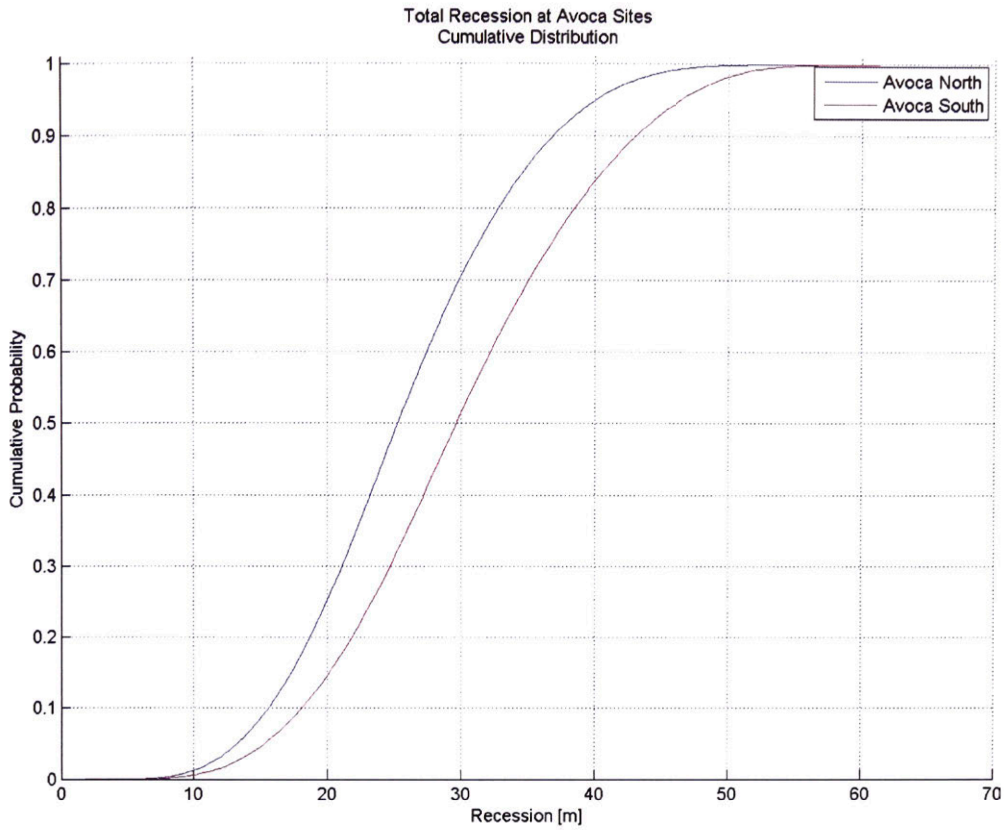


Figure 4.6 Avoca North and South Comparison 2100 Recession Estimates

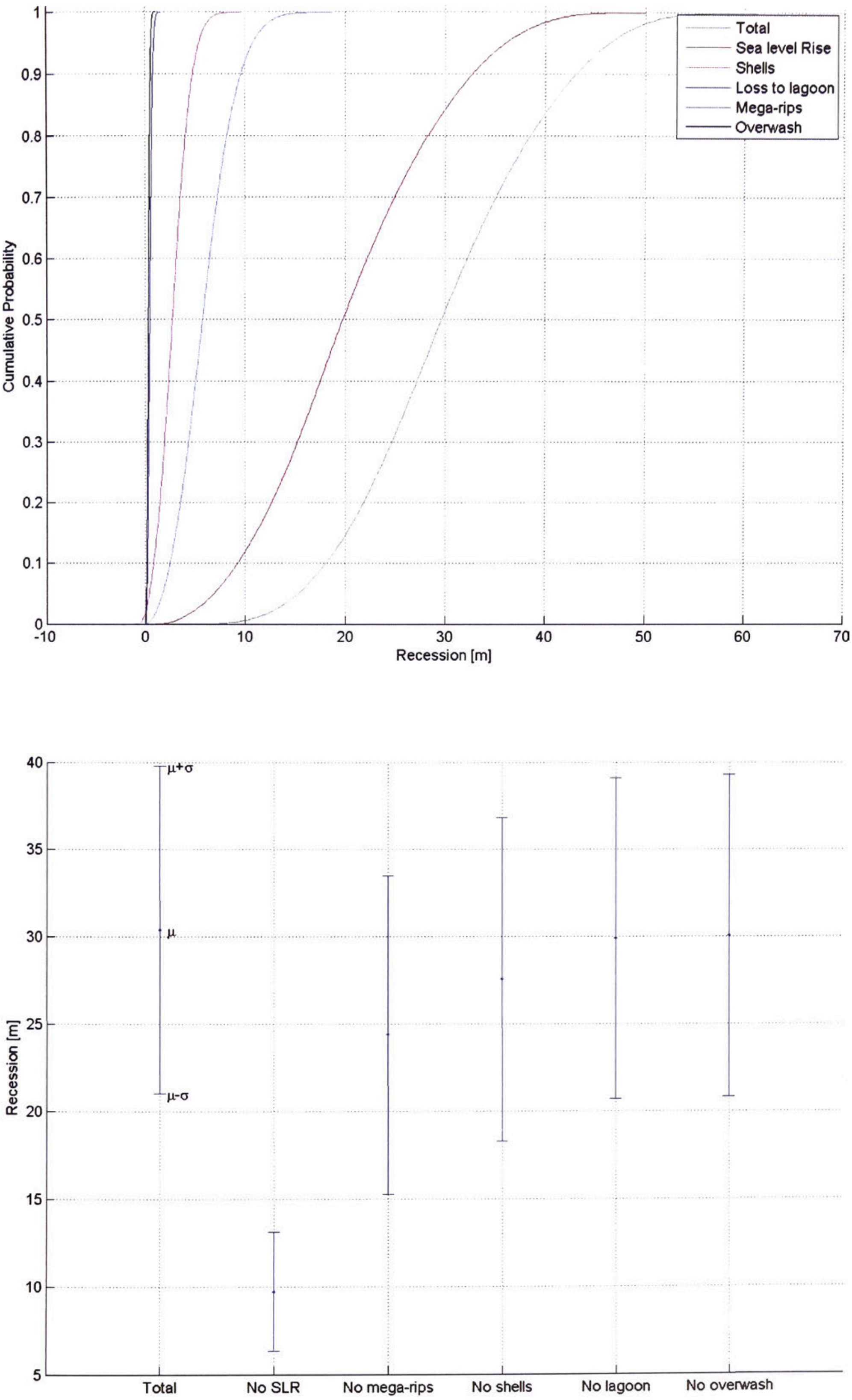
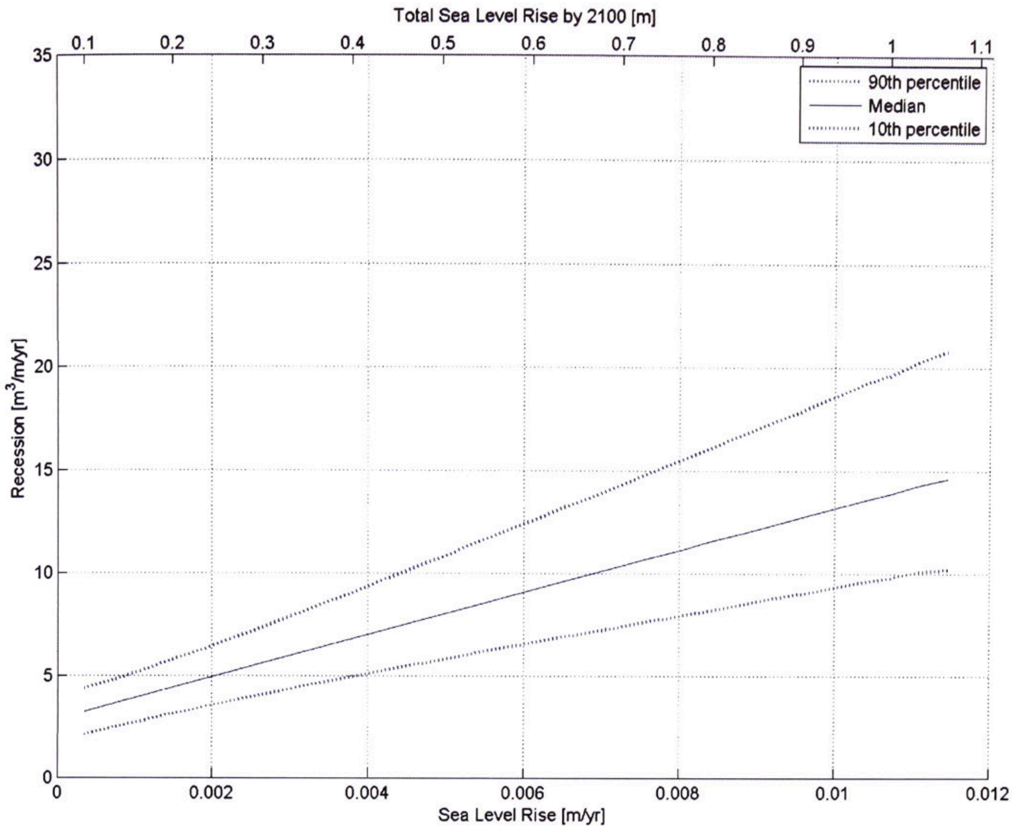


Figure 4.7 Avoca South Contributions to Recession



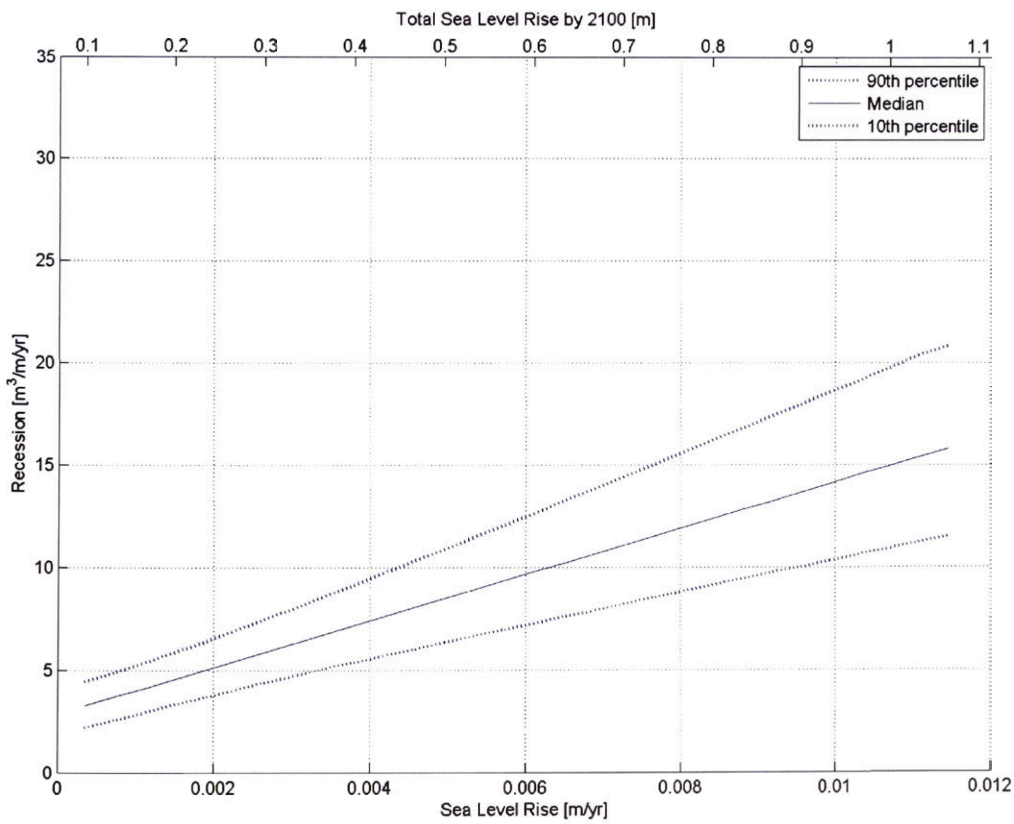


Figure 4.8 Avoca North (above) South (below) Recession Estimates Against SLR

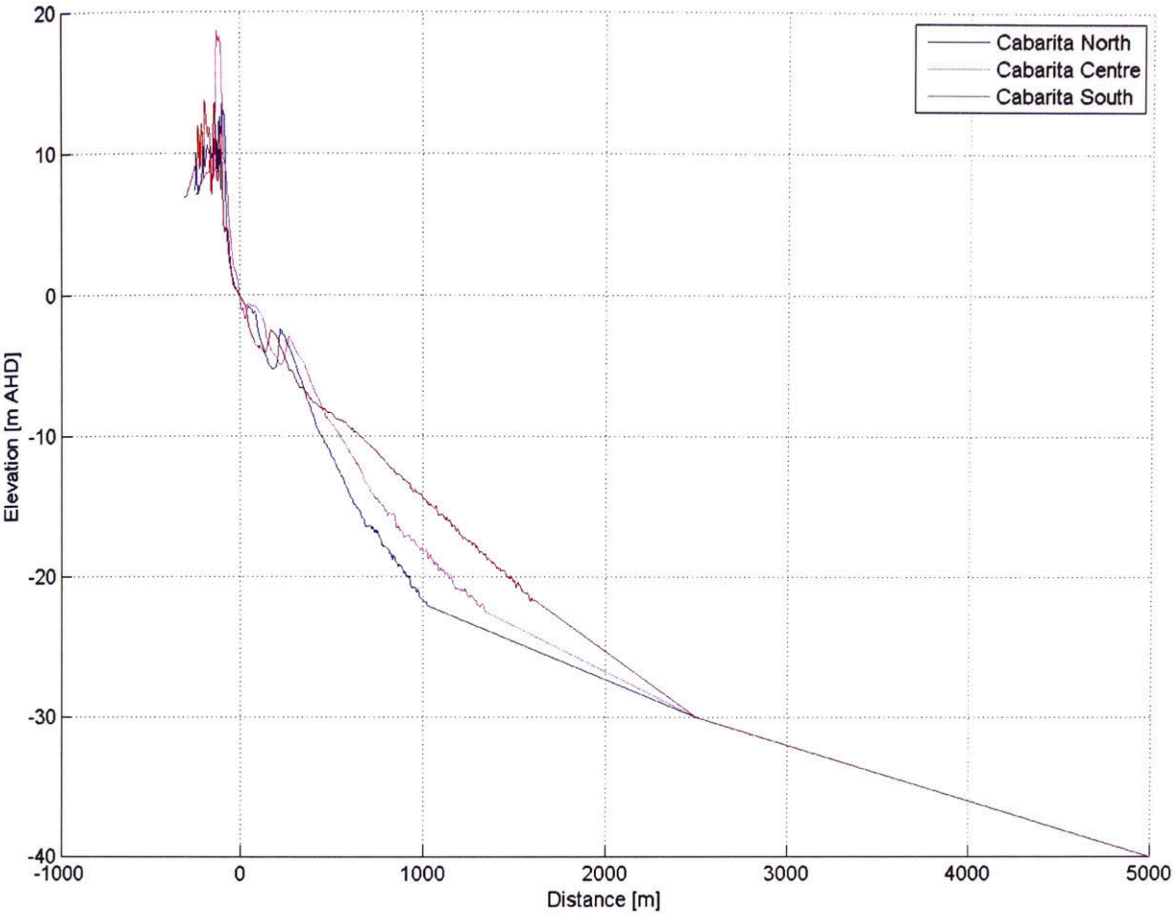
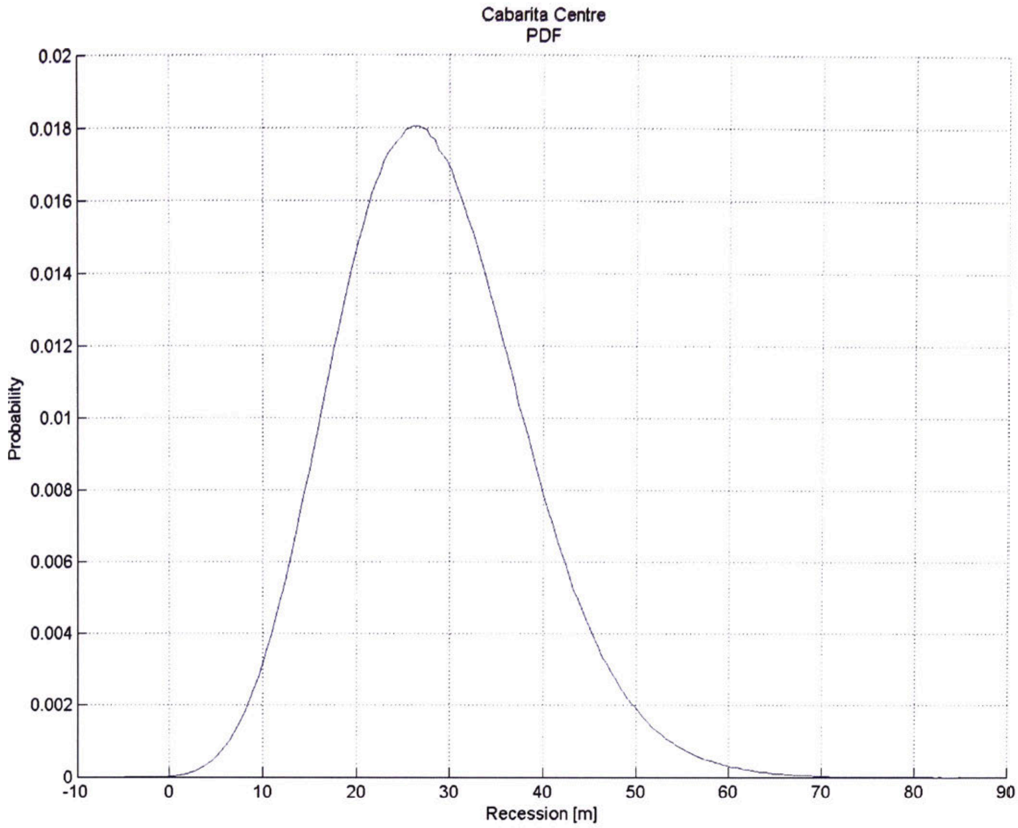


Figure 4.9 Cabarita Beach Representative Beach Profiles



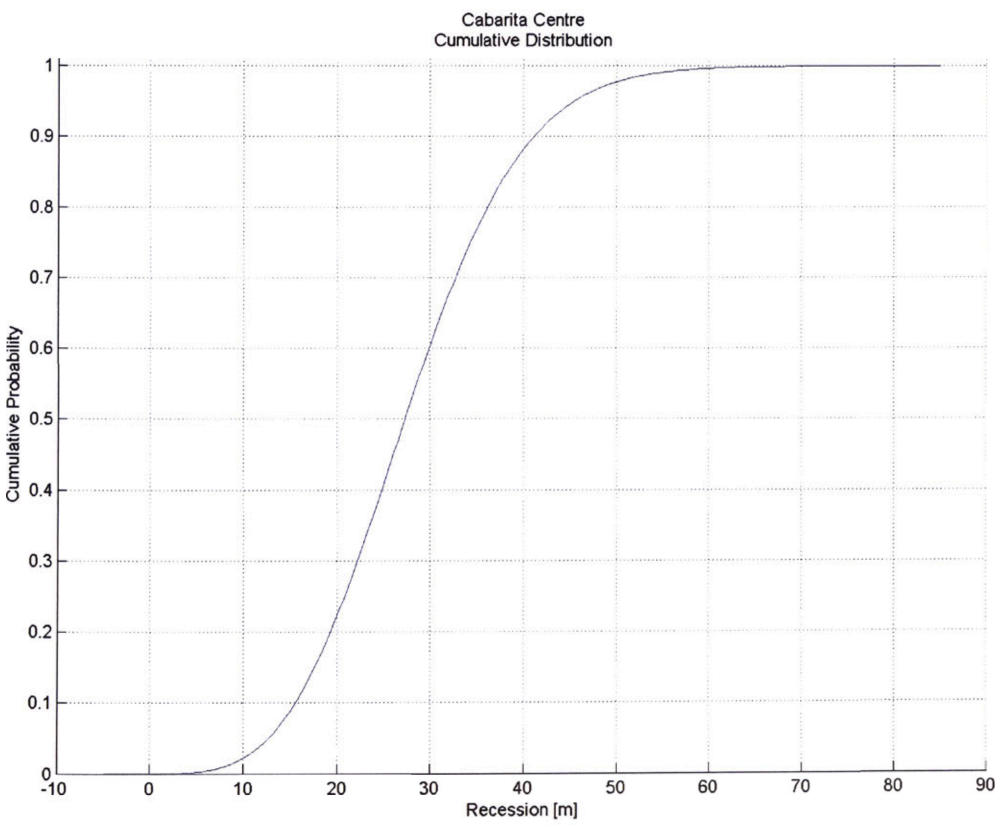


Figure 4.10 Cabarita Beach (Centre) 2100 Recession Estimates

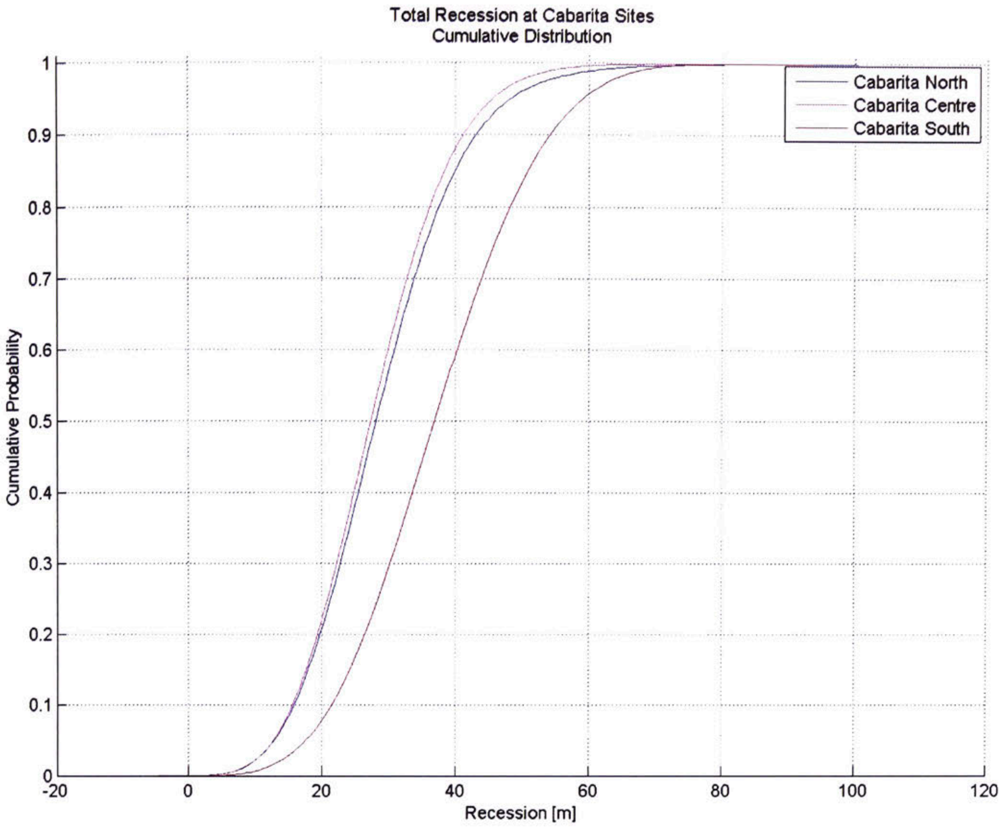


Figure 4.11 Cabarita North South and Centre Comparison 2100 Recession Estimates

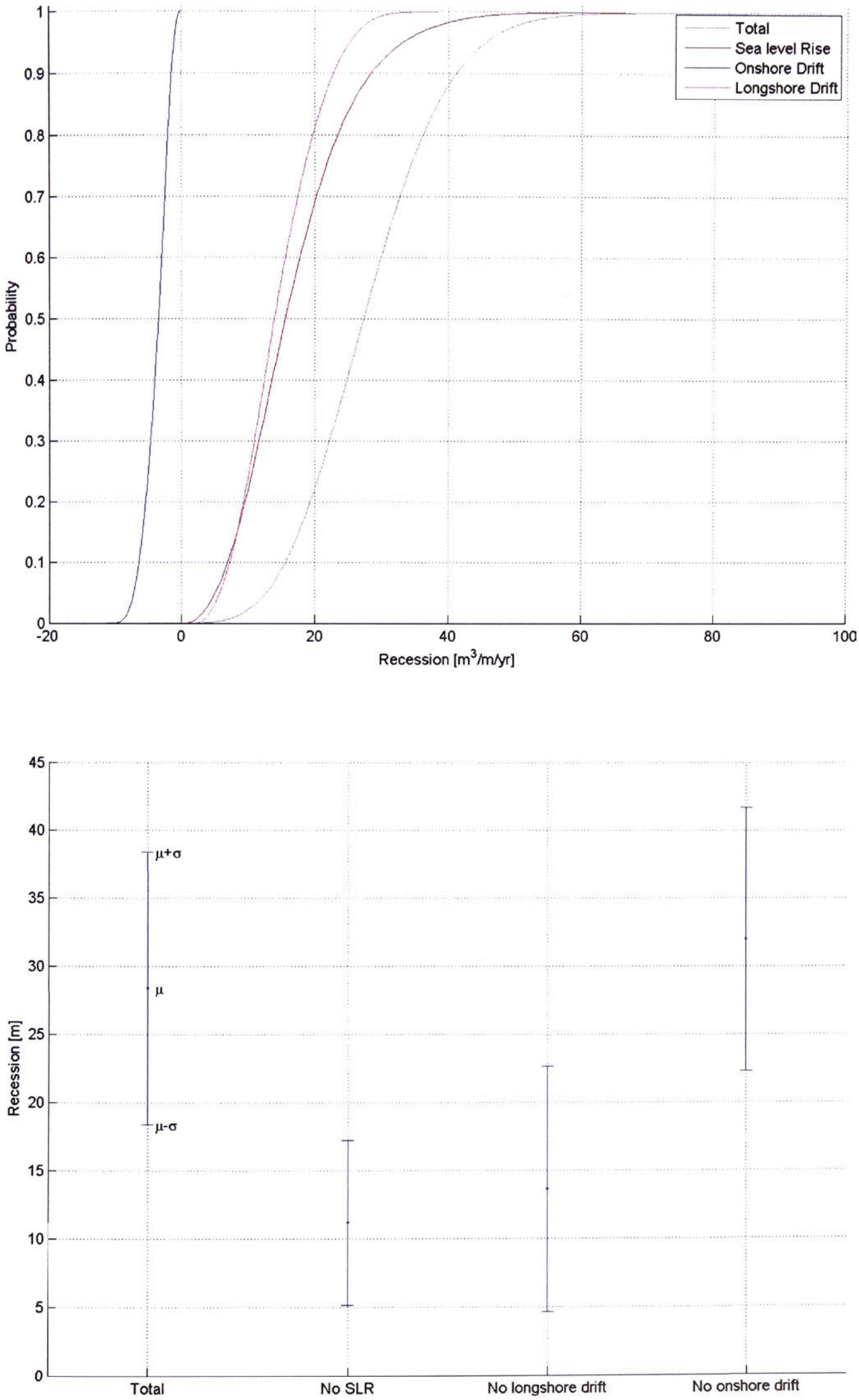


Figure 4.12 Cabarita Centre Contributions to Recession

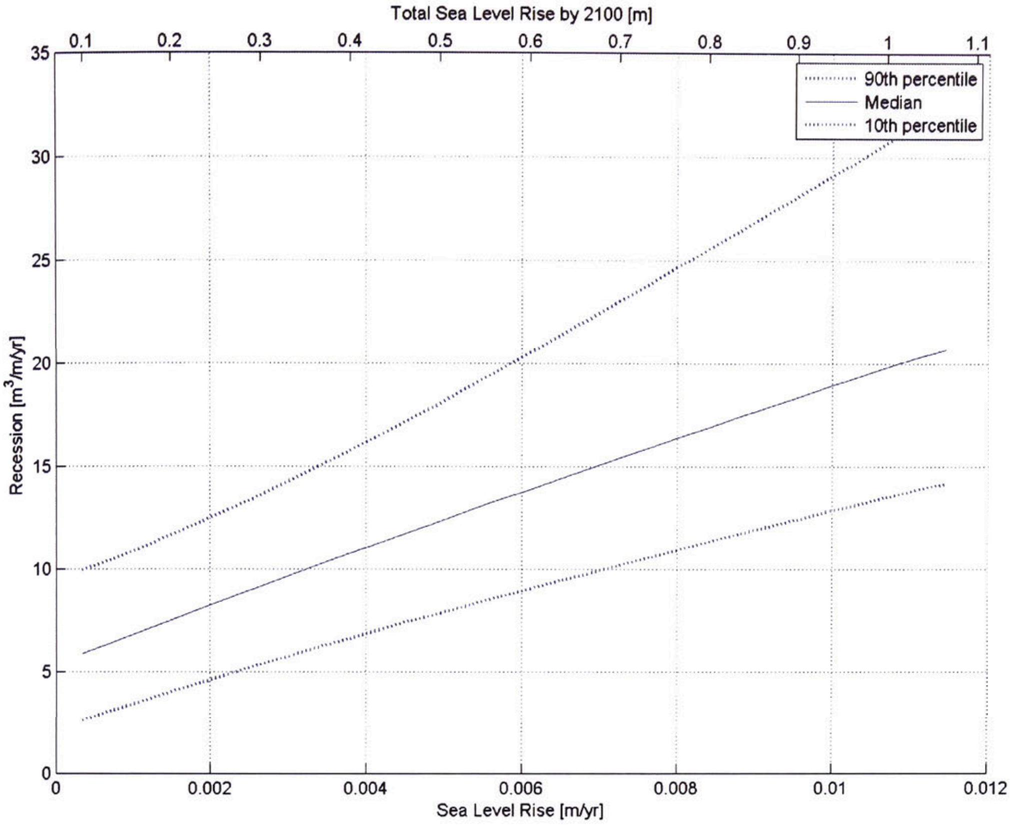


Figure 4.13 Cabarita Centre Recession Estimates Against SLR

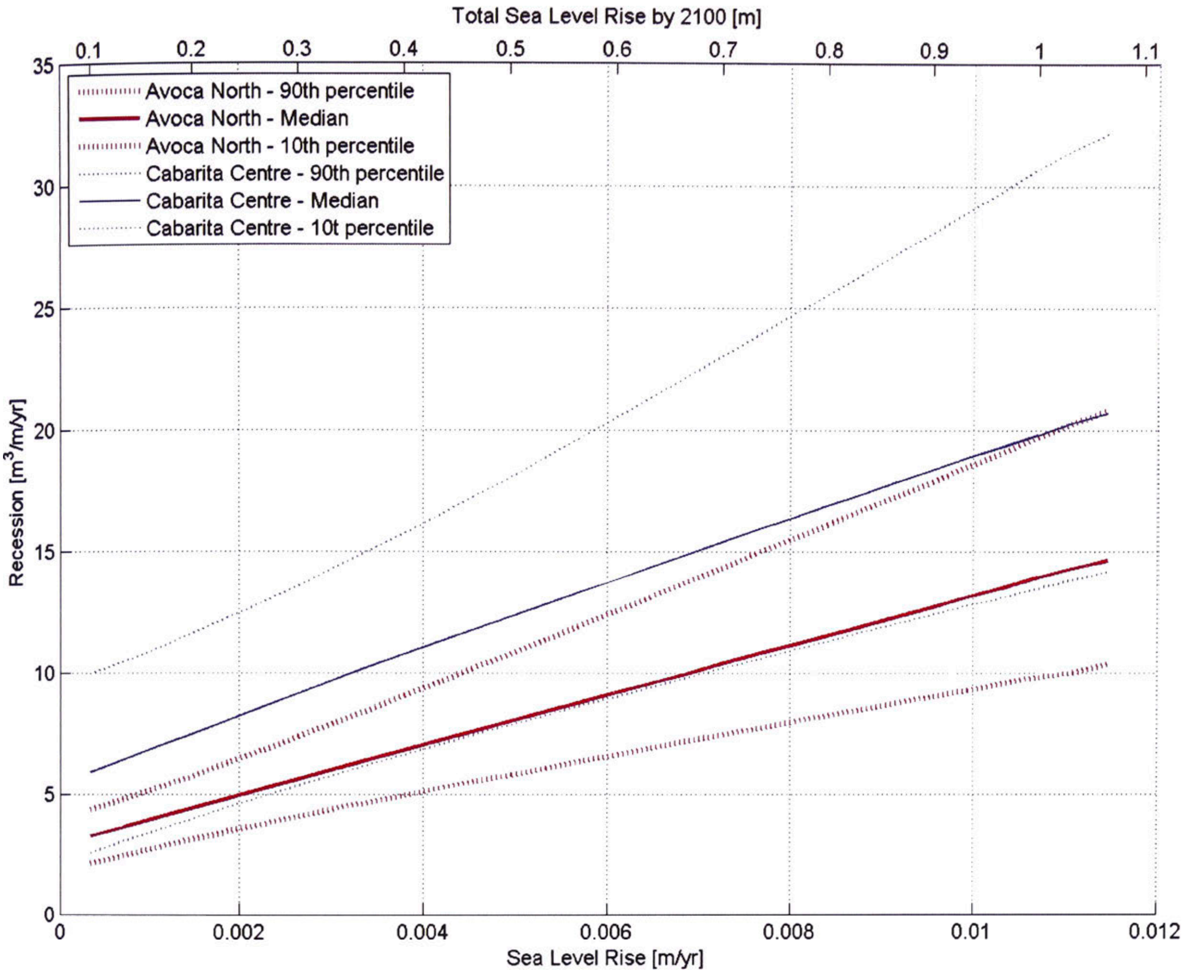
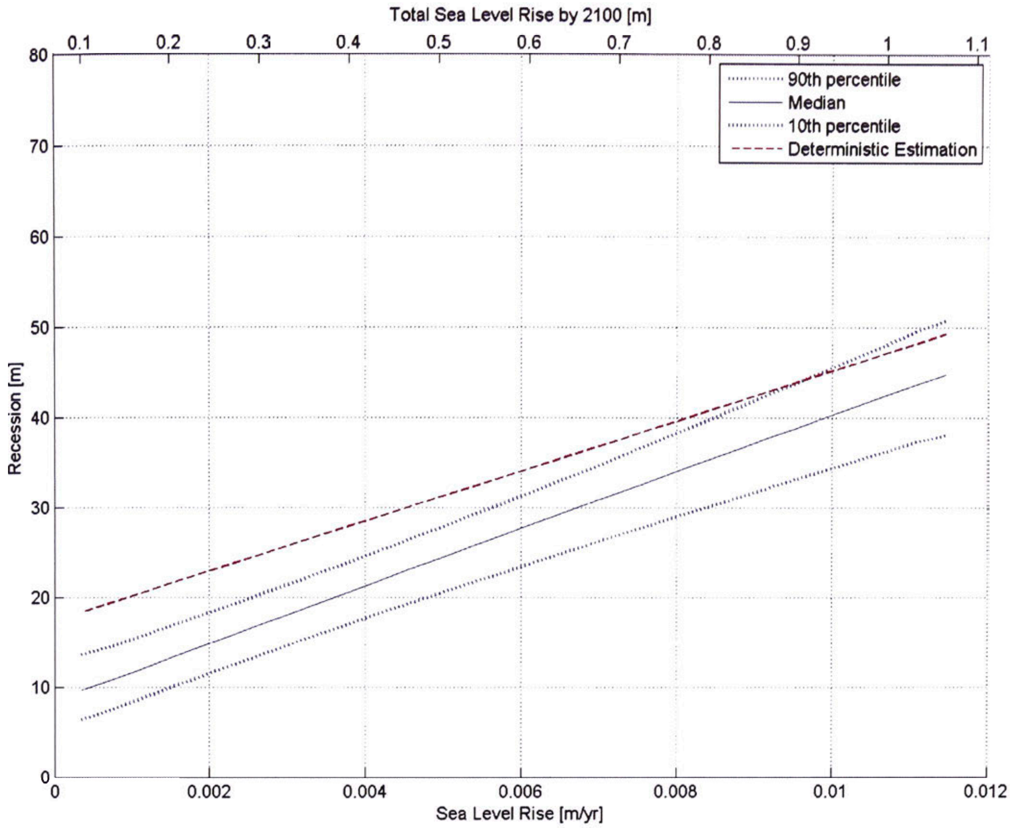


Figure 4.14 Avoca and Cabarita Comparison



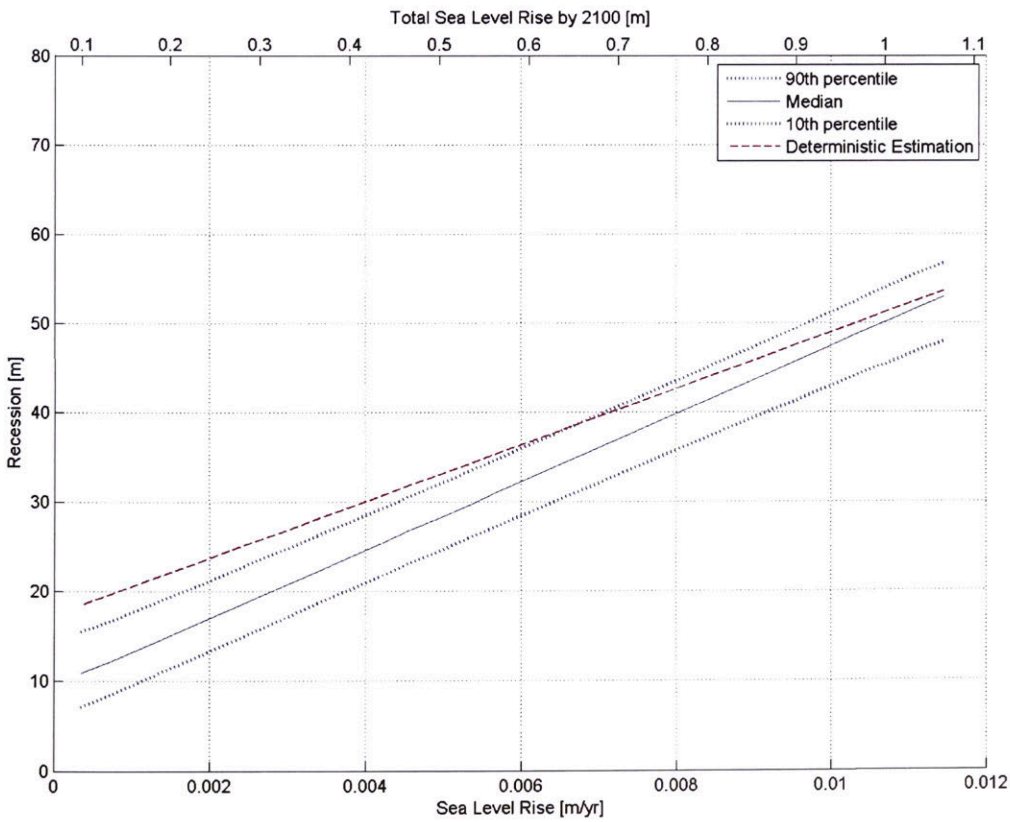


Figure 4.15 Avoca Beach North (upper plot) and South (lower plot) Deterministic and Probabilistic Comparison

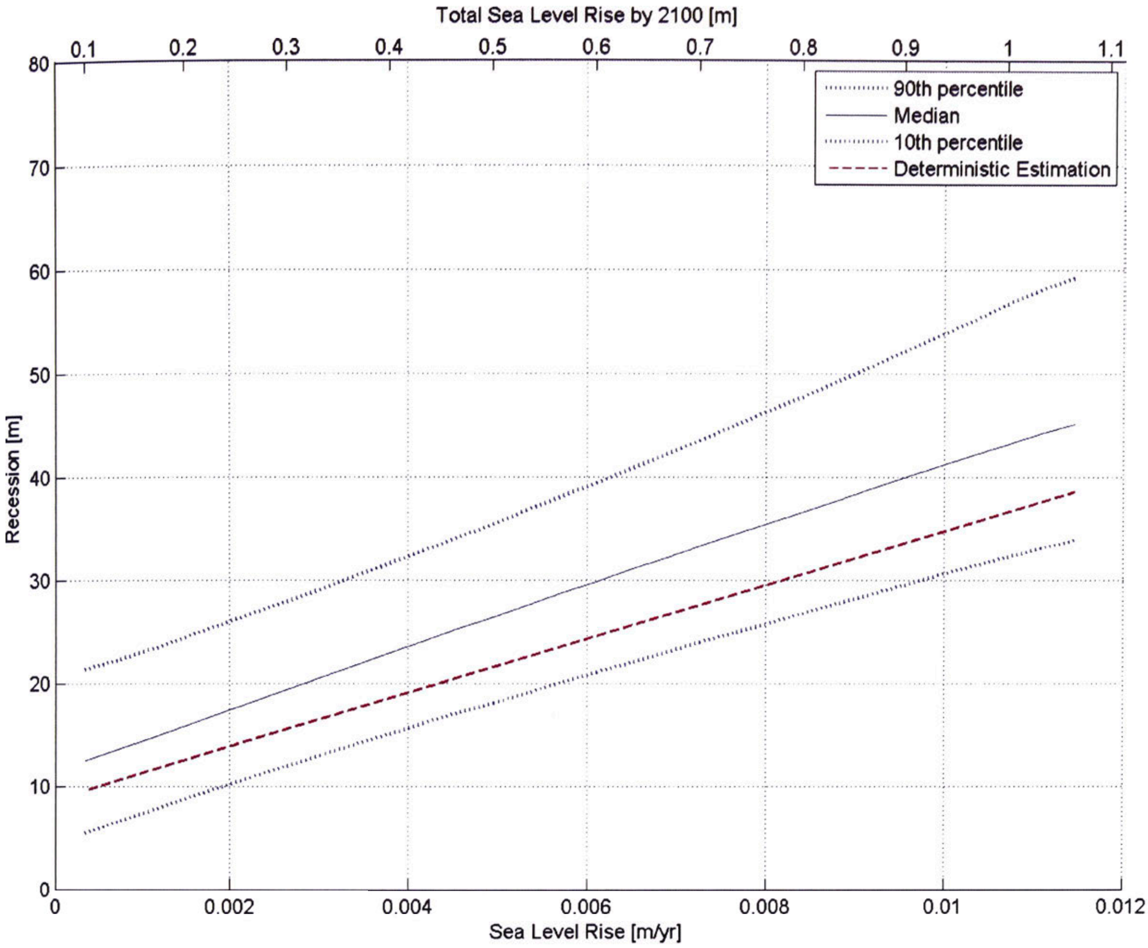
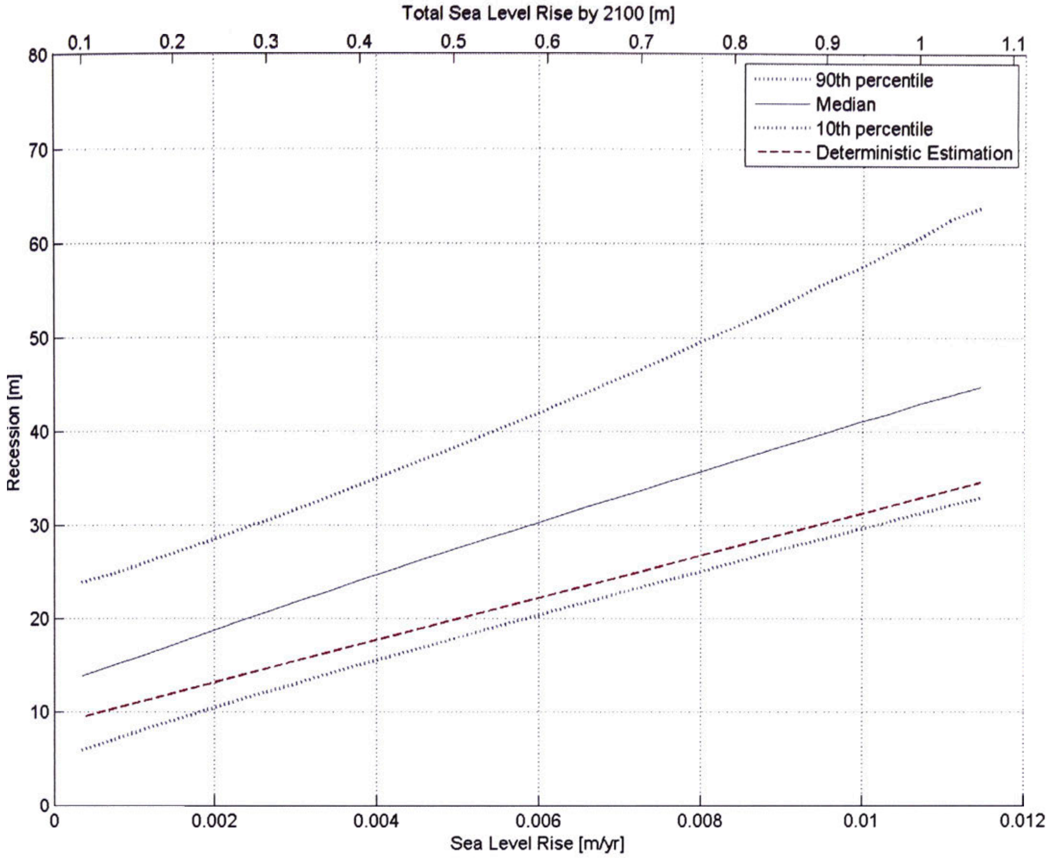


Figure 4.16 Cabarita Centre Deterministic and Probabilistic Comparison



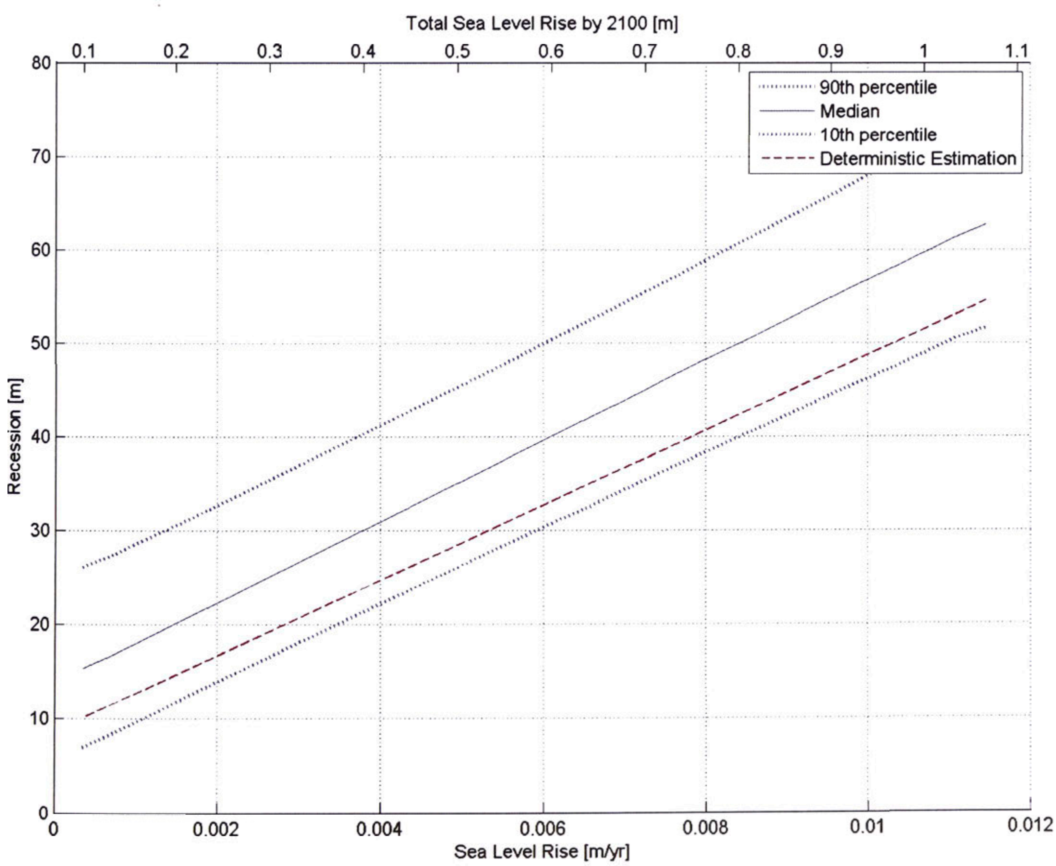


Figure 4.17 Cabarita North (upper plot) and South (lower plot) Deterministic and Probabilistic Comparison

Appendix A Site Characterisation: Coastal Processes

A. Study Site 1 - Avoca Beach, NSW

Avoca Beach is located within Bulbararing Bay between Broken Head and Tudibaring Head near the northern boundary of the Sydney Metropolitan Area and it includes the townships of South and North Avoca.

A.1 History of Development

It is reported (PWD, 1985) that development of the Avoca Beach area, with emphasis on providing accommodation for recreational purposes, started as early as 1910s, with the construction of usually modest cottages. Analysis of aerial photography reveals that between 1941 and 1965, the number of dwellings increased from 17 to about 50 on South Avoca and respectively from 15 to 40 on North Avoca, and has remained constant since then. The Avoca Beach Surf Life Saving Club was first established in 1929 against the southern headland, while North Avoca Beach Surf Life Saving Club was established in 1957 towards the northern end of the beach. It should be noted that the 1960s saw significant redevelopment of the older modest holiday cottages into the more substantial buildings which predominate today. Some of these properties are used today either as full-time private homes or holiday homes and all properties along Avoca Beach are of relatively high value due to increasing accessibility from the nearby Sydney Metropolitan Area.

A.2 Oceanic Processes

A.2.1 Design Water Levels

Tides are fairly uniform with only a small phase shift between locations along the open coast of NSW. As such, the tidal planes at the study site have been considered in previous studies (PWD, 1994) to be equivalent to the tidal planes calculated for Sydney's Fort Denison (considered to be an open ocean tide site) (Table A-1).

Table A-1 Tidal Planes at Sydney (source DECCW, 2008)

Tidal plane	Elevation (m AHD)
Highest Astronomical Tide (HAT)	1.15
Mean High Water Springs (MHWS)	0.68
Mean High Water Neaps (MHWN)	0.43
Mean Sea Level (MSL)	0.05
Mean Low Water Neaps (MLWN)	-0.33
Mean Low Water Springs (MLWS)	-0.58
Lowest Astronomical Tide (LAT)	-0.88

Design elevated water levels for a range of average recurrence intervals (ARI) are typically considered for coastal hazards studies. While the previous studies (PWD, 1985; PWD, 1994) provided estimates of elevated water levels during specific storms events, the only available design elevated water levels are provided in the Coastal Risk Management Guide (DECCW, 2010) and are presented in Table A-2.

Table A-2 Design Water Levels Tide +Storm Surge (source DECCW, 2010)

Average Recurrence Interval ARI (yr)	Water Level Excl. Wave Setup and Runup (m AHD)
1	1.24
10	1.35
50	1.41
100	1.44

While these design water levels incorporate allowance for tides, barometric setup and wind setup (i.e. storm surge), wave setup and wave runup are excluded and need to be accurately determined through data and/or modelling for inundation modelling. Wave setup and runup are intrinsically dependent on the determination of the nearshore wave conditions and are typically calculated separately for individual locations along the investigated coastline.

The sea level rise projections for the 2050 and 2100 planning periods typically adopted in NSW are usually derived from the NSW Sea Level Rise Policy Statement (DECCW, 2009 repealed in 2012) and are shown in Table A-3. These benchmarks were established considering the now repealed NSW Sea Level Rise Policy Statement (DECCW, 2009) and the most recent international (Intergovernmental Panel on Climate Change, IPCC, 2007a and 2007b) and national (McInnes, 2007) projections. While a recent review of the NSW Sea Level Rise Policy Statement (DECCW, 2009) by the NSW Chief Scientist and Engineer (CSE, 2012) queried the methodology used to arrive at these benchmarks, the overall values were considered adequate for the present study.

Table A-3 Sea Level Rise Projections (source DECCW, 2010)

Planning Period (year)	(1)Sea Level Rise (m)
2050	0.40
2100	0.90

Notes: (1) increase above 1990 Mean Sea Level

A.2.2 Offshore Wave Climate

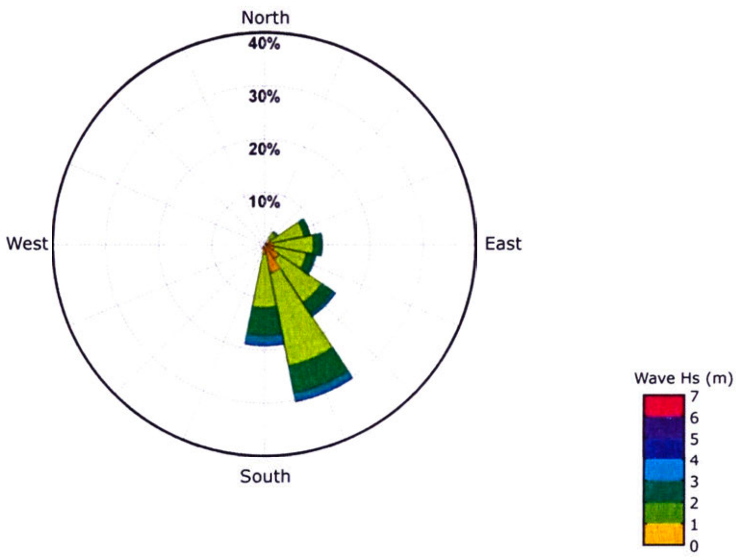
The best available data source for wave data is wave buoys. The closest known wave buoy to the site is the directional Sydney Waverider Buoy (SWB), located 35 km south of the study site. This buoy is directional and provides valuable information (H_s, H_{max}, T_p, D_p) for input into the local wave transformation processes along this particular section of the coastline.

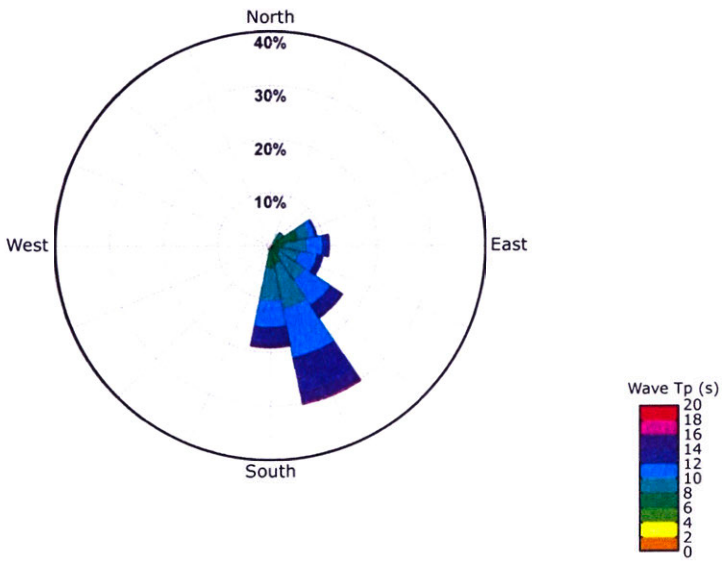
A detailed analysis of the wave climate was undertaken recently by WorleyParsons (2009) as part of a review of environmental factors in relation to the scuttling of the Ex-HMAS Adelaide frigate off the coast of Avoca Beach. The derivation of the regional wave climate has been based primarily on directional wave data obtained from the 16 years of records of the SWB.

Wave roses (Figure A-1) derived from the buoy data show that the majority (approximately 65%) of offshore wave energy propagates from the south to south-east (i.e. south, south-south-east and south-east cardinal directions). The largest period waves typically occur from the south-south-east sector in the winter months. These waves originate from storms and swells in the Tasman Sea and Southern Ocean and can occur during any season. Easterly waves (i.e.

east-south-east, east and east-north-east cardinal directions) make up approximately 30% of the total offshore wave energy. North-easterly waves make up approximately 3% of the offshore wave energy and are generated by summer sea breeze systems and occasionally, tropical cyclones in the Coral Sea.

The largest observed waves had a significant wave height of 8.4 m and originated from the SSE (157.5°N).





Metadata:
Project: Scuttling ex-HMAS Adelaide
Location: Offshore of Curl Curl, Sydney [353490.00000 , 6261620.00000]
Data period: 03-Mar-1992 09:00:00 to 31-Aug-2008 23:00:00
Data source: Sydney Directional Buoy
Data summary: All records
Number of Records: 116808

Figure A-1 Offshore Wave Roses, H_s (top) and T_p (bottom) (source WorleyParsons, 2009)

It should be noted that no separation of the sea and swell components of the overall wave climate has been considered in the 2009 WorleyParsons study as the study site was located at about 32 m water depth. While specific information on wind waves (i.e. shorter period waves) can be useful for long-term modelling, as in the case of sediment transport studies, it is of lesser importance in comparison to swell waves during storm events on an open-coast site such as Avoca Beach.

A.2.3 Offshore Extreme Waves

Large, low probability wave events are generally defined in terms of an average recurrence interval (ARI). The commonly used approach to derive extreme wave height for a particular ARI is to fit a theoretical distribution to historical storm wave data. If the record is of insufficient length to provide the event magnitude for the ARI of interest, the distribution is extrapolated.

In WorleyParsons (2009), calculation of extreme wave height was performed using the methodology recommended by Goda (2000) and You (2007). The raw wave data was analysed to obtain statistically independent storm wave heights. The wave height likely to occur or be exceeded, on average, every 100 years was estimated to be 9.3 m. This value compared well to previously reported values for the 100-year ARI significant wave height for the Sydney region (You, 2007; Shand et al., 2011).

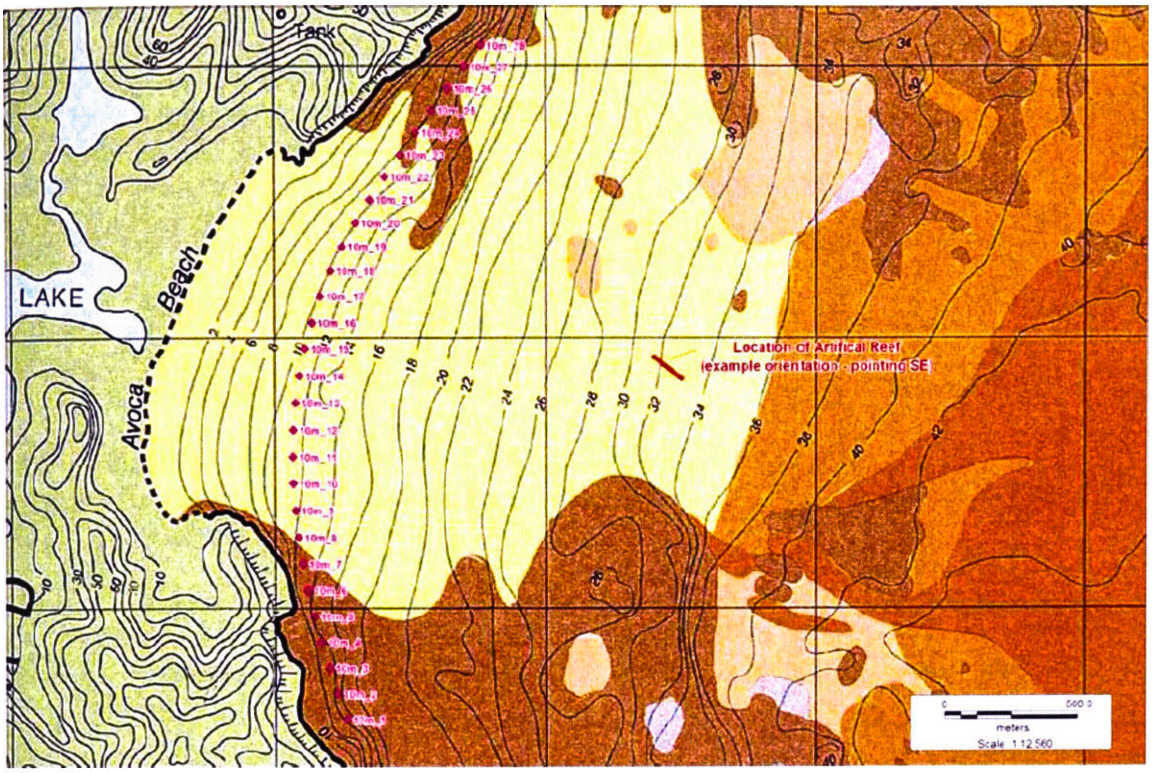
Table A-4 presents the directional wave extremes as calculated for the region offshore of the study area, based on directional data from the SWB.

Table A-4: Offshore Directional Wave Extremes for the Study Region (source WorleyParsons, 2009)

Direction Bin	Direction (° TN)	H_s (m) / Tp (s)					
		Hs 1 year ARI	*Tp 1 year ARI*	Hs 50 year ARI	*Tp 50 year ARI*	Hs 100 year ARI	*Tp 100 year ARI*
NE	45.0	3.0	*7.6*	4.1	*8.9*	4.4	*9.2*
ENE	67.5	4.2	*8.9*	5.7	*10.5*	6.0	*10.7*
E	90.0	4.8	*9.6*	6.6	*11.2*	7.0	*11.6*
ESE	112.5	5.0	*9.8*	6.9	*11.4*	7.3	*11.8*
SE	135.0	5.6	*10.5*	8.0	*12.4*	8.5	*12.7*
SSE	**157.5**	**6.4**	***11.1***	**8.8**	***13.0***	**9.3**	***13.3***
S	180.0	6.1	*10.8*	8.4	*12.6*	8.8	*13.0*
SSW	202.5	3.8	*8.5*	5.2	*10.0*	5.5	*10.2*

A.2.4 Nearshore Wave Climate

The Gosford coastline is subject to extreme waves originating from offshore storms. Swell waves reaching the coast may be modified by the processes of refraction, diffraction, wave-wave interaction and dissipation by bed friction and wave breaking. The model SWAN (Simulating WAves Nearshore) was used by WorleyParsons (2009) to quantify the change in wave conditions from a deepwater boundary to a nearshore site (32m water depth) off the coast of Avoca Beach (see Figure A-2). Details of SWAN can be found in Booij et al. (1999a, 1999b) and is described in brief below.



LEGEND

ROCK REEF

REEF MATERIALS CONSISTING OF SHELL, REEF & CORAL FRAGMENTS AND SMALL AMOUNTS OF SAND & GRAVEL

AREAS OF REEF PARTLY COVERED BY SAND

FINE GRAINED, GREY COLOURED SAND WITH 5% TO 20% MUD AND 30% TO 40% SHELL

FINE GRAINED, FAWN COLOURED SAND WITH 30% SHELL

FINE TO MEDIUM GRAINED, GOLDEN COLOURED SAND WITH VARYING SHELL CONTENT

MEDIUM TO COARSE GRAINED, ORANGE COLOURED SAND WITH TYPICALLY 40% SHELL

VERY COARSE GRAINED ORANGE COLOURED GRAVELLY SAND

• ARTIFICIAL REEF

—— ROCK SHORELINE

------ SANDY SHORELINE

—— MAJOR CONTOUR

—— MINOR CONTOUR

Figure A-2 Location of Outputs for Nearshore Wave Climate Modelling (source WorleyParsons, 2009)

SWAN is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters. The SWAN model is based on the wave action balance equation with sources and sinks; and accommodates the processes of wind generation, white capping, bottom friction, quadruplet wave-wave interactions, triad wave-wave interactions and depth induced breaking (Ris et al., 1994).

The formulation of the SWAN wave model imposes a number of restrictions which should be acknowledged. While the model may be used on domains of any scale, its use in oceanic scale domains is not recommended for reasons of computation efficiency compared to models such as WAM and WaveWatchIII. Additionally, the spectral formulation of the model limits its ability to accurately model wave diffraction and some surf zone processes such as wave setup (in a two-dimensional simulation).

Despite these limitations, the SWAN model is considered an industry-standard spectral wave generation and propagation model and with appropriate acknowledgment and allowance for such limitations, provides accurate and robust values.

Correct representation of natural bathymetry within the model computational domain is critical to simulating representative wave propagation and transformation processes. Sources of bathymetric and topographic data of the Avoca Beach study area used within the 2009 study are presented within Table A-5.

Table A-5: Bathymetric Data Used in WorleyParsons 2009 Study

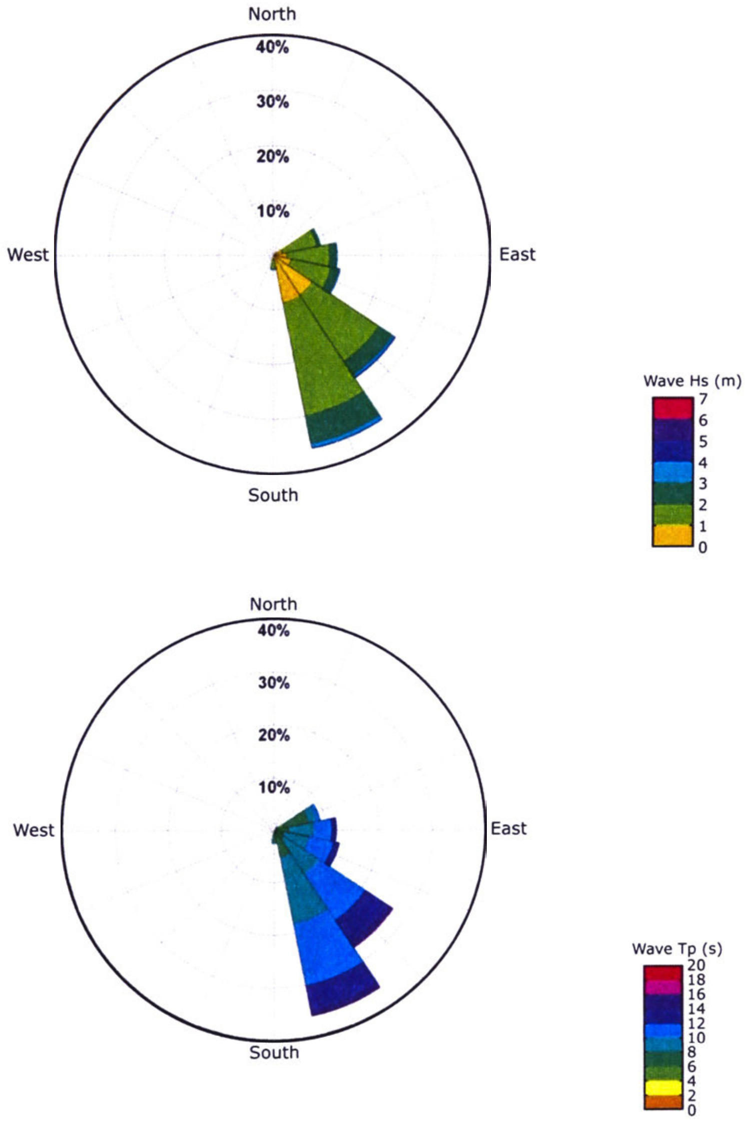
Area covering	Data Source
Offshore region (depths >50 m)	Aus Chart 809 (Australian Hydrographic Service, 1994)
Nearshore region (depths <50 m)	Digitised from NSW Public Works Department (PWD) survey (1m contours) (1984-1989)
Bulbararing Bay (depths <46 m and >10 m)	Detailed site specific multibeam hydrographic survey data undertaken in 2008 by the then NSW Department of Environment and Climate Change (DECC)

The nearshore wave climate at the proposed scuttling location (356,560mE, 6,296,080mN) was based on results extracted from the wave transformation model. The main findings of the wave transformation study are detailed below:

- Wave refraction is the main process acting on waves propagating from the offshore regions, across the inner shelf slope to the nearshore;
- Wave heights decrease as a result of wave energy dissipation through refraction due to the angle between incoming waves and the coastal contour orientation, and due to bottom friction; and
- The directional distribution of wave energy has changed when compared to the offshore record due to wave refraction, being more centred around the east.

The effect of wave refraction is such that incoming wave crests tend to align with the bottom contours. The inner shelf (water depths greater than 35 m but less than 90 m) slope faces approximate SE with the nearshore slope becoming more E facing. This results in a tightening of the nearshore directional distribution of the wave energy such that all waves propagating onshore have a direction at this location of between 45°N and 180°N. Waves with an offshore direction from the SSW to SSE directions are refracted by the inner shelf slope to be more easterly in direction (anticlockwise rotation of wave directions as the wave propagates over the shelf slope). Waves with an offshore direction propagating from the NE to E are refracted to be more southerly (clockwise rotation of wave directions as the wave propagates over the shelf slope).

Previous nearshore transformation wave analysis has been performed by the Public Work Department (PWD, 1985) using REF-DIF software at multiple locations along Avoca Beach. This showed limited influence of wave shoaling from the offshore to the 10 m water depth contour and concluded that breaking wave heights varied moderately from north to south.



Metadata:
Project: 301017-00077 - exHMAS Adelaide
Location: Propsoed Scuttling Site [356552.00000 , 6296077.00000]
Data period: 03-Mar-1992 09:00:00 to 31-Aug-2008 22:00:00
Data source: Mike 21 SW
Data summary: All records
Number of Records: 130217

Figure A-3 Nearshore Wave Roses, H_s (top) and T_p (bottom) (source WorleyParsons, 2009)

A.2.5 Nearshore Extreme Waves

A directional extreme wave analysis was conducted (WorleyParsons, 2009) on the nearshore wave record obtained with SWAN, using the same methodology used for the offshore wave buoy analysis.

The expected 100 year ARI design wave height (H_s) at the scuttling location was calculated as 8.4 m and occurring from the SE and is slightly lower than the deepwater value due to refraction, friction and shoaling. This is compared to the equivalent offshore design wave height of 9.3 m from the SSE. The scuttling location is offshore from Avoca Beach as shown in Figure A-2 and nearshore extreme wave results could be used, for the purpose of this study, as nearshore boundary conditions for Avoca Beach.

Table A-6 Directional Wave Extremes Nearshore of Avoca Beach (approx.. 32 m depth)

Direction Bin	Direction (° TN)	H_s (m) / Tp (s)					
		Hs 1 year ARI	*Tp 1 year ARI*	Hs 50 year ARI	*Tp 50 year ARI*	Hs 100 year ARI	*Tp 100 year ARI*
NE	45.0	2.1	*7.5*	2.5	*8.5*	2.6	*9*
ENE	67.5	3.5	*8.9*	4.9	*10.2*	5.3	*10.4*
E	90.0	4.6	*9.5*	5.7	*11.2*	6.1	*11.6*
ESE	112.5	5	*9.8*	6.6	*11.4*	7	*12*
SE	**135.0**	**5.8**	**11**	**7.8**	**13**	**8.4**	**13.3**
SSE	157.5	5	10.5	5.9	12.7	6.1	13
S	180.0	3.2	*7.8*	3.8	*8.7*	4	*9.2*

A.3 Coastal and Erosion Processes

A.3.1 Introduction

This section provides a description and analysis of the main coastal processes which have been identified to have a role in the erosion processes around Avoca Beach. The coastal erosion processes can be separated into two categories, namely:

- **Short Term Storm Erosion** – refers to the short-term response of a beach to changing wave and water level conditions during ocean storms. This response is generally manifested in a "storm bite" from the sub-aerial beach moving offshore during the storm as well as localised erosion due to the presence of a lagoon entrance and stormwater outlets; and

- **Shoreline Recession** – refers to the long-term trend of a shoreline to move landwards in response to a net loss in the sediment budget over time (Ongoing Underlying Recession). Shoreline recession is also predicted to result from sea level rise (Sea Level Recession).

A.3.2 Short Term Processes

- **Storm Erosion - Introduction**

Beach erosion is defined as the erosion of the beach above mean sea level by a single extreme storm event or from several storm events in close succession. During storms sand is eroded from the beachface and transported offshore to the nearshore bars and shoreface. As the bars build up, wave energy dissipation within the surf zone increases and eventually wave attack at the beachface reduces. If the volume of sand available within the beach berm is not sufficient to meet the requirements for offshore transport and bar formation then erosion continues into the backbeach/ foredune region resulting in considerable threat to any development located on or near the foredune.

The amount of sand (above 0 m AHD) transported offshore by wave action is referred to as "storm demand" and is expressed as a volume of sand per metre length of beach *(m^3/m)*. This can be converted to a horizontal "storm bite" which is easier to visualise.

On Avoca Beach, storm demand varies depending on several factors such as:

- exposure of the beach;
- wave conditions (i.e. wave height, period and direction relative to the beach alignment);
- water levels; and
- steepness of the profile offshore from the beach.

Precise determination of storm demand requires frequent surveys which enable the calculation of beach volume before and after major events but were not available for the purpose of this study.

- **Storm Erosion – Previous Studies**

There have been a number of previous coastal hazards studies undertaken for this section of coastline, including PWD (1985), WRL (1988), PWD (1994), WBM (1995). These studies have all investigated the coastal erosion hazards caused by storm demand based on photogrammetric analysis of aerial photography. It should be noted that the more recent WBM (1995) study used results of the PWD (1994) storm demand analysis but re-contextualised them into a coastal management plan.

The storm bite analysis on Avoca Beach was performed by WRL and PWD, and was based on the volume changes between 22/4/72 and 19/6/74; 9/1/77 and 2/8/78; and 23/8/84 and 18/8/86 measured above 0 m AHD and 2 m AHD. These sets of photographs separated the major storm events in June 1974, June 1978 and August 1986.

The PWD (1994) study reported that volume changes during storms were the largest in the central and northern parts of the beach. Maximum storm bite was measured between 22/4/72 and 19/6/74 just north of Avoca lagoon entrance. Here volume change of around 200 m^3/m above 0 m AHD was measured. The calculated storm bite in the southern section of Avoca Beach was found to be significantly lower (a storm bite of around 50 m^3/m) due to its orientation offering natural protection from storm events originating from the south-east.

Table A-7 Design Storm Demands from Previous Studies

Representative Profile Location	Volume of Storm Demand (m^3/m)		
	Previous Studies		
	PWD (1985)	PWD (1994)	WBM (1995)[1]
Avoca North	200	120-160	205
Avoca Central North	200	150-200	205
Avoca Central South	50	50-170	100-200
Avoca South	50	0-60	50-100

Notes:
(1) WBM (1995) study provide design storm erosion demand based on the results of the PWD (1994) study.

It should be noted the design volumes of storm demand given in the WBM (1995) study were significantly higher on the northern sections of the beach as they allowed for additional storm erosion due to formation of rips during the storm. Moreover, while all the photogrammetric analysis was based on the volume changes in the beach system due to predominantly south-east wave attack, it is important to consider the potential risk of storm erosion at the southern end by north-east wave attach and adopt a conservative erosion extent on this section of beach.

- **Rip Current Erosion**

Rip currents may contribute to short-term beach fluctuations by producing highly localised short-term coastal erosion. Rips are localised seaward flowing currents which usually occupy channels between the nearshore bars. They promote seaward transport of sediment resulting in localised erosion of the beach face.

When present during storm events rips also allow larger waves access to the beachface resulting in further localised beach erosion. They also provide a mechanism for the seaward transport of sediment to considerable depths and possibly even the inner continental shelf where it may have difficulty returning to the beach. During storms large scale 'mega rips' tend to form within relatively embayed beaches like those found on the Central Coast (Short, 1985). These rips are usually controlled by the embayment dimensions, and tend to be located near headlands on shorter beaches and in the central portion of longer beaches.

Localised erosion associated with rip development has been observed by Council officers on Avoca beach both during and immediately following storms in both 1974 and 1978 (PWD, 1994). Large scale 'mega rips' have been observed by Council officers on the beach during storms. The erosion associated with these rips is reported in PWD (1994) to have directly threatened development north of the Avoca lagoon entrance.

From the analysis of aerial photography taken immediately following the 1974, 1978 and 1986 storms, PWD reported that multiple rips could be observed to have developed within the inner bar north of the Avoca lagoon entrance. The rip in this location was reported in 1974 to have caused major scarping of the back beach and have directly threatened development north of the Avoca lagoon entrance. Smaller rips are also evident south of the lagoon entrance and towards the northern end of the beach but were observed to have not been as significant for beach erosion.

- **Stormwater Erosion**

There are several stormwater outlets along Avoca Beach. These include two stormwater pipes which drain onto the back beach south of the lagoon entrance and a larger drain in the northern corner of the beach. The middle stormwater pipes have required some shore protection works indicating past erosion. The drain at the northern end of the beach is also armoured suggesting past erosion. The scarp alignment here is influenced by the drain location.

While it is not possible to qualify in a quantitative manner the importance of stormwater erosion on overall short-term erosion, it is important to note that their presence can have an influence on the multiple coastal processes driving beach erosion:

- localised erosion produced by stormwater scour and the resulting access of large waves to the back beach region;
- potential influence of storm water discharge on rip locations;
- groyne type effects on longshore transport particularly in relation to storm water outlet structures which run across the beach, discharging to the surf zone.

A.3.3 Long Term Trends in Sediment Transport

- **On-going Sediment Imbalance**

Beaches undergo long term fluctuations which may involve either addition or removal of sediment. Those beaches receiving a net addition of sediment, are called accreting or prograding beaches. While still experiencing short term erosion events, these beaches generally display a seaward movement or progradation of the beach-foredune system. Beaches undergoing longer term removal of sand are called receding beaches and experience a landward migration of the beach/ dune system. They are generally characterised by a prominent back beach escarpment which moves landward during major storm events.

Ongoing underlying recession is the progressive onshore shift of the long term average land-sea boundary which may result from sediment loss. It is expressed in terms of change over years in volume of sand within the beach fronting the seawalls *(m^3/m/year)* and/or corresponding landward shoreline movement *(m/year)*.

Recession rates due to sediment loss on Avoca Beach coastline were derived through the analysis of the scarp movement analysis (PWD, 1994) using photogrammetric data from 1941 to 1993. The results of the exercise revealed that most of Avoca Beach has receded over the period of measurement, although there is considerable variability along the beach with some accretion evident towards the northern end. The overall recession rate was estimated at around 0.2 m/year and can be considered as quite low in terms of other Australian beaches. Higher localised rates of recession of around 0.4 m/year were estimated in several locations, and appear to be related to stormwater outlets.

It should be noted that a long term recession rate of 0.2 m/year estimated by PWD was over a period of nearly 50 years (1941 to 1993) is very close to the recession rate reported by Gordon (1987) for a number of embayed beaches on the NSW coast. Gordon attributed such rate to the recession that can be expected from the average rate of sea level rise observed at the Fort Denison tide gauge over the period of reliable record. Interestingly, in projecting future recession rates for Avoca, WBM (1995) used a value of 0.4 m/year, twice that obtained by the historical analysis. This produced setbacks of 8 m for the following 20 years, and 20 m for a 50 year period. According to WBM (1995) this is equivalent to volume losses of 145 m^3/m to 185 m^3/m for 20 years and 360 m^3/m to 460 m^3/m for 50 years.

It is surmised that WBM may not have given consideration to the possibility that the 0.2 m/year calculated in PWD (1994) may have resulted from historical sea level rise and a direct application of the Bruun Rule (Gordon, 1987). Instead, they appear to have surmised that the historical 0.2 m/year, reported in PWD (1994) resulted from some long-term offshore/longshore loss mechanism. So, WBM applied a future recession rate equal to the historical rate plus an allowance of 0.2 m/year for sea level rise. That is, they may have doubled up on the likely recession rate by not realising that the historical trend may have already had embedded in it the recession to be expected from the historical sea level rise.

Hence, it is not considered unreasonable to project a figure of 0.2 m/year for the likely recession (rather than the 0.4 m/year) for the foreseeable future, particularly given Watson's (2011) findings that there is no evidence, at present, of an accelerating sea level rise trend.

- **Recession due to Sea Level Rise**

It is expected that open coast beaches will recede under conditions of accelerated sea level rise (SLR). Recession rates due to SLR are typically estimated using the *Bruun Rule* (Bruun, 1962,

1988) as the rate of sea level rise divided by the average slope ("Bruun Factor") of the active beach profile. This rule is based on the concept that the existing beach profile is in equilibrium with the incident wave climate and existing average water level; and it assumes that the beach system is two-dimensional and that there is no interference with the equilibrium profile by headlands and offshore reefs.

The Bruun rule is typically expressed as:

$$R = \frac{SLR * X}{h + d_c}$$

where R is horizontal recession (m);
SLR is sea level rise (m);
X is the horizontal distance between h and d_c;
h is active dune/berm height (m);
d_c is profile closure depth (m, expressed as a positive number).

This is frequently simplified to

$$R = BF * SLR$$

where R is horizontal recession (m);
BF is the Bruun Factor, being a function of X, h and d_c.

For a given sea level rise and profile, the only contentious variable in the Bruun rule is the closure depth (d_c) for which various formulations and methods exist.

The sea level rise benchmarks over a range of planning periods used in PWD (1994) were based on the IPCC recommendations of1990, and are provided in Table A-8.

Table A-8 Sea Level Rise Projections Adopted in PWD (1994)

Planning Period (year)	Sea Level Rise (m)		
	Low	Best Estimate	High
50	0.13	0.26	0.49
100	0.29	0.61	1.00

PWD (1994) estimated the closure depth (d_c) via a range of widely accepted methods:

- Hallermeier Outer (1981) which gave a d_c of 37 m; (grain size of 2 mm);
- Bruun and Schwartz (1985), based on the significant wave height for 50 to 100 years ARI events, giving d_c ranging from 32 to 35 m;
- Sediment boundaries between the nearshore sands and inner shelf sands, reported at 36 m at Avoca Beach.

Based on these results, a closure depth (d_c) of 35 m in conjunction with dune heights measured across the beach was used to estimate beach recession due to sea level rise. The calculated recession rates are given in Table A-9.

Table A-9 Setbacks Associated with Sea Level Rise Projections Adopted in PWD (1994)

Planning Period (year)	Recession R (m)		
	Low	Best Estimate	High
50	6	13	24
100	14	30	49

- **Avoca Lagoon Infilling**

The Avoca lagoon entrance displays the characteristics expected of an Intermittently Closed and Open Lagoon (ICOL). During heavy rain the water level in the lagoon elevates until the entrance berm is overtopped and a breakout channel develops across the beach. Once the breakout is complete, the lagoon experiences a short period of tidal action until sand from the nearby beach berm and surf zone reforms the entrance plug by a process of gross littoral drift into the entrance. Successive tides overwash the incipient plug, building it up until it is at the same berm level as the adjacent beach.

During the latter stages of the breakout and the tidal phase the entrance channel may wander, in either direction, along the beach face, depending on the dominant wave direction at the time. However, local observations suggest the tendency is to meander south (PWD, 1994). The breakout jets the sand from the scour channel directly offshore into the surf zone but the subsequent process of channel infill may "borrow" sand from the beach region adjacent to the entrance. Hence, in the short term, the beach berm on either side of the channel may erode, and the back-of-beach areas become more vulnerable, during and immediately following, the breakout. Usually by the time the plug has fully developed, the sand that was jetted offshore during the breakout has returned to the beach and the beach berm level, and location, is re-established both at the entrance and on either side.

- ***Aeolian Sand Transport***

Analysis of aerial photographs indicate that there are no substantial hazards due to wind blown sand (aeolian drift) along Avoca Beach. A quantity of wind blown sand will still reach the built environment during strong winds, but as all dunes are developed and vegetated, this quantity is minor and mobile dunes are not threatening the built environment. The exceptions are the lagoon entrance and some beach access points, where pedestrian traffic has removed vegetation and lowered the sand, thus forming a potential dune breach point.

Higher wind speeds are required to mobilise wet sand compared with dry sand. Therefore, it should noted that reduced rainfall due to climate change has the potential to increase the potential for wind blown sand. The modelling of this is beyond the scope of this study.

There is no evidence of any significant, present day, wind driven sand losses into the dunes along the length of the embayment. Hence, this potential sink can reasonably be eliminated from sediment budget considerations.

Study Site 2 – Cabarita and Casuarina/Salt Beach, NSW

Cudgen Headland is the northern point of the Cabarita and Casuarina/Salt embayment (referred to as Cabarita Beach in this report). It is approximately 10 km south of the border between New South Wales and Queensland. The Cabarita embayment stretches 8.5 km south from Cudgen Headland to Norries Head at the village of Cabarita/Bogangar.

A.4 History of Development

Despite pockets of industry in the Tweed by the start of the 20th century, there is no evidence of specific use or development of coastal land along Cabarita Beach by this time. However, dairy farming for butter making joined the timber industry in becoming key industries for the Cabarita Beach/Bogangar hinterland. Hoop pine for butter boxes was cut from the Cudgen Lake area, rafted across the lake to be carried by bullocks to the mill on the Old Bogangar Road from 1910-20 up to the early 1930s (Duke, 2012).

The mining of mineral sands to extract heavy minerals such as zircon, rutile and ilmenite was undertaken at numerous North Coast beach locations between the 1930s and late 1970s. The Tweed District between Fingal Head and Pottsville was mined from the late 1930s until the 1970s.

The first recorded mining lease was issued in 1937 and covered an area of 20.75 ha as a narrow strip about 20 m wide, behind the frontal dunes, for the full length of the beach (Hoffman, 1979 and PWD, 1982). The mining was aimed at extraction of heavy minerals, mainly rutile and zircon, from the Holocene deposit. The mining was not associated with winning material for the construction industry. The volume of the heavy minerals extracted was generally between 1% and 3% of the total volume mined.

Subsequent leases were granted from 1940 through to 1977. A majority of the Holocene Outer Barrier was mined with the greatest activity being between the early 1960s and the late 1970s. Therefore, during that period the overall volume of the Holocene dune system may have been reduced by approximately 2%. Initially the vegetation was cleared and simple strip mining took place. However, by the 1960s this was up-scaled to dredges, with associated processing plants floating in large artificial ponds, working their way throughout the dunes, either side of the coast road (Figure A-4 and Figure A-5).

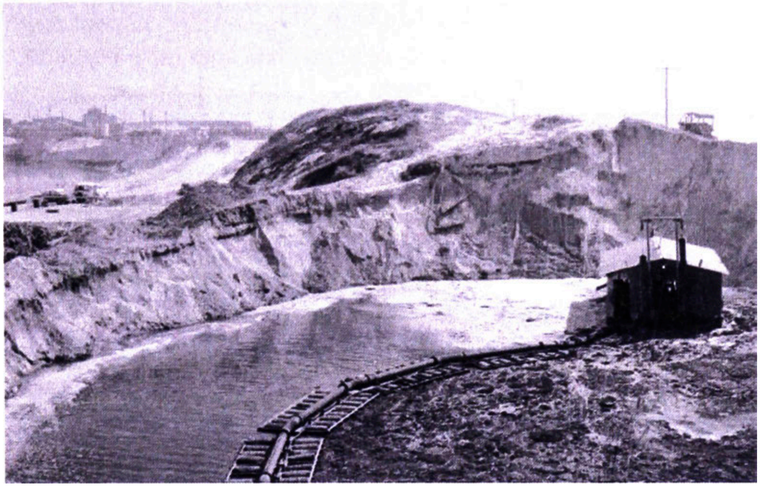


Figure A-4 Sand Mining near Cudgen Creek circa 1960s (source National Library of Australia)

Figure A-5 Sand Mining near Casuarina circa 1970s (source Dallas and Tuck, 2008)

The bases of the ponds were the below water table level, at the reach of the dredge, which was generally of the order of 5 to 6 m, that is, at approximately 4 m below sea level. The dredges progressively worked their way through the dunes by excavating a face of the pond and then passing the material through a floating processing plant, on a raft in the pond, which removed the heavy minerals, and then discharged the bulk of the sand in its wake. Bulldozers re-shaped the discharged sand into an approximation of the previous surface. Vegetation was cleared from the path the dredge was heading on and the reformed dune area left behind by the operation was re-stabilised with vegetation, which was mainly Bitou bush and Horse Tail sheoaks.

On occasions, the seaward extent of the mining ponds breached the back-of-beach escarpment and sometimes the frontal dunes. At such times some of the tailings were discharged directly onto the beach. During the cyclones of the early 1970s the sea broke through into the dredge ponds on several occasions resulting in localised increases in shoreline recession.

Over a 40 year period, the heavy mineral mining operations re-worked most of the Holocene, Outer Barrier deposit to below sea level. This makes reliance on historical survey data difficult when attempting to establish historical shoreline recession trends. It is, however, important to note that the earliest aerial photographs, before the mining disturbed the area immediately behind the beach, shows the presence of an erosion escarpment and the present day beach also features an erosion escarpment.

Most of the coastal beach area remained largely undeveloped until the late 1950s and early 1960s, when sand mining operations ceased. A new coast road opened the way for the development of seaside villages at Cabarita/Bogangar, Hastings Point and Pottsville. By the late 1950s development had begun with residential lots and a hotel established in Bogangar. The area rapidly became a popular fishing and beachside holiday location.

Cudgen Lake became part of Cudgen Nature Reserve, which was dedicated in late 1995. Many of the past activities are no longer permitted in the Reserve and the scout camp ceased operations a number of years ago.

A.5 Oceanic Processes

A.5.1 Design Water Levels

Elevated water levels consist of (predictable) tides, which are forced by the sun, moon and planets (astronomical tides), and a tidal anomaly. The nearest location where astronomical tidal planes are available is Kingscliff (Table A-10), based on values from MSQ (2011), which can be reasonably used at Cabarita Beach without any modification. Tidal anomalies primarily result from factors such as wind setup (or setdown) and barometric effects, which are often combined as "storm surge". Additional anomalies occur due to "trapped" long waves propagating along the coast. The top 10 recorded anomalies at the nearest nearshore tidal gauge, Tweed Heads, are reproduced in Table A-11 (MHL, 2010). This gauge is located on the northern breakwater of the Tweed River approximately 600 m upstream of the entrance. Note that no attempt was made to remove non-tidal freshwater flooding events from the recorded anomalies in the MHL study. As such, these anomalies are considered slightly conservative for design purposes at Cabarita Beach. Water levels within the surf zone are also subject to wave setup and wave runup.

Table A-10 Tidal Water Level for Kingscliff (MSQ, 2011)

Tide	Level	
	(m LAT)	(m AHD)
Highest Astronomical Tide (HAT)	1.90	1.14
Mean High Water Springs (MHWS)	1.40	0.64
Mean High Water Neaps (MHWN)	1.10	0.34
Mean Sea Level (MSL)	0.76	0.00
Mean Low Water Neaps (MLWN)	0.40	-0.36
Mean Low Water Springs (MLWS)	0.20	-0.56
Lowest Astronomical Tide (LAT)	0.00	-0.76

* Note that 0 m AHD ≈ MSL

Table A-11: Ranking of Highest Recorded Anomalies for Tweed Heads (MHL, 2010)

Rank (on Anomaly)	Peak Anomaly (m)	Date	Duration (hours)	Anomaly ARI (1 in x years)
1	0.87	03/05/1996	46	21.4
2	0.78	05/03/1987	31	10.7
3	0.68	02/02/1990	38	7.1
4	0.62	26/04/1989	29	5.4
5	0.53	11/04/1988	31	4.3
6	0.51	06/03/2004	13	3.6
7	0.46	09/03/1990	22	3.1
8	0.46	15/02/1995	21	2.7
9	0.46	05/02/1999	9	2.4
10	0.43	05/03/2006	8	2.1

Design storm surge levels (astronomical tide + anomaly) are recommended in the Coastal Risk Management Guide (DECCW, 2010) based on data from the Fort Denison tide gauge in Sydney. However, these levels are only applicable in the Newcastle - Sydney – Wollongong area and analysis of local tidal records on the NSW north coast is recommended.

Storm surge levels, tabulated in Table A-12, have previously been predicted for the Gold Coast region (James Cook University of North Queensland, 1977) and adopted in the Tweed Coastline Hazard Definition Study (WBM, 2001) and subsequent studies.

Table A-12 Superseded Water Levels Tide + Storm Surge (source James Cook University, 1977)

Average Recurrence Interval ARI (year)	Water Level Excl. Wave Setup and Runup (m AHD)
20	1.24
50	1.30
100	1.35

However, the storm surge levels tabulated in Table A-12, have been superseded by joint probability analysis undertaken for the Tweed Heads tide gauge by MHL (2010). This analysis was undertaken up to the 1 in 100 year ARI condition in 0.5 m increments using the method described by Pugh and Vassie (1979). This calculates the chance that high astronomical tide levels and high anomaly levels occur together. The elevated water levels for the upper range of average recurrence intervals (ARI) from this analysis are reproduced in Table A-13.

Since the maximum ARI water level quoted in the MHL study was 93.9 years (1.71 m AHD), WRL undertook a minor log-linear extrapolation to infer a slightly higher water level of 1.72 m AHD as the 1 in 100 year ARI storm tide level to be adopted for preliminary design.

Table A-13: Joint Probability of Return Water Levels (Astronomical Tide + Anomaly) for Tweed Heads (MHL, 2010)

Elevation (m Local Datum)	Elevation (m AHD)	ARI (1 in x years)
2.70	1.81	>100
2.61	***1.72***	***100#***
2.60	1.71	93.9
2.50	1.61	28.2
2.40	1.51	10.4
2.30	1.41	4.2
2.20	1.31	1.6
2.10	1.21	0.4
2.00	1.11	0.1

* Note that 0 m AHD = Local Datum 0.893 m

Note too that the estimated 1 in 100 year ARI value has been inferred by WRL.

The sea level rise (SLR) projections for the 2050 and 2100 planning periods endorsed by Tweed Shire Council on 25 October 2012 (TSC, 2012d) are shown in Table A-14. These benchmarks were established considering the now abandoned NSW Sea Level Rise Policy Statement (DECCW, 2009) and the most recent international (Intergovernmental Panel on Climate Change, IPCC, 2007a and 2007b) and national (McInnes, 2007) projections. While a recent review of the NSW Sea Level Rise Policy Statement (DECCW, 2009) by the NSW Chief Scientist and Engineer (CSE, 2012) queried the methodology used to arrive at these benchmarks, the overall values were considered adequate.

Table A-14 Sea Level Rise Projections (source TSC, 2012d)

Planning Period (year)	(1)Sea Level Rise (m)
2050	0.4
2100	0.9

Notes: (1) increase above 1990 Mean Sea Level

A.5.2 Offshore Wave Climate

A non-directional wave buoy operated offshore of Byron Bay from 1976 to 1999 and was upgraded to measure wave direction since 1999. WRL, in conjunction with the NSW Office of Environment and Heritage (OEH formerly DECCW) have completed an assessment of the buoy data for NSW extreme wave climatology (Shand et al 2010). The results from the study for the wave buoy at Byron Bay and two adjacent wave buoys at Brisbane and Coffs Harbour are the most recent available and are tabulated in Table A-15.

The mean offshore wave conditions for the wave buoy at Byron Bay and two adjacent wave buoys at Brisbane and Coffs Harbour are tabulated in Table A-15 (Shand et al 2010). In the absence of available data for a nearer location, it is reasonable to assume the mean wave conditions (H_s = 1.66 m, T_p = 9.59 s) from the Byron Bay wave buoy for consideration of typical offshore wave conditions at Cabarita Beach.

Table A-15 Mean Offshore Wave Conditions (All Directions) (source Shand et al, 2010)

Wave Parameter	Brisbane	Byron Bay	Coffs Harbour
Mean H_S (m)	1.63	1.66	1.58
Mean T_P (s)	9.32	9.59	9.58

A.5.3 Offshore Extreme Wave Climate

Cabarita Beach is subject to waves originating from offshore storms (swell) or produced locally (wind waves) within the nearshore coastal zone. Swell waves reaching the coast may be modified by the processes of refraction, diffraction, wave-wave interaction and dissipation by bed friction and wave breaking. Locally generated waves undergo generation processes as well as the aforementioned propagation and dissipation processes.

WRL, in conjunction with OEH (formerly DECCW) have completed an assessment of coastal storms and extreme waves for NSW which involves the identification of all measured coastal storms during the period 1971 – 2009 and derivation of directional design storm events for annual recurrence intervals of 1 to 100 years (Shand et al 2010). The results from the study for the wave buoy at Byron Bay and two adjacent wave buoys at Brisbane and Coffs Harbour are the most recent available and are tabulated in Table A-16.

Table A-16 Extreme Offshore Wave Conditions (All Directions) (source Shand et al, 2010)

Average Recurrence Interval ARI (year)	One Hour Exceedance H_S (m)		
	Brisbane	Byron Bay	Coffs Harbour
1	5.1	5.2	5.2
10	6.6	6.4	6.7
50	7.6	7.2	7.7
100	8.0	7.6	8.1

Note that the extreme wave heights extrapolated from the wave record of Byron Bay are shown to be smaller than those from the wave record at Brisbane and Coffs Harbour. The capture rates for the three wave buoys are 85.9% (Brisbane), 73.1% (Byron Bay) and 84.7% (Coffs Harbour). It has been suggested that this difference is due to the fact that the wave buoy at Byron Bay may not have been in operation during several large storm events (You, 2011). Due to this uncertainty, WRL has adopted the (more conservative) 1 in 100 year ARI offshore significant wave height of 8.1 m from the Coffs Harbour wave buoy for previous coastal studies at Kingscliff, NSW. Note also that this wave height is slightly higher than the 1 in 100 year ARI H_S of 7.75 m adopted in the *Tweed Coastline Hazard Definition Study* (WBM, 2001) and subsequent studies which may be due to an additional 10 years of analysed data and/or slightly different analysis techniques.

WRL, in conjunction with the Australian Climate Change Adaptation Research Network for Settlements and Infrastructure (ACCARNSI), reviewed Australian storm climatology and previous extreme wave analyses undertaken using instrument and numerical model data (Shand et al. 2011). Importantly, the study defined the peak spectral wave period during storm events around the Australian coast. The nearest location to Cabarita Beach where this analysis was undertaken was Brisbane, with results presented in Table A-17. The peak spectral wave period associated with the 1 in 100 year ARI offshore significant wave height was adopted as 13.1 s for this study.

Table A-17 Associated Wave Period for Extreme Wave Events (source Shand et al. 2011)

Average Recurrence Interval ARI (year)	Peak T_P (s) Brisbane
1	11.4
10	12.3
50	12.9
100	13.1

In the aforementioned study by WRL (Shand et al 2010), WRL also examined the influence of wave direction on extreme storm wave height. For significant wave heights exceeding 5 m at the Byron Bay wave buoy, extreme wave heights are predicted to be highest from the east to the east-south-east (90 to 112.5°). However, it is acknowledged that damaging storm conditions from a wider directional window from the north-east to the south-south-east (45 to 157.5°) may still impact Cabarita Beach.

Detailed wave refraction modelling has not been undertaken for Cabarita Beach. Such a study may better define waves reaching the embayment, however, due to the depth limitation of waves inside the surf zone and exposure to easterly cyclone waves, a design condition of 1 in 100 year ARI waves (Table A-16) from the east to south-east has been assumed.

A.6 Coastal and Erosion Processes

A.6.1 Introduction

This section provides a description and analysis of the main coastal processes which have been identified to have a role in the erosion processes around Cabarita Beach. The coastal erosion processes can be separated into two categories, mainly:

- **Short Term Storm Erosion** – refers to the short-term response of a beach to changing wave and water level conditions during ocean storms. This response is generally manifested in a "storm bite" from the sub-aerial beach moving offshore during the storm. No other short-term processes were identified around Cabarita Beach.

- **Shoreline Recession** – refers to the long-term trend of a shoreline to move landwards in response to a net loss in the sediment budget over time (Ongoing Underlying Recession). Shoreline recession is also predicted to result from sea level rise (Sea Level Recession).

A.6.2 Short Term Processes

- **Storm Erosion**

There have been a number of previous coastal hazards studies undertaken for this section of coastline, including PWD (1982), WBM (1988), WBM (2001), WRL (2012).

The PWD (1982) and WBM (2001) studies have investigated the coastal erosion hazards caused by storm demand based on photogrammetric analysis of aerial photography.

The storm bite analysis on Cabarita Beach performed by PWD (1982) was based on the volume changes between 1962 and 1975. From this analysis, the anticipated storm demand was estimated to be approximately 200 m^3/m of shoreline, above AHD (Hoffman 1979 and PWD 1982), and which is usually taken as a regional recommended design storm demand volume.

In their 2001 photogrammetric analysis of Cabarita Beach, WBM reported that the existing beach/foredune (1999/2000 photogrammetry) was partially eroded in the central to northern sections of the compartment as part of short term cross-shore fluctuations (i.e. 1996 and 1999 storms). On that basis, the 200 m^3/m storm bite provision in the 1982 assessment was found to be potentially conservative and it was considered appropriate to adopt a reduced volume of sand removed where it was clear that the base profile used for analysis already contained some short term loss. On the other hand, the southern section of the beach unit was found to have exhibited substantial accretion since the 1960s, and on that basis, the full 200 m^3/m above AHD was used in the storm bite calculations. As discussed above, the central and northern sections having experienced recent erosion and taking this into consideration a reduced storm bite quantity of 160 m^3/m above AHD was been adopted in these areas relative to the 2000 profiles in determining the immediate hazard zone.

- **Rip Current Erosion**

Rip currents may contribute to short-term beach fluctuations by producing highly localised short-term coastal erosion. Rips are localised seaward flowing currents which usually occupy channels between the nearshore bars. They promote seaward transport of sediment resulting in localised erosion of the beach face.

A further complication is the relatively complex nature of the surf zone's response to differing conditions. During extended periods of mild weather the nearshore bar can attach to the beach resulting in there being no offshore bar formation at all, just a wide flat swash zone with a "shore break". However, under "normal" conditions there is usually a single, shore-parallel bar extending from around Norries Head to around Cudgen Headland. If the dominant wave energy is from the southern sector, this bar can be surprisingly linear, especially at high tides. If there is more of an easterly component and/or larger waves the bar tends to be broken up by rip cells, even at high tide.

During major storm events, a second "cyclone" bar forms further offshore, producing a multiple bar profile. Under such conditions there are rip cells though both bars. At times these line up as mega rips, in which case a phenomenon locally termed "holes" develop. These features could be described as "anti-bars" as they often retain their basic form for many months, as a channel from the shore to deep water. They migrate northward driven by the littoral drift with the southern side infilling but the northern side scouring. The significance of these "holes" is that, should further wave events occur, even relatively minor storms, the localised beach erosion at the landward head of these "holes" is exacerbated by the easy passage of unbroken waves to the beach face.

- **Stormwater Erosion**

WBM (2001) reported the presence of only one stormwater outlet at Cabarita Beach, which discharges at the southern end. This outlet is reported to drain the developed section of the beach seaward of the Coast Road. While some scour of the beach occurs as a result of the discharge, the location is in the vicinity of rocky outcrops which limit the potential for recession. Stormwater erosion can therefore be considered as relatively minor hazard on Cabarita Beach.

A.6.3 Long Term Processes

- **On-going Sediment Imbalance**

As indicated previously, there is the likelihood that, following the onshore movement of sand during the Holocene sea level transgression, longshore processes began to dominate sediment movement due to the obliquity of the "new" shoreline to the net offshore wave energy flux. South and North Stradbroke Islands in Queensland are the sinks for net northward drift on the NSW north coast during both the Pleistocene and Holocene epochs.

Over a 40 year period, the heavy mineral mining operations re-worked most of the Holocene, Outer Barrier deposit to below sea level. This makes reliance on historical survey data difficult when attempting to establish historical shoreline recession trends. It is, however, important to note that the earliest aerial photographs, before the mining disturbed the area immediately behind the beach, show an erosion escarpment and the present day beach also features an erosion escarpment.

Taking into account the history of mining, but seeking to interpret the aerial photography and survey evidence, PWD (1982) concluded that the average shoreline recession rate for the Cabarita shoreline was 1 m/year. However, it is important to note that the latter part of the 14 year period analysed by PWD was known to have been characterised by both frequent and intensive cyclone occurrences in the area, particularly in 1967, 1972, 1973, 1974 and 1976. Therefore, extrapolation of any erosion trend based on the 14 years of data to time spans of 50-100 years would be conservative.

The 1988 WBM photogrammetric analysis incorporated more data up to 1984 and indicated most probable rates of shoreline recession at Cabarita Township in the range 0.2 to 0.4 m/year. However, the more southern profiles appeared to have been substantially modified by dune works affecting the main erosion scarp. The northern profiles gave a more reliable indication of recession based on the photogrammetry. These showed indicative rates in the range 0.1 to 0.3 m/year from the photogrammetry over the 40 years to 1984.

Based on updated photogrammetric data and ground survey data, WBM (2001) concluded that any trend of long term shoreline recession in the Cabarita embayment was occurring at the lower end of the range assessed in WBM previous study (1998). No evidence was found suggesting any greater rate of recession than the regional average for the beach unit as a whole. It was noted that while the southern end at Cabarita might be experiencing slightly higher recession, the photogrammetry shows stability (slight accretion for the available data).

WBM concluded that a best estimate recession rate of 0.1 m/year in the central section reducing to 0.05 m/year at the northern end was recommended for Casuarina Beach to Sutherland Point (upper and lower limits of 0.2 to 0.075 m/year and 0.10 to 0.04 m/year respectively apply as elsewhere). WBM considered appropriate to adopt the regional rate of 0.1 m/year as the lower limit for the Cabarita township, with a feasible upper limit based on available information of 0.25 m/year and a best estimate of 0.15 m/year.

- **Recession due to Sea Level Rise**

WBM in their 2001 study performed an analysis of recession due to potential future sea level rise on Cabarita Beach and the whole coast of the Tweed Shire.

Based on the Intergovernmental Panel on Climate Change (IPCC) and Engineers Australia (2004), National Committee on Coastal and Ocean Engineering recommendations, WBM based their analysis on the a range of sea level rise scenarios given in Table A-18.

Table A-18: Anticipated Future Sea Level Rise (metres), relative to 1990 (source: WBM, 2001)

Year	Sea Level Rise (m)		
	Low	Best Estimate (Adopted) (1)	High
2020	0.05	0.10	0.20
2050	0.10	0.20	0.40
2100	0.15	0.50	0.95

Using a "Bruun Rule" (Bruun, 1962) based approach, WBM calculated shoreline recessions setbacks for the whole Tweed Shire study area (Table A-19). While the method used to derive the depth of closure is not explicitly provided in their report, it is probable that it was based on a depth of active sediment transport in the range of 10 - 15 m, resulting in an adopted Bruun Factor (BF) of 50, which fits within the standard range of BF of 50 to 100 usually used in NSW.

Table A-19: Predicted Regional Shoreline Recession due to Sea Level Rise (source: WBM, 2001)

Year	Sea Level Rise (m)	Shoreline Recession (m)
2020	0.10	5
2050	0.20	10
2100	0.50	25

- **Sand Mining**

A complicating, but also simplifying factor to the beach erosion analysis of this embayment is the fact that the Cabarita embayment has been extensively mined in the past. The complication is because the disturbance caused by mining may limit the reliability of early survey and aerial photogrammetry data. Both the changes in consolidation and the possible breaking up of indurated sand layers which has resulted from the mining may have potentially increased the embayment's vulnerability to erosion, and thereby shoreline recession. It is simplified because, by the mining breaking up any previous soil profiles and sand cementation layers, the beach and dunes are of a more homogenous structure and therefore more amenable to simplified deterministic analysis techniques.

In terms of contribution to beach erosion, it should be noted that generally gold and heavy metal mining of beaches was confined to the beach berm and incipient foredunes. Hence, the level of disturbance was akin to that caused by minor storm erosion. PWD (1982) reported that the volume of the heavy minerals extracted from Cabarita dunes was generally between 1% and 3% of the total volume mined. Hence, its volumetric contribution to the regional sand loss from within the active littoral system cannot be quantified, but is relatively small.

References

Booij N, Ris R C and Holthuijsen L H (1999a), *"A third-generation wave model for coastal regions, Part II,Verification"*, Journal of Geophysical Research C4, 104, 7667-7681.

Booij N, Ris R C and Holthuijsen L H (1999b), *"A third-generation wave model for coastal regions, Part I, Model description and validation"*, Journal of Geophysical Research C4, 104, 7649-7666.

Bruun, P (1962), "Sea-level rise as a cause of shore erosion" *Journal of Waterways and Harbours Division*, 88:117-130.

Bruun, P (1988), The Bruun Rule of erosion by sea level rise: a discussion on large-scale two- and three-dimensional usages. *Journal of Coastal Research,* 4, 627–648.

Bruun, P and Schwartz, M (1985), "Analytical predictions of beach profile change in response to a sea-level rise.", *Z. Germorph.,* Suppl-Bd 57 pp33-50.

Chief Scientist and Engineer (2012), "Assessment of the Science Behind the NSW Government's Sea Level Rise Planning Benchmarks", NSW Government.

Dallas, M and Tuck, D, (2008), "Aboriginal and European Cultural Heritage Assessment Casuarina Town Centre Kingscliff South, NSW", *Mary Dallas Consulting Archaeologists*, Report to Kings Beach No. 2 Pty Ltd.

Department of Environment, Climate Change and Water (2009), "Sea Level Rise Policy", NSW Government.

Department of Environment, Climate Change and Water (2010), "Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments", NSW Government.

Duke, A, (2012), "Cabarita Beach/Bogangar Community Project Plans Report", Report for the Cabarita Beach Bogangar Community Economic Development Committee.

Goda, Y (2000), "Random Seas and design of Maritime Structures." *World Scientific.*

Gordon, A D (1987), Beach Fluctuations and Shoreline Change: NSW, *8th Australasian Conference on Coastal and Ocean Engineering*, pp 104-108.

Hallermeier, R (1981), A profile zonation for seasonal sand beached from wave climate, *Coastal Eng.*, Vol 4, pp 253-277.

Harley M D, Turner I L, Short A D and Ranasinghe, R (2009), "Interannual variability and controls of the Sydney wave climate", *International Journal of Climatology*, Royal Meteorological Society.

Hoffman, J. G & Evans, H. G. & Messner, J. P (1979), "Bogangar-Kingscliff coastal engineering advice", Dept. of Public Works, Coastal Engineering Branch, Sydney

Institute of Engineers Australia (2004), National Committee on Coastal and Ocean Engineering. "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering 2004 Update." *ACT: The Institution of Engineers Australia.*

IPCC (2007a), *Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2007b), *Climate Change 2007 - The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (ISBN 978 0521 88009-1 Hardback; 978 0521 70596-7 Paperback), [Solomon, S, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp

James Cook University of North Queensland (1977) *Numerical Simulation of Tropical Cyclone Surge Along the Queensland Coast*, Part X, Gold Coast. Report Prepared for Beach Protection Authority of Queensland, November

Lord D B and Kulmar M A (2000), "The 1974 Storms Revisited: 25 years. Experience in Ocean Wave Measurement Along the South-East Australian Coast", *Proceedings International Conference of Coastal Engineering*, pp 559-572, ASCE.

Manly Hydraulics Laboratory (2010), NSW Ocean Water Levels, Draft MHL Report 1881, December.

McInnes, K, Abbs, D, O'Farrell, S, Macadam, I, O'Grady, J and Ranasinghe, R (2007), *Projected changes in climatological forcing for coastal erosion in NSW*, a project undertaken for the Department of Environment and Climate Change NSW, CSIRO Marine and Atmospheric Research, Victoria.

MSQ (2011), Semidiurnal Tidal Planes. Queensland Tide Tables 2012, Marine Safety Queensland, September 2011.

Public Works Department, NSW, (1982), "Bogangar Beach Coastal Engineering Advice", *Public Works Department*- Coast and Flood Division, Report No PWD 81022.

Public Works Department, NSW, (1985), "Wamberal Beach and Avoca Beach Coastal Engineering Advice" *Public Works Department*- Civil Engineering Division, Report No PWD 85040.

Public Works Department, NSW, (1994), "Gosford Coastal Process Investigation", *Public Works Department*- Coast and Flood Division.

Pugh, D T and Vassie, J M (1979), "Extreme Sea Levels from Tide and Surge Probability", pp.911-930 in Vol 1, *Proceedings of the Sixteenth Coastal Engineering Conference*, 1978, Hamburg, Germany. New York: American Society of Civil Engineers. 3060pp.

Ris, R C, Holthuijsen L H and Booij N (1994), "A spectral model for waves in the near shore zone", *24th International Conference of Coastal Engineering, Kobe*, Oct. 1994, pp 68-78.

Shand, T D, Goodwin, I D, Mole, M A, Carley, J T, Coghlan, I R, Harley, M D and Peirson, W L (2010a), *NSW Coastal Inundation Hazard Study: Coastal Storms and Extreme Waves*, prepared by the Water Research Laboratory and Macquarie University for the Department of Environment, Climate Change and Water. WRL Technical Report 2010/16.

Shand, T D, Mole, M A, Carley, J T, Peirson, W L and Cox, R J (2011) *Coastal Storm Data Analysis: Provision of Extreme Wave Data for Adaptation Planning*, WRL Research Report 242.

Short A D (1985), "Rip-current Type, Spacing and Persistence, Narrabeen Beach, Australia." *Journal of Marine Geology*, 65 1985.

Tweed Shire Council (2012d), *Ordinary Council Meeting Thursday 25 October 2012*, Council Minutes.

Watson, P J, (2011), "Is there evidence yet of acceleration in mean sea level rise around mainland Australia?", *Journal of Coastal Research*, 27(2), 368–377. West Palm Beach (Florida), ISSN 0749-0208.

WBM (1995), "Coastal Management Study and Coast Management Plan- Gosford City Open Coast Beaches", *WBM Oceanics Australia.*

WBM (1988) "Coastal Engineering Advice: Ocean Paradise Estates Bogangar Beach Tweed Shire, NSW", Prepared for Lenen Developments Pty Ltd by Winders, Barlow & Morrison, QLD, Report number 3869

WBM (2001), "Tweed Coastline Hazard Definition Study" - Final Report (Revision 3), R.B12876.002.03.doc, Brisbane, (Council has advised that the stated year of 2007 is a typographical error, with 2001 being the correct year of issue).

WorleyParsons (2009), "Ex-HMAS Adelaide Artificial Reef Coastal and Oceanographic Processes", *Report prepared for NSW Land and Property Management Authority,* Newcastle NSW.

WRL (1988), Coastal Storms in N.S.W. in August and November 1986 and their effect on the coat. *Report Prepared for Public Works Department NSW Australia.* University of NSW Water Research Laboratory.

You, Zai-Jin (Bob) (2007), "Extrapolation of Extreme Wave Height with a Proper Probability Distribution Function", *Proceedings of the Australasian Coasts and Ports Conference*, Melbourne, The Institute of Engineers Australia.

Appendix B SBEACH Modelling

B. SBEACH Modelling

B.1 Model Description/Background

The modelling program SBEACH (**S**torm-induced **BEA**ch **CH**ange) was developed by the U.S. Army Corps of Engineers (USACE) and is an empirically based two-dimensional model used to examine the short-term response of beach, berm and dune profiles to storm events. A fundamental assumption of the model is that an equilibrium beach profile exists whereby incident wave energy is dissipated across it without any significant net change in beach shape (Garber et al., 2010).

The model simulates the formation and movement of major morphologic features such as longshore bars, troughs, and berms due to varying storm waves and water levels (Kraus et al., 1993). This is achieved by using a temporally varying wave-breaking point. It is suitable to be applied to sandy beaches with fine to medium grain sizes (from 0.13 to 1.0 mm) and the model includes shoaling, refraction, breaking, set-up and run-up (Kraus et al., 1993).

A strength of the model is its ability to include wave reforming and sequential breaking if the wave height to water depth ratio becomes sufficiently small enough (Carley et al., 2008). This process occurs frequently on beaches that form outer bars, such as those of the East Coast of Australia.

The driving agents within SBEACH are breaking waves and changing water levels. Of these two, the water level is the most important (Kraus et al., 1993) and consists of data input quantifying the contributions from tides and storm surge. Wind-induced setup and wave run-up are calculated in the model process. It is for this reason that caution must be exercised when selecting the time series which represents the astronomical tide and storm surge. SBEACH can only be used to analyse processes involving cross-shore sediment transport and should therefore only be used if sediment movement alongshore can be neglected. Another limitation of the model is its inability to predict erosion caused by rip formations which can contribute considerably to storm cut values.

SBEACH has been calibrated and successfully verified on the Australian east coast for measured storm erosion at sites including Warilla, Collaroy, Narrabeen, Wamberal and the Gold Coast (Carley et al., 2003, Carley et al., 1998).

SBEACH modelling was undertaken in accordance with the principles of Carley and Cox (2003), and Nielsen and Adamantidis (2007). Using idealised, deepwater synthetic design storms (SDS) derived in Shand et al. (2011), synthetic design storm time series comprising wave height and period were constructed for extreme swell and wind-wave events. Example time series for the 100 year ARI event is shown in Figure B-1. Consistent with verified modelling undertaken at Narrabeen Beach by Carley and Cox (2003), design event time series comprised three sequential design storms.

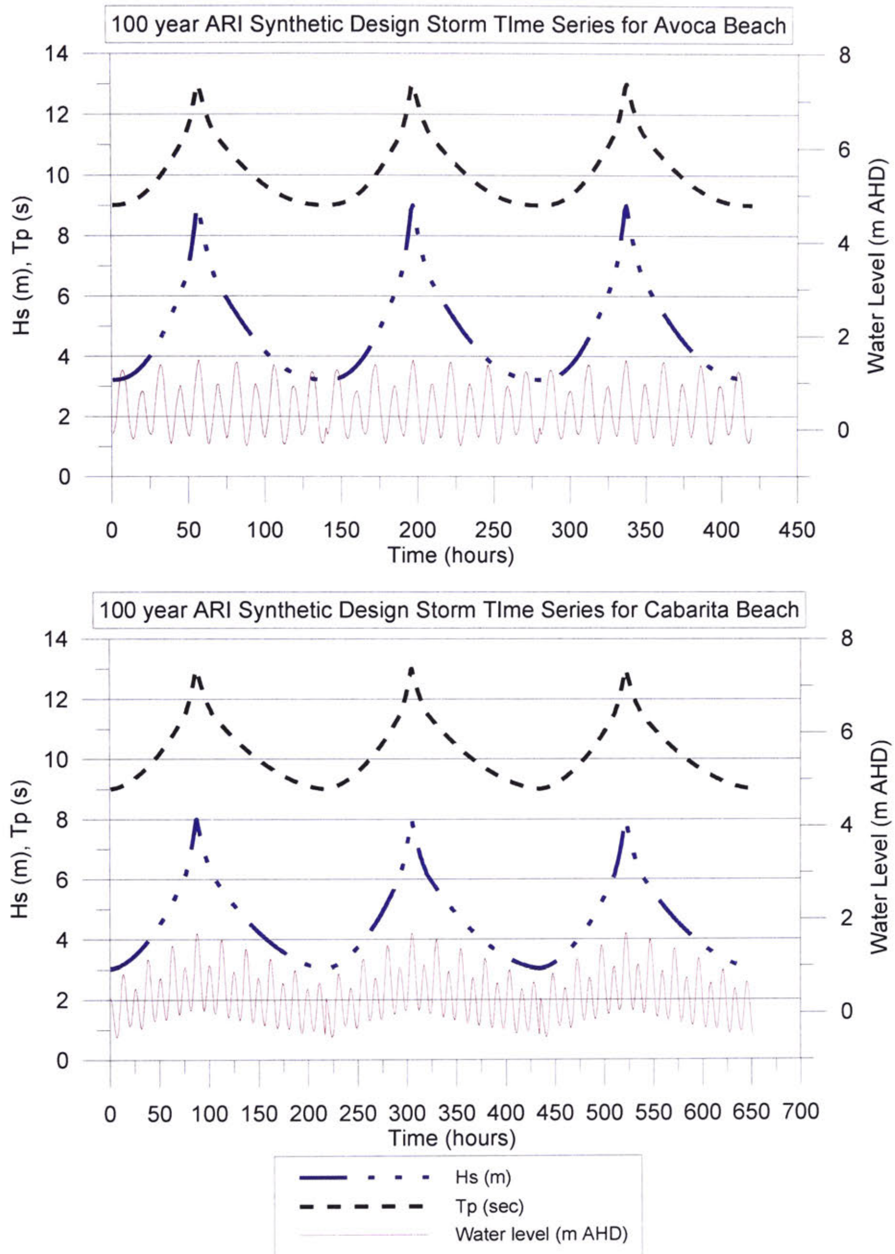


Figure B-1 100 year ARI Synthetic Design Storm Sequence for Avoca and Cabarita Beach

B.2 Design Water Levels

For storm erosion modelling purposes, a spring tide time series was generated, to which a tidal anomaly was added, such that the peak water level corresponded to the ARI of the storm.

Design storm surge levels (astronomical tide + anomaly) specific to Avoca Beach are recommended in the Coastal Risk Management Guide (DECCW, 2010) based on data from the Fort Denison tide gauge in Sydney and reproduced in Table B-1. These levels are applicable to the Newcastle - Sydney – Wollongong area only.

The water levels adopted for SBEACH modelling in this report at Avoca Beach are shown in Table B-3. These values are slightly higher than the values suggested by the DECCW (2010), however, they are considered acceptable as it will lead to a slightly more conservative erosion value modelled by SBEACH.

Table B-1 Water Levels Tide + Storm Surge
Newcastle – Sydney – Wollongong (source DECCW, 2010)

Average Recurrence Interval ARI (year)	Water Level Excl. Wave Setup and Runup (m AHD)
1	1.24
10	1.35
50	1.41
100	1.44

Tidal anomaly data for Cabarita Beach was derived through joint probability analysis undertaken for the Tweed Heads tide gauge by MHL (2010). This analysis was undertaken up to the 1 in 100 year ARI condition in 0.5 m increments using the method described by Pugh and Vassie (1979). This calculates the chance that high astronomical tide levels and high anomaly levels occur together. Since the maximum return water level quoted in the MHL study was 93.9 years (1.71 m AHD), WRL undertook a minor log-linear extrapolation to infer slightly higher water level of 1.72 m AHD as the 1 in 100 year ARI storm tide level to be adopted for preliminary design which is shown in Table B-2.

Table B-2: Joint Probability of Return Water Levels (Astronomical Tide + Anomaly) for Tweed Heads (MHL, 2010)

Elevation (m Local Datum)	Elevation (m AHD)	ARI (1 in x years)
2.70	1.81	>100
2.61	***1.72***	***100#***
2.60	1.71	93.9
2.50	1.61	28.2
2.40	1.51	10.4
2.30	1.41	4.2
2.20	1.31	1.6
2.10	1.21	0.4
2.00	1.11	0.1

* Note that 0 m AHD = Local Datum - 0.893 m

Note too that the estimated 1 in 100 year ARI value has been inferred by WRL.

Peak water levels used for the purpose of SBEACH modelling at Avoca Beach and Cabarita Beach are summarised in Table B-3.

Table B-3 Design Peak Water Levels

Location	Average Recurrence Interval ARI (year)	Peak Water Level (Spring tide + Anomaly) (m AHD)
Avoca	100	1.50
	10	1.40
	1	1.25
Cabarita	100	1.72
	10	1.51
	1	1.26

For modelling, the peak in the predicted tide and tidal anomaly was assumed to coincide with the peak wave height of the storm. While these combinations remain somewhat conservative, they are not considered unreasonable since intense low pressure systems are responsible for large waves, strong winds and storm surge. Further refinement of the assumptions requiring additional data and a full statistical joint-probability analysis is beyond the present scope of works.

B.3 Design Wave Conditions

Offshore wave characteristics were derived through statistical analysis of recorded data from the Sydney and Brisbane directional wave buoys and extrapolated to extreme events (Shand *et al.*, 2010, 2011). Nearshore wave transformation coefficients (when available) were derived from numerical modelling undertaken in previous studies.

B.3.1 Avoca Beach Wave Conditions

The non-directional deepwater synthetic design storm characteristics derived by Shand *et al.* (2011) are shown in Table B-4.

Table B-4 Sydney Extreme Offshore Wave Conditions (All Directions) (source Shand et al., 2010)

Average Recurrence Interval (years)	One hour exceedance at Sydney offshore buoy	
	Hs (m)	Tp (s)
1	5.9	11.0
10	7.5	12.1
50	8.6	12.7
100	9.0	13.0

Numerical wave modelling results from WorleyParsons (2009) study were used to derive the directional wave transformation coefficients to apply to the deepwater synthetic design storm specific to each section of the beach as follows:

- Avoca North: South-east wave transformation
- Avoca Central: South-east wave transformation
- Avoca South: East-north-east wave transformation

Model input wave conditions are summarised in Table B-5.

Table B-5 Adopted Storm Characteristics for Avoca Beach

Direction	SE		ENE		Storm Duration
ARI	Peak H_s (m)	T_P (s)	Peak H_s (m)	T_P (s)	(hour)
1	5.8	11.0	3.5	8.9	90
10	7.5	12.2	4.4	9.7	120
100	8.4	13.3	5.3	10.4	140

B.3.2 Cabarita Beach Wave Conditions

At Cabarita Beach, the offshore wave height was derived from the extreme offshore wave conditions reported by Shand et al. (2011). As the beach has a consistent eastern facing alignment along its length, the same input wave conditions were applied along Cabarita Beach. The adopted storm characteristics used for Cabarita Beach are shown in Table B-6.

Table B-6 Brisbane Extreme Offshore Wave Conditions (All Directions) (source Shand et al., 2011)

Average Recurrence Interval (years)	One hour exceedance at Brisbane offshore buoy		Adopted Storm
	Hs (m)	Tp (s)	Duration (hour)
1	5.0	11.4	95
10	6.6	12.3	145
100	8.1	13.1	220

B.3.3 Storm Clustering

The worst erosion experienced by a beach is generally caused by the sequencing of closely-spaced events such that there is insufficient time for beach recovery between storms. Historically, major erosion events such as the storms of 1974, have been the result of the rapid succession (clustering) of storms. In response to this problem, the Western Australian Government specified that three consecutive design storms should be run back to back through SBEACH or a similar model in order to establish the storm erosion for coastal planning purposes. SBEACH modelling was undertaken in this study considering a single and a sequence of up to three storm events.

Subject to the assumption made on storm clustering, the actual ARI of three closely spaced 100 year ARI storms could range from 300 to 100,000 years. However, the purpose of using three closely spaced 100 year ARI storms in SBEACH is to model a sequence of lesser storms which have been observed to cause "design" erosion volumes on well monitored beaches while still properly considering the wave exposure of each beach. As shown in Thom and Hall (1991), when the time gap between individual storms is small (of the order of one week to several months), beach recovery does not have sufficient time to progress, as it occurs at much slower timescales than erosion (Carley *et al.*, 1998). Therefore, for SBEACH erosion modelling, defining the time gap between storms within a cluster is not needed.

B.4 Beach Profiles

Profile response to the design events was assessed at three locations at each study location. The pre-storm beach cross-sections were based on LiDAR data. These profiles provide just a single snapshot of the beach, and would in fact be changing in time.

For Avoca, the three profile locations were selected along the beach to represent northern, central and southern alignments. An effective mean grain size of 0.3 mm for the beach was adopted from available literature. Pre-storm beach cross-sections at Avoca Beach were based on marine LiDAR profiles by OEH taken on the 14th to 19th March 2008.

For Cabarita Beach, three profile locations were selected along the beach to represent northern, central and southern alignments. The effective mean grain size of 0.2 mm for the beach was adopted from available literature. Pre-storm beach cross-sections at Cabarita Beach were based on marine LiDAR profiles by OEH.

B.5 Model Validation

Validation of the model involves the attempt to reproduce a surveyed change in profile shape of a beach in the model using wave and water level data records from a storm event.

Adequate measurements of post and pre storm profiles were not available for calibration at Avoca Beach, however, reference was made to a calibrated SBEACH model for nearby Wamberal Beach for a storm in August 1986 for which the required field measurements were available (Drummond, 2011).

Similarly, measurements of post and pre storm profiles were not available for calibration at Cabarita Beach. SBEACH modelling of Kingscliff Beach to the north of the study site was undertaken by Coghlan et al. (in prep.) which have been used to inform the selection of calibration parameters.

The model parameters chosen for modelling for Avoca and Cabarita Beach are shown in Table B-7.

Table B-7 SBEACH Validated Model Parameters

Coefficient / Variable (notation used in model)	Value Avoca	Value Cabarita	Brief Description
DXC	Variable (5 and 10 m)	Variable (5 and 10 m)	X grid
DT	20 minutes	20 minutes	Time step
K	2.5 x 10^{-6} m^4/N	2.5 x 10^{-6} m^4/N	Sediment transport rate coefficient
KB	0.005	0.005	Overwash transport parameter
EPS	0.002 m^2/s	0.002 m^2/s	Slope dependent transport rate coefficient
LAMM	0.4	0.4	Transport rate decay coefficient multiplier
TEMPC	20°C	20°C	Water temperature
ISEED	4567	4567	Seed for random number generator
RPERC	20%	20%	Random variation in wave height
DFS	0.3 m	0.3 m	Landward surfzone depth
D50	0.3 mm	0.2 mm	Effective median grain size in the surfzone
BMAX	30°	30°	Avalanching angle

B.6 Model Scenarios

The SBEACH model was run for the 1, 10 and 100 year ARI storm events. Single and sequences of up to three consecutive storms were modelled.

B.7 Model Output

B.7.1 Tabulated results

The results of the SBEACH modelling are presented in Tables B-8 and B-9.

Table B-8 SBEACH Erosion Modelling Results at Avoca Beach

Profile	Storm Scenario	ARI (years)	Cumulative Erosion above 0 m AHD (m^3/m)
Avoca North	1x100ARI	100	40
	1x10ARI	10	26
	1x1ARI	1	17
	2x100ARI	100	86
	2x10ARI	10	55
	2x1ARI	1	27
	3x100ARI	100	133
	3x10ARI	10	91
	3x1ARI	1	45
Avoca Central North	1x100ARI	100	47
	1x10ARI	10	38
	1x1ARI	1	28
	2x100ARI	100	92
	2x10ARI	10	66
	2x1ARI	1	40
	3x100ARI	100	134
	3x10ARI	10	96
	3x1ARI	1	56
Avoca Mid South	1x100ARI	100	45
	1x10ARI	10	31
	1x1ARI	1	20
	2x100ARI	100	69
	2x10ARI	10	50
	2x1ARI	1	35
	3x100ARI	100	88
	3x10ARI	10	64
	3x1ARI	1	45

Table B-9 SBEACH Erosion Modelling Results at Cabarita Beach

Profile	Storm Scenario	ARI (years)	Cumulative Erosion above 0 m AHD (m^3/m)
Cabarita North	1x100ARI	100	48
	1x10ARI	10	24
	1x1ARI	1	9
	2x100ARI	100	105
	2x10ARI	10	50
	2x1ARI	1	27
	3x100ARI	100	166
	3x10ARI	10	83
	3x1ARI	1	42
Cabarita Central	1x100ARI	100	46
	1x10ARI	10	32
	1x1ARI	1	24
	2x100ARI	100	77
	2x10ARI	10	51
	2x1ARI	1	33
	3x100ARI	100	117
	3x10ARI	10	73
	3x1ARI	1	41
Cabarita South	1x100ARI	100	72
	1x10ARI	10	40
	1x1ARI	1	26
	2x100ARI	100	121
	2x10ARI	10	76
	2x1ARI	1	39
	3x100ARI	100	167
	3x10ARI	10	107
	3x1ARI	1	60

B.7.2 Plots

Results of the SBEACH modelling are presented in Figures B-2 to B-5.

B.8 Gordon Storm Cut Statistics

Estimates of extreme storm demands can be obtained from the analysis of historical beach profile variations due to large storms. Ideally, field data sets would incorporate pre and post storm beach profile and nearshore bathymetry. However, these data sets are often scarce and limited to selected key locations where beach surveys have been undertaken regularly and in concomitance with significant storm events. Narrabeen Beach and Bengello/South Broulee/Moruya Beach in NSW, Gold Coast in QLD are examples of data rich sites.

In the absence of such survey records, photogrammetry data is important in identifying historical profile variations and deriving estimates of storm demand. The main limitations of photogrammetry data are that it provides no information on the underwater bathymetry, and analysis is restricted to the dates for which aerial photography exists (usually 2 to 10 years apart) which does not necessarily coincide with pre and post storm conditions.

Gordon (1987) presented storm bite statistics for the New South Wales coast between Sydney and the Queensland border. These statistics were based on 10 years of detailed profile surveys and photogrammetric analysis of 40 years of aerial photos. Due to the limitations of photogrammetry, only eroded volumes above mean sea level were given. A distinction was made between volumes for "low demand, open beaches" and "high demand, rip heads" with the following equations presented:

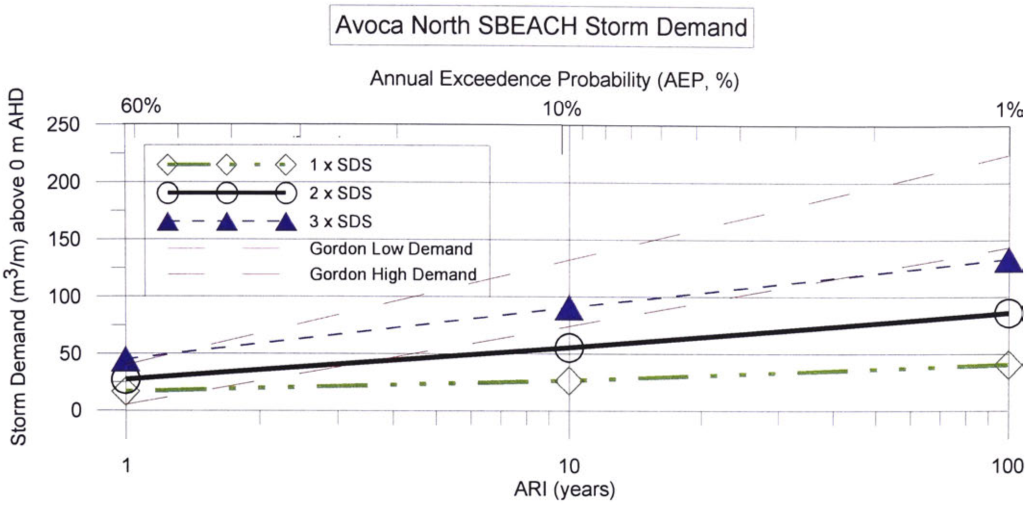
- $V_L = 5 + 30 \ln(ARI)$
- $V_H = 40 + 40 \ln(ARI)$

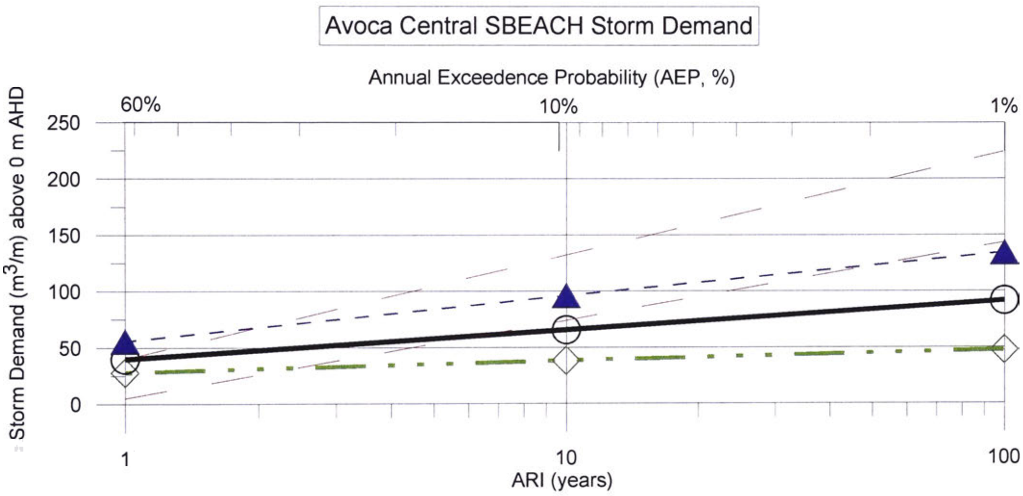
Where:

- V_L and V_H are eroded volumes above AHD for "low demand, open beaches" and "high demand, rip heads" respectively (m^3/m);
- ln is the natural (base e) logarithm;
- ARI is average recurrence interval (years);

Due to the nature of the timing of the aerial photography, the eroded volumes may not have resulted from a single storm event, but rather the cumulative effect of several storm events. Thus the ARIs presented referred to "erosion event" eroded volumes rather than erosion arising from single storm events of a particular ARI.

Gordon suggested that the erosion that occurs on the NSW coast for a 100 year ARI event falls between 140-220 m^3/m for low and high demand beaches respectively. It is cautioned by Gordon (1987) that the indicated equations are suggested relationships only and that the database behind them is limited. The findings however provide a useful order of magnitude for the erosion volumes expected for the NSW coast and have been widely used by practitioners for the past 25 years.





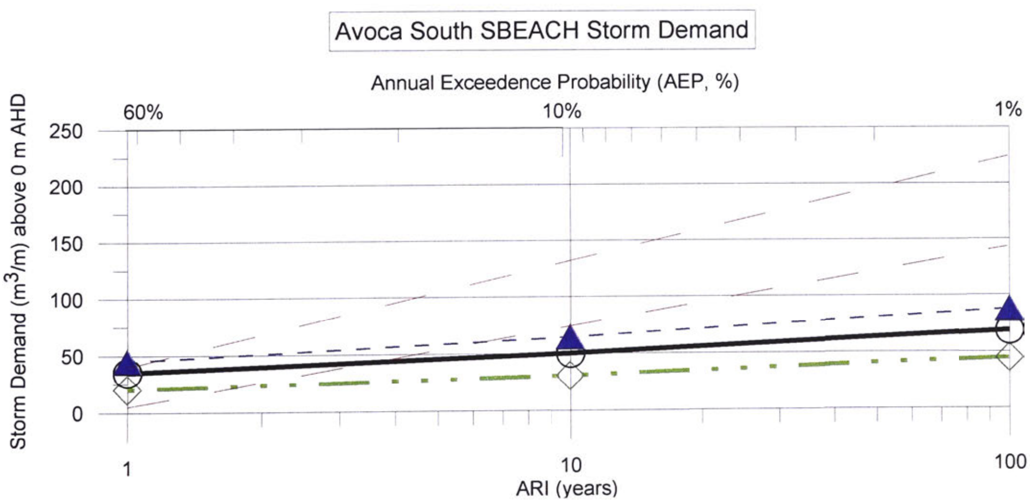
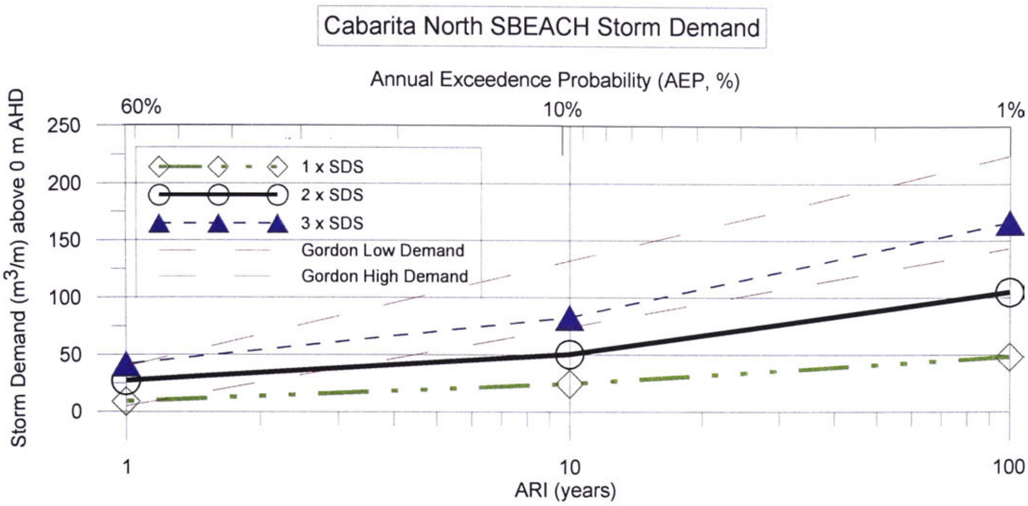
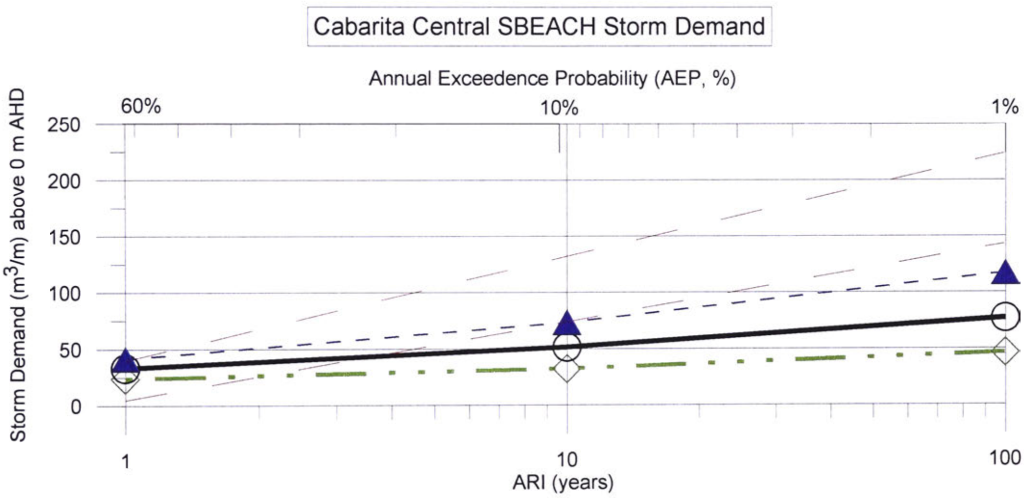


Figure B-2 Avoca Beach Estimates of Storm Demand





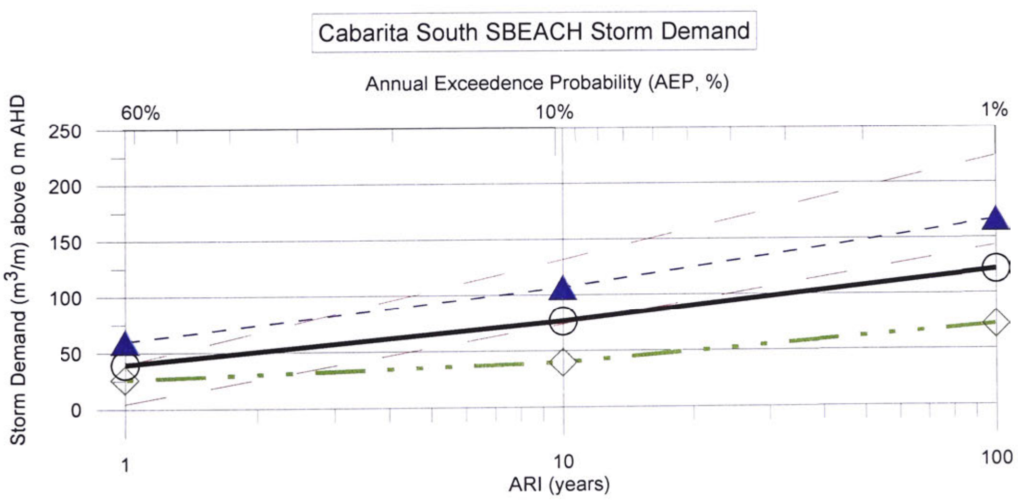
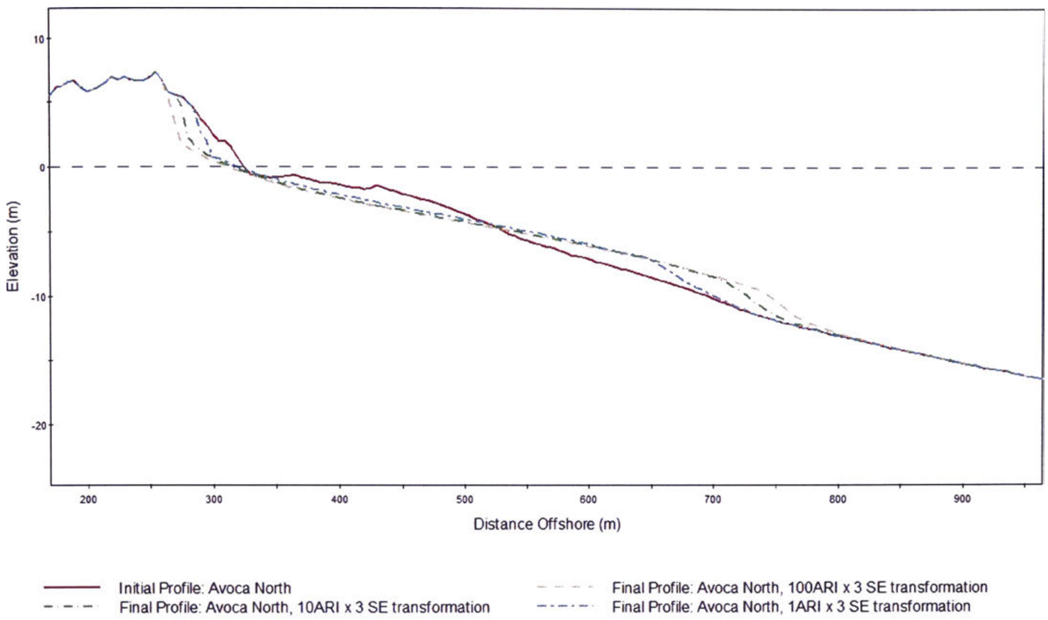
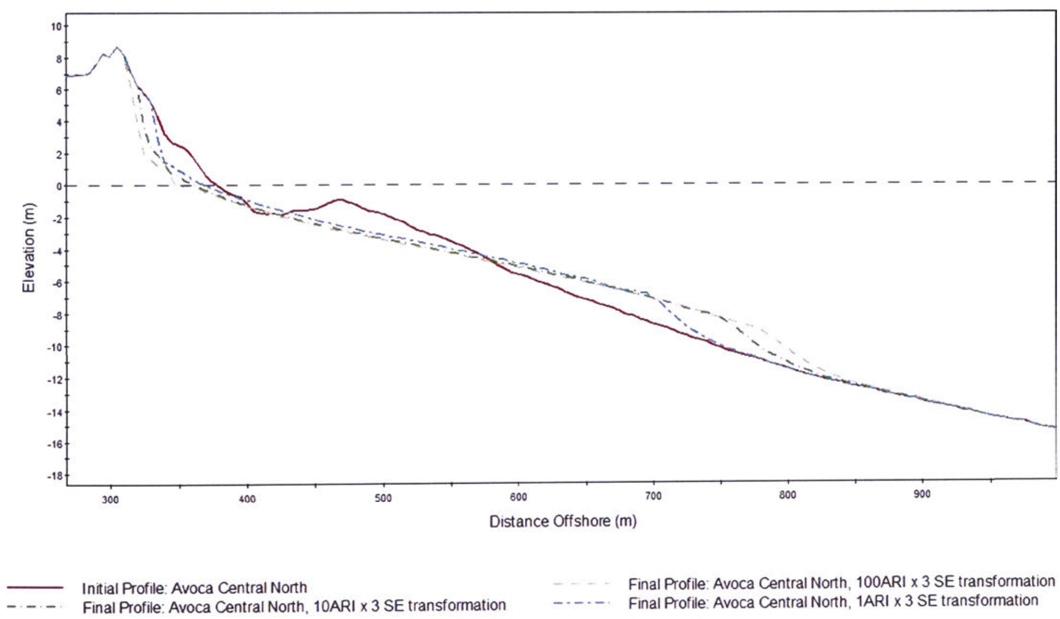


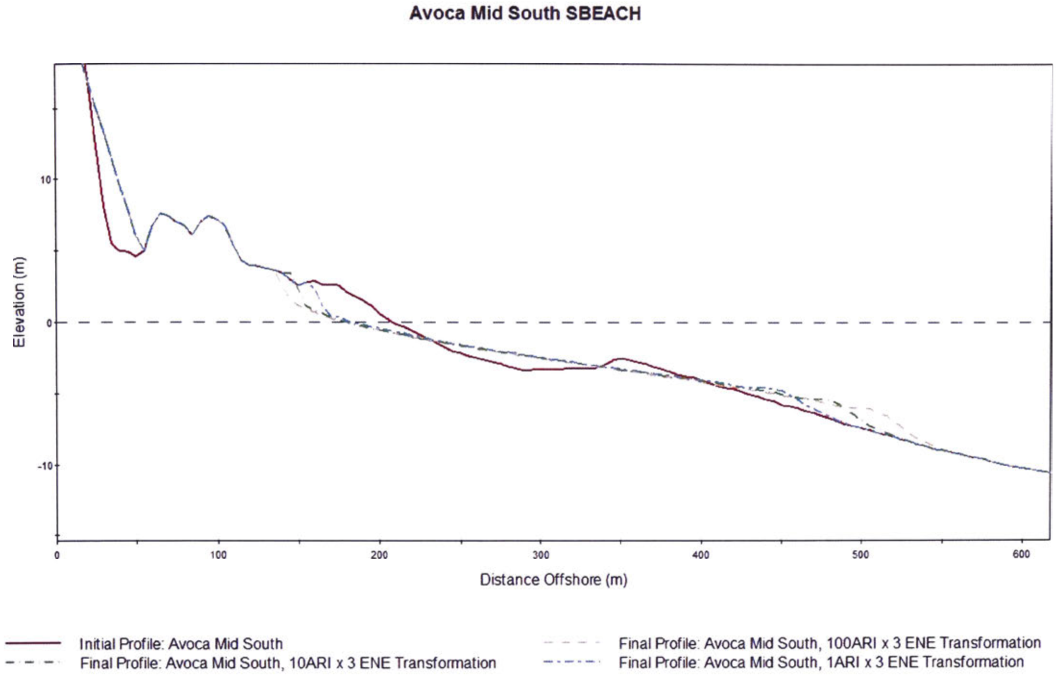
Figure B-3 Cabarita Beach Estimates of Storm Demand

Avocal North SBEACH



Avoca Central North SBEACH





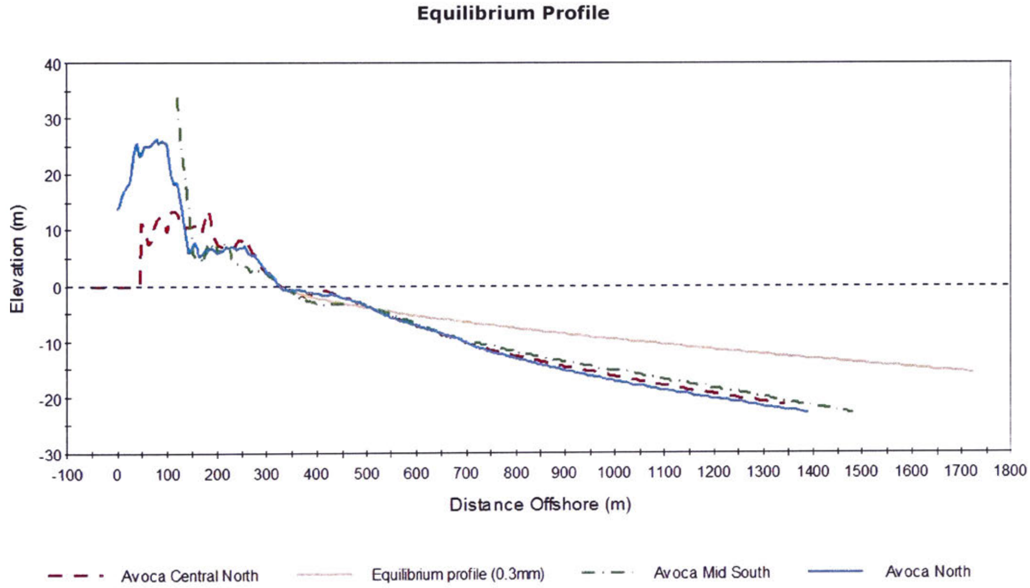
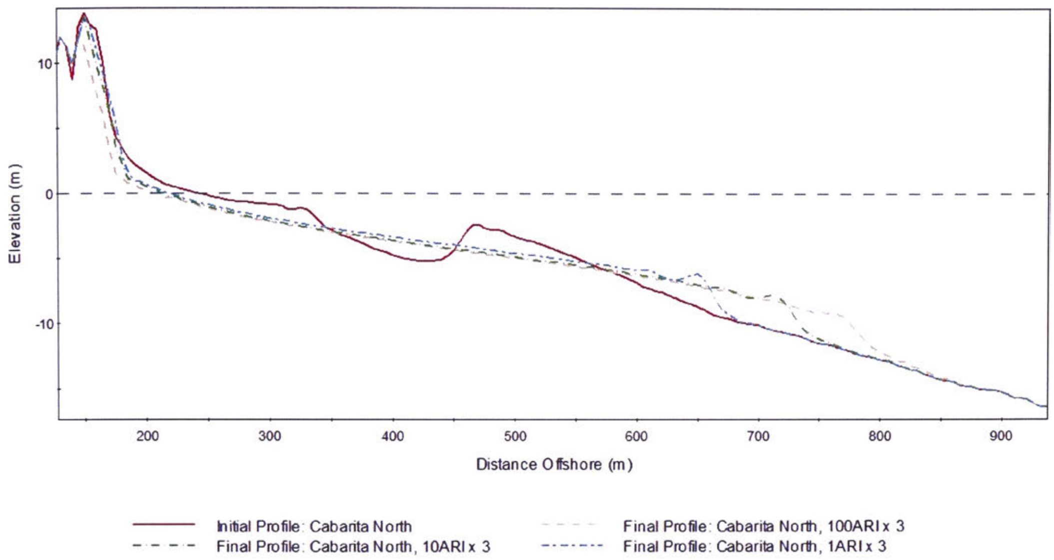
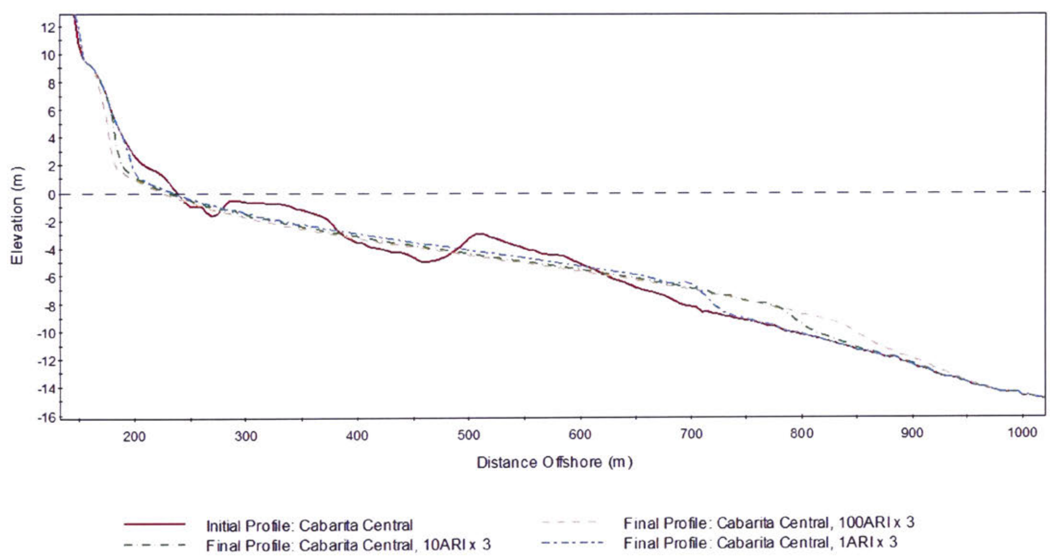


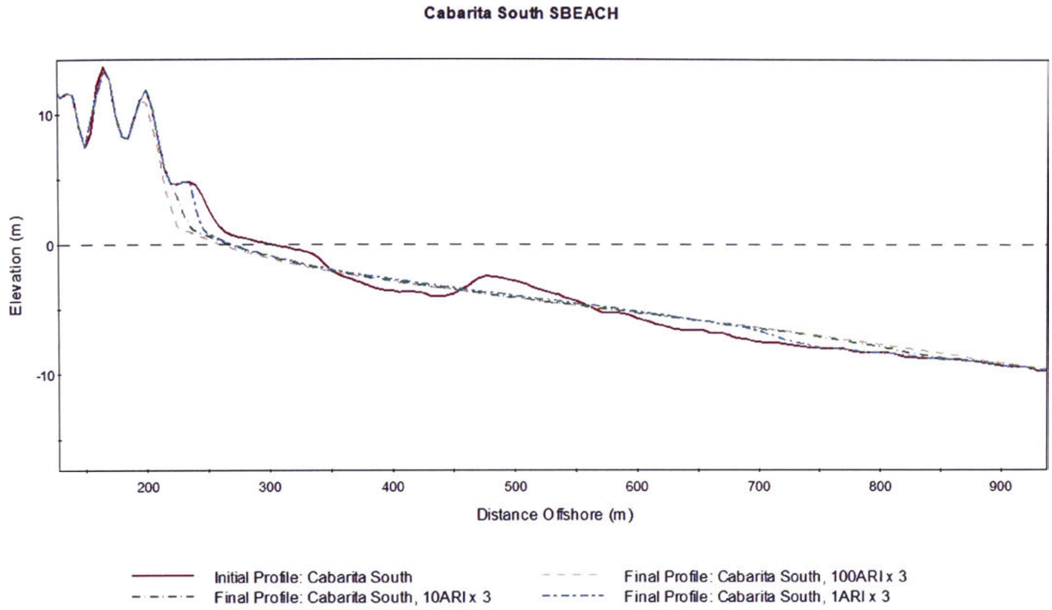
Figure B-4 Avoca Beach Pre and Post Storm Profiles (4 plots)

Cabarita North SBEACH



Cabarita Central SBEACH





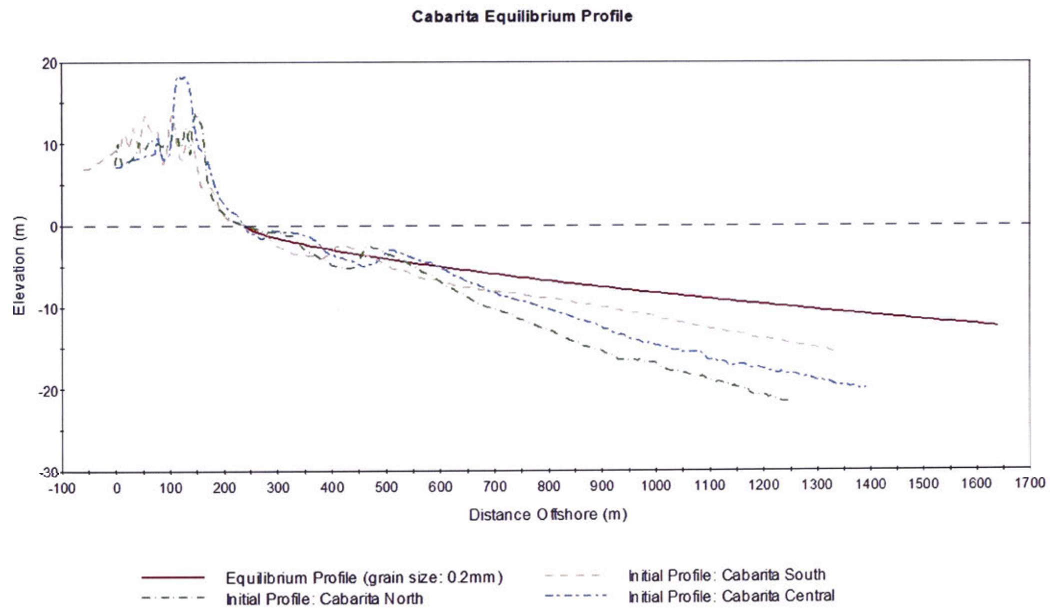


Figure B-5 Cabarita Beach Pre and Post Storm Profiles (4 plots)

B.9 References

Callaghan, D P, Nielsen, P, Short, A D. and Ranasinghe, R (2008), Statistical Simulation of Wave Climate and Extreme Beach Erosion, *Coastal Engineering*, 55(5), 375-390.

Carley, J T, Couriel, E D and Cox, D R (1998), Numerical Modelling Sand Nourishment Profiles/Quantities and Beach Erosion due to Storms and Sea Level Rise, WRL Technical Report 98/04.

Carley, J T and Cox, R J (2003), A Methodology for Utilising Time-Dependent Beach Erosion Models for Design Events, *Proceedings of 16th Australasian Coasts and Ports Conference*, Auckland, New Zealand.

Coghlan I R, Carley J T, Shand T D, Blacka M J, Cox R J, Davey E K and Blumberg G P (in prep.), Kingscliff Beach Foreshore Protection Works Part A - Alternative Terminal Seawall Designs and Beach Nourishment and Beach Nourishment, WRL Technical Report 2011/25

Drummond, C D (2011), The Implications of Climate Change for the Beaches of the Central Coast, B. Eng thesis, University of New South Wales, Sydney.

Department of Environment, Climate Change and Water (2010), Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments, NSW Government.

Garber, S, Treloar, D and Beadle, C, (2010) Wollongong LGA Coastal Hazards Study, Some Unique Aspects, *The 19th NSW Coastal Conference, Batemans Bay, NSW,* Australia.

Gordon, A D (1987), Beach Fluctuations and Shoreline Change: NSW, *8th Australasian Conference on Coastal and Ocean Engineering*, pp 104-108.

Kraus, N, Larson, M, Rosati, J and Wise, R (1993), SBEACH: Numerical Model for Simulating Storm-Induced Beach Change. User's Manual. *US Army Corps of Engineers.*

Larson M and Kraus N C (1989), SBEACH: Numerical Model for Simulating Storm-Induced Beach Change, Report 1: Theory and Model Foundation. Technical Report CERC-89-9, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg USA.

Larson M, Kraus N C and Byrnes M R (1990), SBEACH: Numerical Model for Simulating Storm-Induced Beach Change, Report 2: Numerical Formulation and Model Tests. Technical Report CERC-89-9, US Army Engineer Waterways Experiment Station, Coastal Engineering Research Center, Vicksburg USA.

Manly Hydraulics Laboratory (2010), NSW Ocean Water Levels, Draft MHL Report 1881, December.

McLean, R and Shen, J-S (2006), From Foreshore to Foredune: Foredune Development Over the Last 30 Years at Moruya Beach, New South Wales, Australia, *Journal of Coastal Research*, Volume 22, Number 1, pp 28-36.

Nielsen, AF and Adamantidis, C A (2007), Defining the Storm Erosion Hazard for Beaches, *Australian Journal of Civil Engineering*, Volume 3, Number 1, pp. 39-50.

Pugh, D T and Vassie, J M (1979), Extreme Sea Levels from Tide and Surge Probability, pp.911-930 in Vol 1, *Proceedings of the Sixteenth Coastal Engineering Conference*, 1978, Hamburg, Germany. New York: American society of Civil Engineers. 3060pp.

Shand, T D, Mole, M A, Carley, J T, Peirson, W L and Cox, R J (2011), *Coastal Storm Data Analysis: Provision of Extreme Wave Data for Adaptation Planning*, WRL Research Report 242.

Thom, B G and Hall, W (1991), Behaviour of Beach Profiles During Accretion and Erosion Dominated Periods, *Earth Surface Processes and Landforms*, Volume 16, pp 113-127.

Appendix C Recession Model

C. Recession Model

C.1 Model Description

A simple two-dimensional deterministic model was developed for this study to be used as a platform to simulate probabilistic variations of future long term coastal response to climate changes. The model was developed using a sediment budget approach and simple 2D geometric transformation.

The model was run repeatedly using a Monte Carlo algorithm, by which stochastic variation of the input parameters allowed to obtain numerical results and inference of recession probability distributions. Thus, a distribution of modelled recession was produced. For each model run, each input parameter was randomly selected, according to a predetermined distribution as given below, and the resulting modelled recession was taken as a single point on the final distribution of estimated recession.

Results presented in the report were obtained with running 10,000,000 simulations. However, convergence tests showed that by 100,000 iterations, difference between stochastic output was negligible. Computing time was in all cases of the order of few minutes. Convergence tests were undertaken by comparing the empirical distribution outputs (moment and quantile estimates) produced by parallel consecutive iterations. Results of convergence tests are shown in Section C.3.2.

C.2 Model Setup

C.2.1 Beach Profiles

Two representative profiles were selected for Avoca Beach (North and South) and three profiles were selected as representative of Cabarita Beach (North, Centre and South). Profiles were derived from Marine LIDAR data obtained from OEH. Details of data and sources are given in the main reports. Plots of profiles are presented below in Section C.3.

C.2.2 Input Variables

Recession, R [m], at Avoca beach was modelled as:

$$R = \left(\frac{S \cdot L_* + Q_{shells}}{h_d + h_*} + \frac{V_{lagoon} + V_{mega-rips} + V_{overwash}}{L \cdot (h_d + h_*)}\right) \cdot t$$

Where:

S – Sea level rise [m/yr].
L_* – Distance of closure [m].
h_* – Depth of closure [m].
h_d – Dune height [m].
L – Beach length [m].
Q_{shells} – Biogenic production/degradation [m^3/m/yr].
V_{lagoon} – Loss to lagoon [m^3/yr].
$V_{mega-rips}$ – Loss due to mega-rips [m^3/yr].
$V_{overwash}$ – Loss due to overtopping [m^3/yr].

Recession at Cabarita Beach was modelled as:

$$R = \left(\frac{S \cdot L_* + Q_x}{h_d + h_*} + \frac{Q_y}{L \cdot (h_d + h_*)}\right) \cdot t$$

For:

Q_x – Onshore drift [m^3/m/yr].
Q_y – Longshore drift [m^3/yr].

C.2.3 Input Variables Distributions

The assignment of pdfs to each of the input variable was essentially an heuristic process based on site specific knowledge and expert judgement. For the purpose of this study and in the absence of additional information, simplified triangular pdfs were assigned (Table C-1) to each input variables through the definition of:

- more frequent expected value (mode);
- lower and upper bounds (min and max).

The values for min/max and mode were obtained by independent polling of five senior coastal engineers and scientists experienced on the NSW coast. Their independently preferred values were then blended into a consensus range for input into the model. Note that not all practitioners agreed with the full range of values presented in Table C-1.

Table C-1 Summary of Input Variables Distributions

Parameter	Units	Distribution	Min	Mode	Max
Avoca					
S - Sea Level Rise (by 2100 & relative to 1990)	m	Triangular	0.1	0.5	1.1
h_* - Depth of closure	m	Triangular	12	20	35
(1)V_{Lagoon} – Loss to Lagoon (assuming 1.1 m SLR in 2100)	$\frac{m^3}{yr}$	Triangular	0	250	500
Q_{shells} – Biogenic production/degradation	$\frac{m^3}{m \cdot yr}$	Triangular	-1.8	-0.9	0.2
$V_{mega\text{-}rips}$	$\frac{m^3}{yr}$	Triangular	0	3000	6000
(1)$V_{overwash}$ – Dune overwash (assuming 1.1 m SLR in 2100)	$\frac{m^3}{yr}$	Triangular	0	250	500
Q_x – onshore drift	$\frac{m^3}{m \cdot yr}$	Triangular	0	0	0
Cabarita					
S - Sea Level Rise (by 2100 & relative to 1990)	m	Triangular	0.1	0.5	1.1
h_* - Depth of closure	m	Triangular	12	20	35
Q_y – Differential longshore transport	$\frac{m^3}{yr}$	Triangular	10,000	50,000	120,000
Q_x – onshore drift	$\frac{m^3}{m \cdot yr}$	Triangular	0	1	4

C.3 Model Output

C.3.1 Tabulated Results

Tables C-2 to C-6 show model results for Avoca Beach and Cabarita Beach.

Table C-2 Tabulated Results for Avoca Beach North

Avoca North	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Total Recession									
R_tot [m]	26.1	25.5	1.9	56.6	8.1	37.1	15.8	0.27	2.69
R_pm_py [m3/m/yr]	8.8	8.3	0.5	26.7	3.4	13.4	4.9	0.79	3.60
Components of Recession									
R_S [m3/m/yr]	5.9	5.4	0.2	22.1	3.2	10.4	2.3	0.90	3.73
R_S [m]	17.3	16.6	0.8	46.3	7.7	28.0	7.7	0.44	2.81
R_mrips [m3/m/yr]	1.8	1.8	0.0	3.5	0.7	2.7	0.8	0.00	2.40
R_mrips [m]	5.4	5.3	0.0	16.1	2.4	8.6	2.3	0.34	2.86
R_Q_x_shells [m3/m/yr]	0.8	0.8	-0.2	1.8	0.4	1.4	0.3	-0.10	2.40
R_Q_x_shells [m]	2.6	2.5	-0.9	8.2	1.3	4.3	0.8	0.21	2.76
R_lagoon [m3/m/yr]	0.1	0.1	0.0	0.3	0.1	0.2	0.1	0.19	2.40
R_lagoon [m]	0.5	0.4	0.0	1.4	0.2	0.7	0.2	0.50	2.98
R_overwash [m3/m/yr]	0.1	0.1	0.0	0.2	0.0	0.2	0.0	0.19	2.40
R_overwash [m]	0.3	0.3	0.0	0.9	0.1	0.5	0.1	0.50	2.98
Input Parameters (sample statistics)									
h_star [m]	22.3	21.9	12.0	35.0	4.8	29.1	16.3	0.28	2.40
L_star [m]	1038.0	993.6	431.4	1886.0	329.0	1522.0	628.2	0.37	2.26
S [m/yr]	0.006	0.006	0.000	0.012	0.002	0.009	0.003	0.19	2.40
Q_x_shells [m3/m/yr]	0.8	0.8	-0.2	1.8	0.4	1.4	0.3	-0.10	2.40
V_lagoon [m3/yr]	252	244	16	521	104	398	117	0.19	2.40
V_mrips [m3/yr]	3000	3000	1	5999	1225	4658	1341	0.00	2.40
V_overwash [m3/yr]	168	163	10	348	69	266	78	0.19	2.40

Table C-3 Tabulated Results for Avoca Beach South

Avoca North	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Total Recession									
R_tot [m]	30.4	29.9	1.9	61.4	9.4	43.3	18.4	0.17	2.53
R_pm_py [m3/m/yr]	9.2	8.8	0.6	26.6	3.4	13.8	5.2	0.65	3.32
Components of Recession									
R_S [m3/m/yr]	6.4	5.9	0.2	22.2	3.2	10.8	2.6	0.74	3.40
R_S [m]	20.7	20.0	1.0	49.8	8.8	32.9	9.5	0.28	2.54
R_mrips [m3/m/yr]	1.8	1.8	0.0	3.5	0.7	2.7	0.8	0.00	2.40
R_mrips [m]	6.0	5.8	0.0	18.7	2.7	9.7	2.6	0.41	2.99
R_Q_x_shells [m3/m/yr]	0.8	0.8	-0.2	1.8	0.4	1.4	0.3	-0.10	2.40
R_Q_x_shells [m]	2.8	2.8	-1.0	9.6	1.5	4.8	0.9	0.27	2.87
R_lagoon [m3/m/yr]	0.1	0.1	0.0	0.3	0.1	0.2	0.1	0.19	2.40
R_lagoon [m]	0.5	0.5	0.0	1.6	0.2	0.8	0.2	0.56	3.12
R_overwash [m3/m/yr]	0.1	0.1	0.0	0.2	0.0	0.2	0.0	0.19	2.40
R_overwash [m]	0.3	0.3	0.0	1.1	0.2	0.5	0.1	0.56	3.12
Input Parameters (sample statistics)									
h_star [m]	22.3	21.9	12.0	35.0	4.8	29.1	16.3	0.28	2.40
L_star [m]	1113.0	1091.0	485.3	1906.0	293.5	1523.0	732.7	0.22	2.35
S [m/yr]	0.006	0.006	0.000	0.012	0.002	0.009	0.003	0.19	2.40
Q_x_shells [m3/m/yr]	0.8	0.8	-0.2	1.8	0.4	1.4	0.3	-0.10	2.40
V_lagoon [m3/yr]	252	244	16	521	104	398	117	0.19	2.40
V_mrips [m3/yr]	3000	3000	1	5997	1225	4659	1342	0.00	2.40
V_overwash [m3/yr]	168	163	11	348	69	266	78	0.19	2.40

Table C-4 Tabulated Results for Cabarita Beach North

Cabarita North	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Total Recession									
R_tot [m]	29.5	28.6	-4.7	101.8	10.9	43.5	16.4	0.61	3.87
R_pm_py [m3/m/yr]	12.5	11.6	-1.6	57.0	5.7	19.6	6.4	1.26	5.74
Components of Recession									
R_S [m3/m/yr]	7.3	6.0	0.2	46.6	5.0	13.6	2.6	1.84	7.70
R_S [m]	16.8	15.0	0.7	83.2	9.4	28.7	6.9	1.39	5.99
R_Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40
R_Q_y [m]	16.8	16.1	2.1	45.7	6.8	26.2	8.4	0.46	2.81
R_Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.8	-0.6	-2.9	-0.42	2.40
R_Q_x [m]	-4.1	-3.7	-13.4	0.0	2.2	-1.5	-7.2	-0.58	2.80
Input Parameters (sample statistics)									
h_star [m]	22.3	21.9	12.0	35.0	4.8	29.1	16.3	0.28	2.40
L_star [m]	1274	1045	529	4026	638	2220	711	1.57	5.15
S [m/yr]	0.006	0.006	0.000	0.012	0.002	0.009	0.003	0.19	2.40
Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.8	-0.6	-2.9	-0.42	2.40
Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40

Table C-5 Tabulated Results for Cabarita Beach Centre

Cabarita Centre	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Total Recession									
R_tot [m]	28.4	27.8	-3.9	84.0	10.0	41.6	16.0	0.40	3.19
R_pm_py [m3/m/yr]	13.6	12.8	-1.7	51.5	5.6	20.9	7.1	0.89	4.30
Components of Recession									
R_S [m3/m/yr]	8.4	7.3	0.3	41.1	4.9	14.9	3.2	1.30	5.29
R_S [m]	17.2	16.0	0.7	66.9	8.6	28.7	7.3	0.89	4.05
R_Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40
R_Q_y [m]	14.8	14.2	1.9	38.5	5.9	23.0	7.5	0.42	2.72
R_Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.8	-0.6	-2.9	-0.42	2.40
R_Q_x [m]	-3.6	-3.3	-11.3	0.0	1.9	-1.3	-6.3	-0.55	2.71
Input Parameters (sample statistics)									
h_star [m]	22.3	21.9	12.0	35.0	4.8	29.1	16.3	0.28	2.40
L_star [m]	1461	1310	639	3563	563	2301	869	1.05	3.60
S [m/yr]	0.006	0.006	0.000	0.012	0.002	0.009	0.003	0.19	2.40
Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.8	-0.6	-2.9	-0.42	2.40
Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40

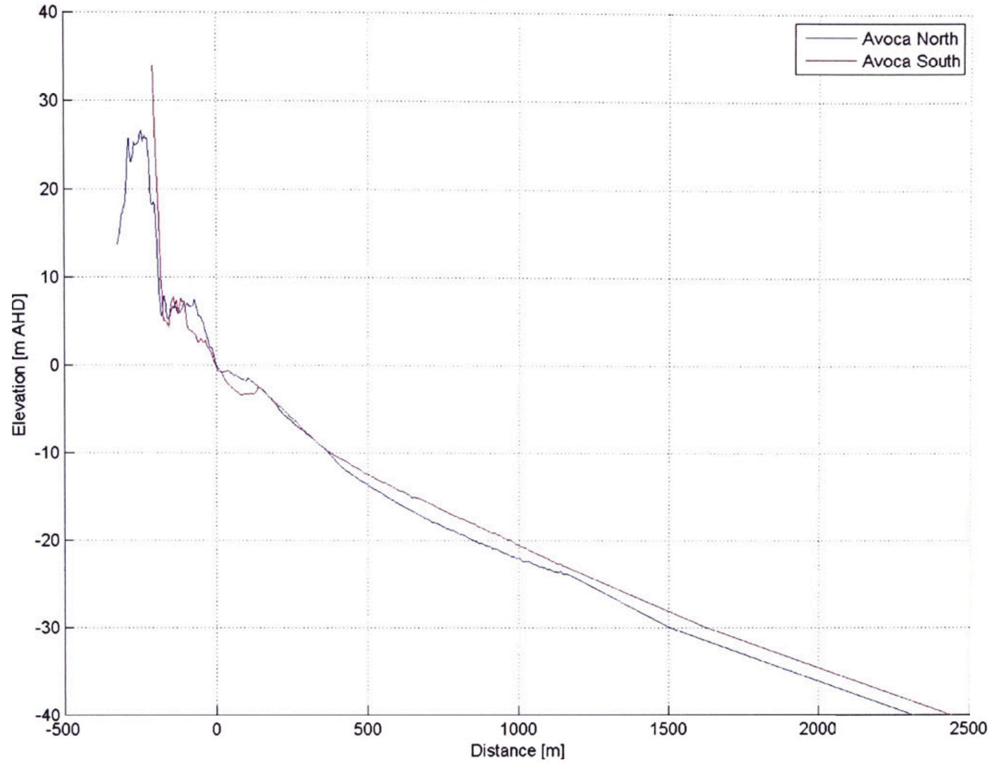
Table C-6 Tabulated Results for Cabarita Beach South

Cabarita South	Mean	Median	Min	Max	std	90%ile	10%ile	Skewness	Kurtosis
Total Recession									
R_tot [m]	37.9	37.4	-4.4	93.8	12.6	54.6	21.9	0.19	2.74
R_pm_py [m3/m/yr]	15.0	14.4	-1.5	49.9	5.7	22.6	8.2	0.65	3.66
Components of Recession									
R_S [m3/m/yr]	9.8	9.0	0.3	40.5	5.0	16.5	4.1	0.93	4.15
R_S [m]	24.4	23.4	1.1	75.4	10.7	39.1	11.0	0.43	2.90
R_Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40
R_Q_y [m]	17.8	17.0	2.2	49.0	7.2	27.8	8.9	0.48	2.86
R_Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.9	-0.6	-2.9	-0.42	2.40
R_Q_x [m]	-4.3	-4.0	-14.3	0.0	2.3	-1.6	-7.6	-0.60	2.85
Input Parameters (sample statistics)									
h_star [m]	22.3	21.9	12.0	35.0	4.8	29.1	16.3	0.28	2.40
L_star [m]	1713	1622	810	3499	481	2400	1167	0.82	3.40
S [m/yr]	0.006	0.006	0.000	0.012	0.002	0.009	0.003	0.19	2.40
Q_x [m3/m/yr]	-1.7	-1.6	-4.0	0.0	0.9	-0.6	-2.9	-0.42	2.40
Q_y [m3/m/yr]	6.9	6.6	1.1	13.7	2.6	10.6	3.5	0.26	2.40

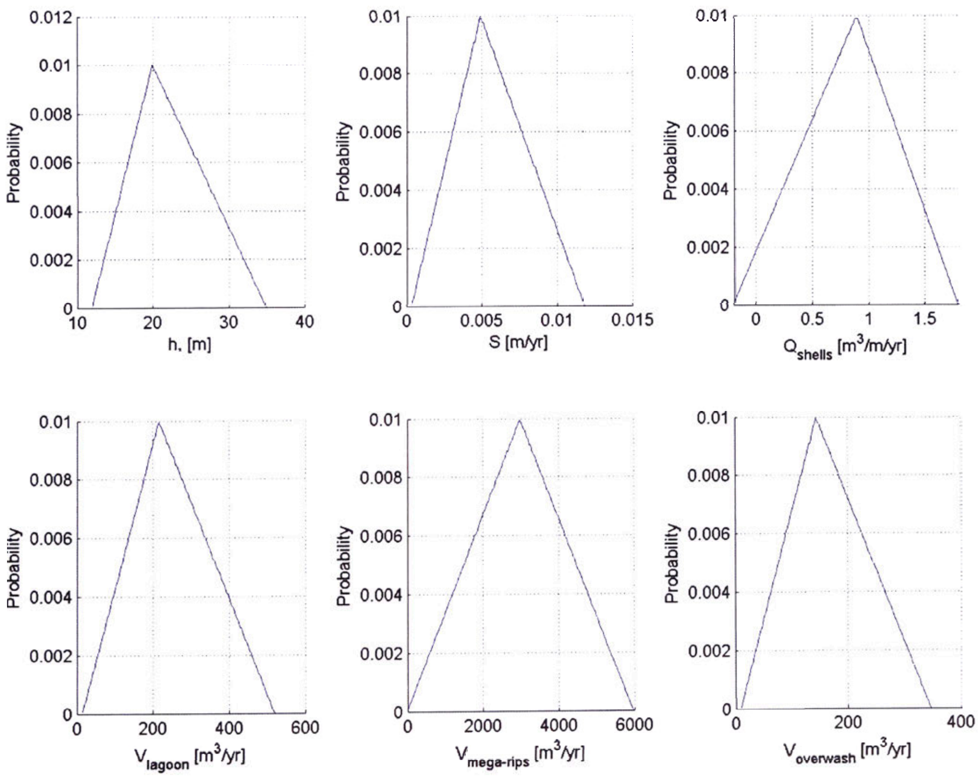
C.3.2 Plots

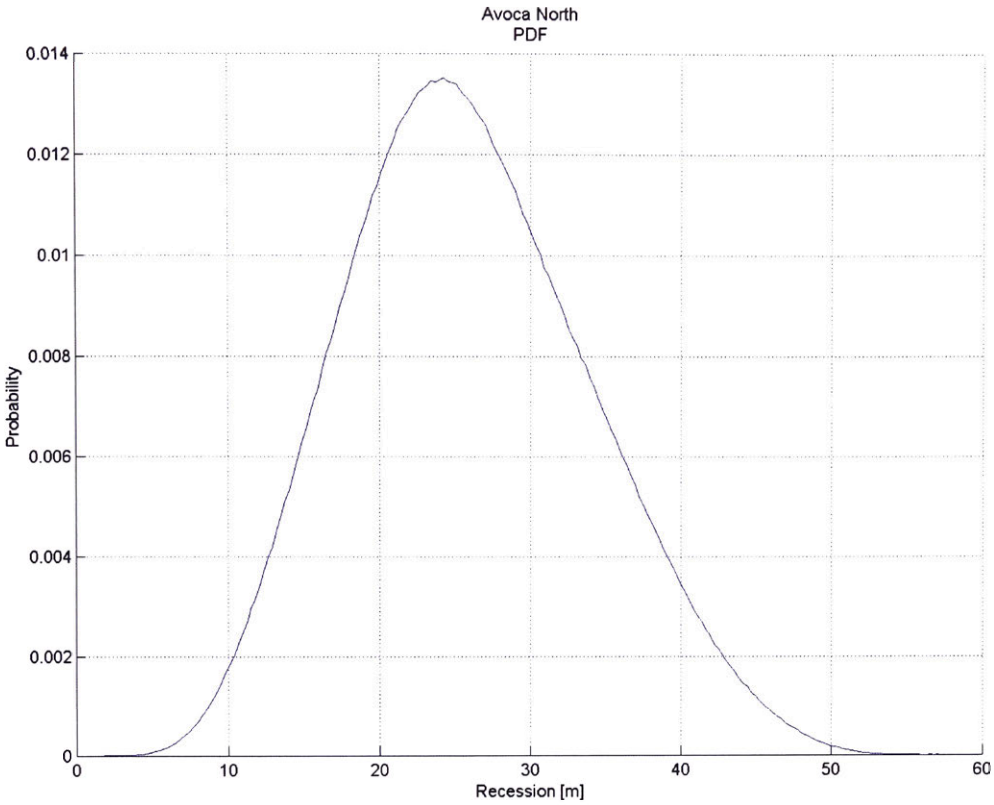
The figures below show plots of model results for Avoca and Cabarita Beach.

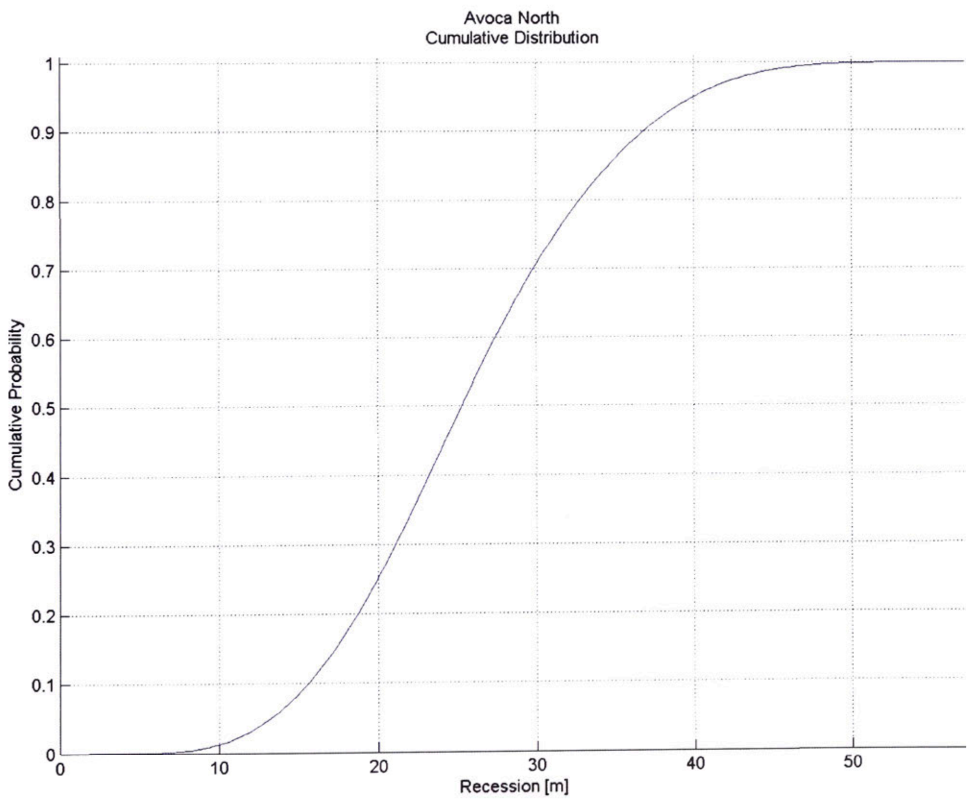
Avoca Beach: Representative Profiles

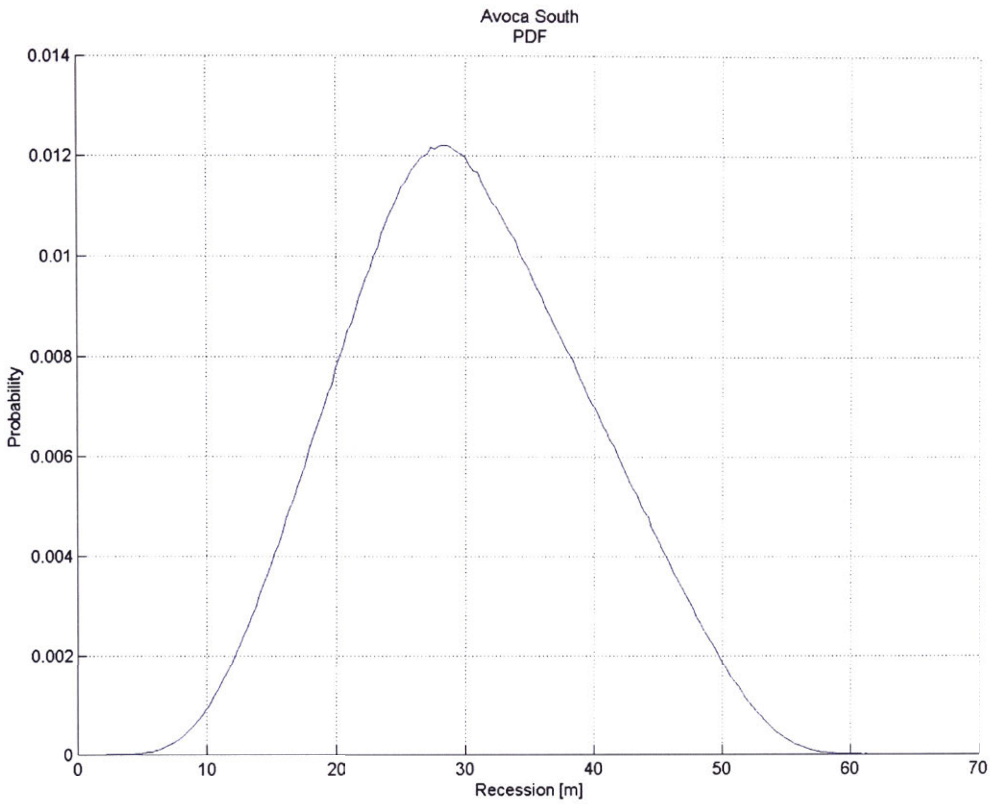


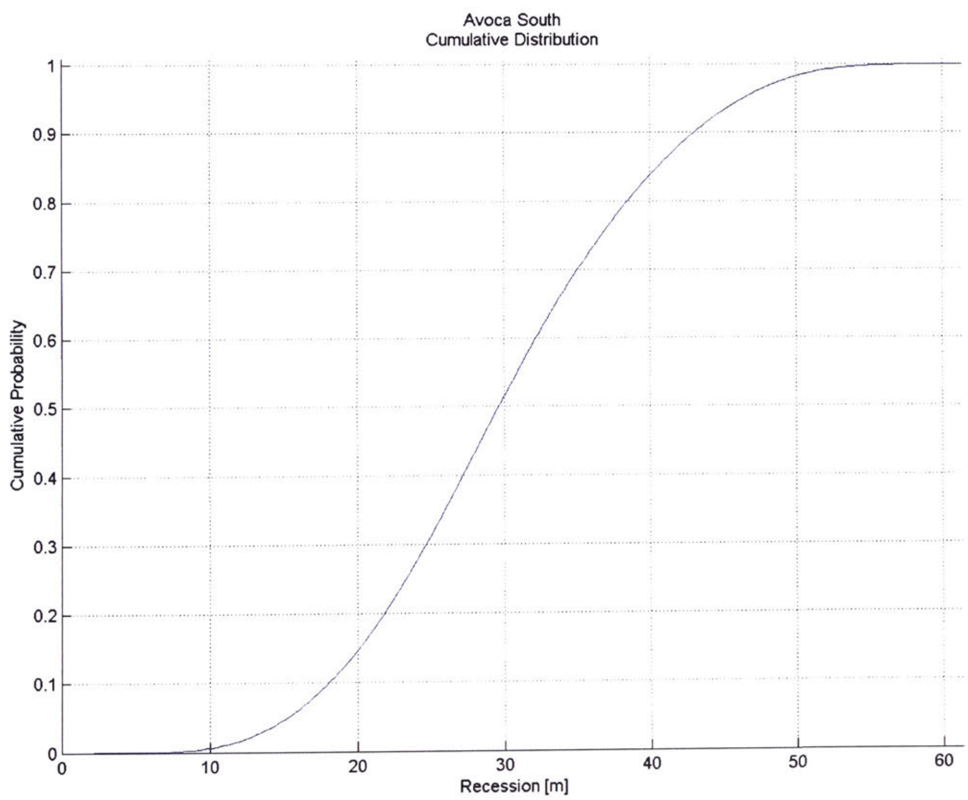
Avoca Beach: Input Variables PDFs

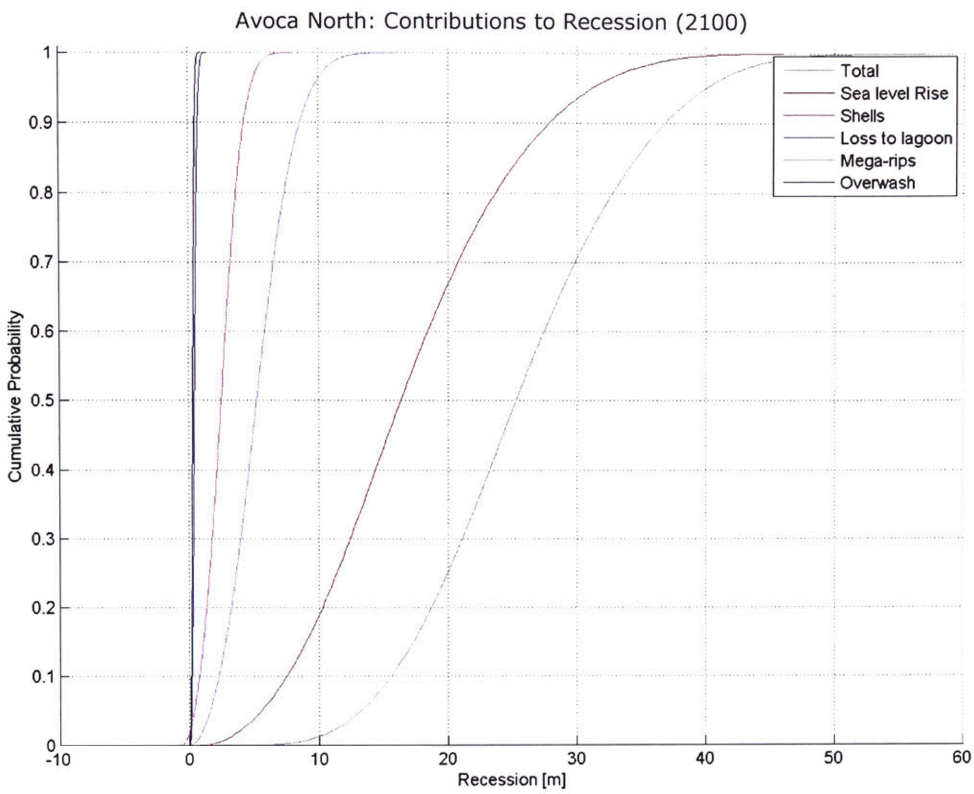


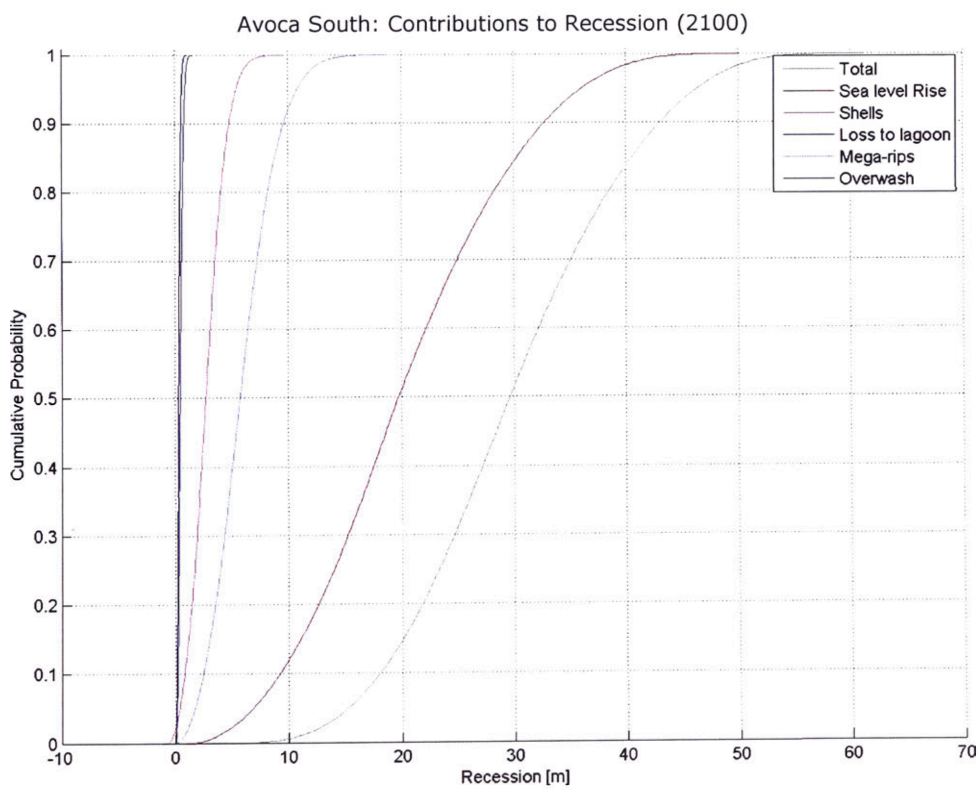

Avoca North
PDF
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Probability
0
10
20
30
40
50
60
Recession [m]

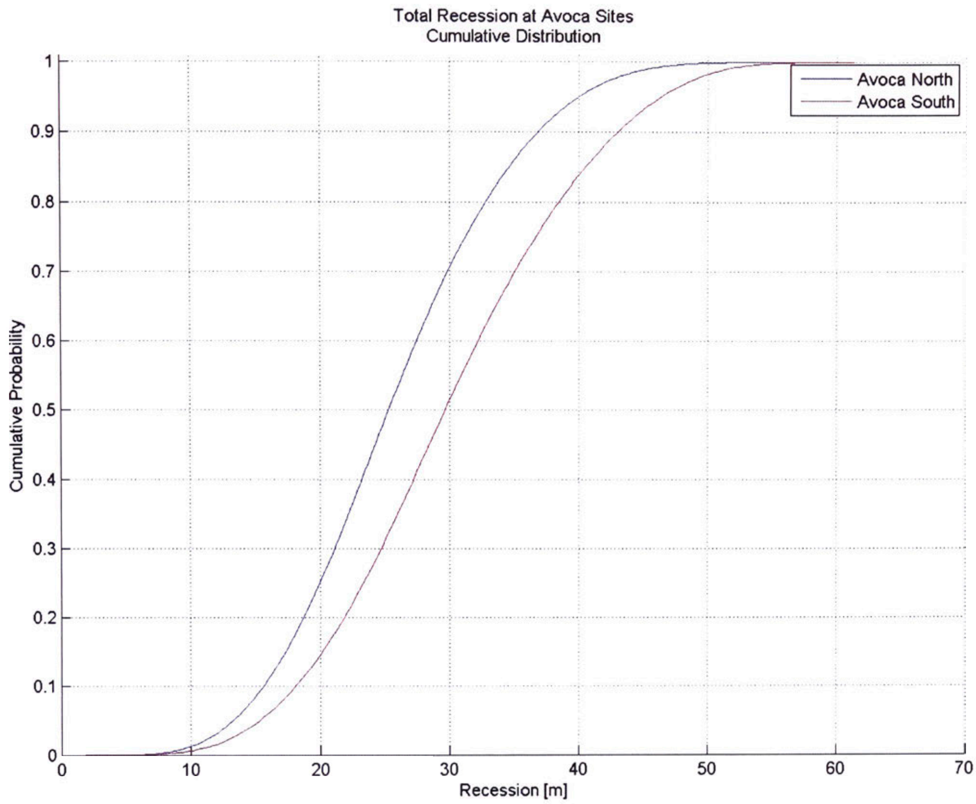

Avoca North
Cumulative Distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative Probability
0
10
20
30
40
50
Recession [m]

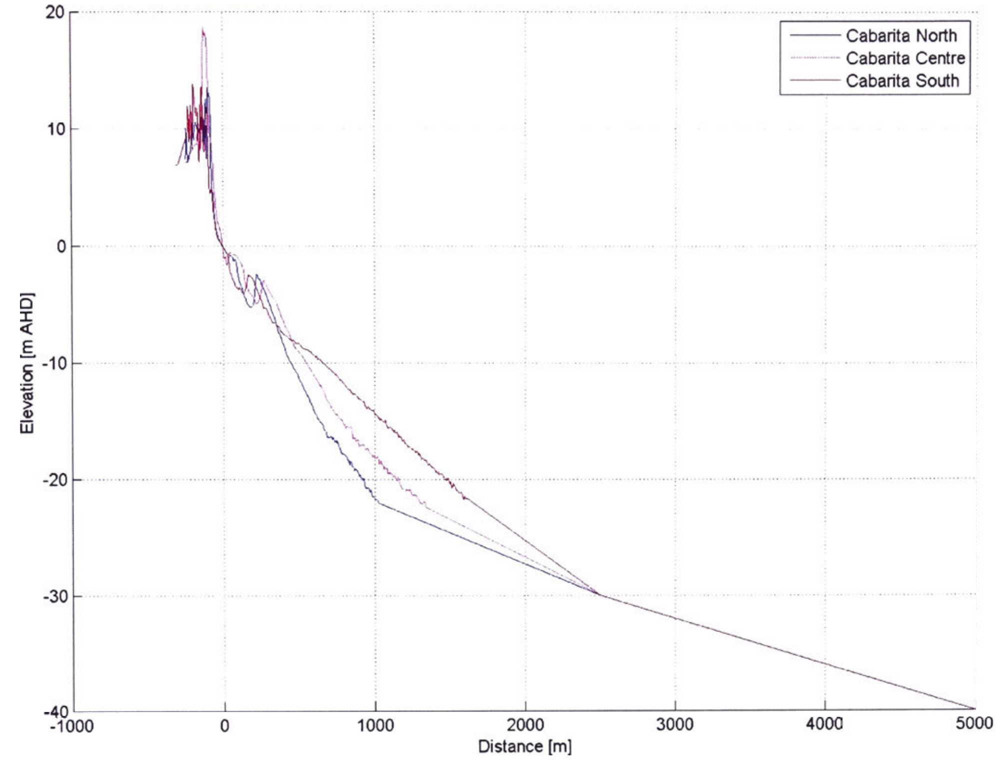

Avoca South
PDF
Probability
Recession [m]
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
0
10
20
30
40
50
60
70

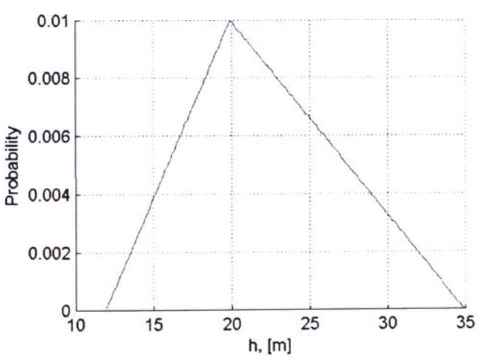

Avoca South
Cumulative Distribution
Cumulative Probability
Recession [m]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60

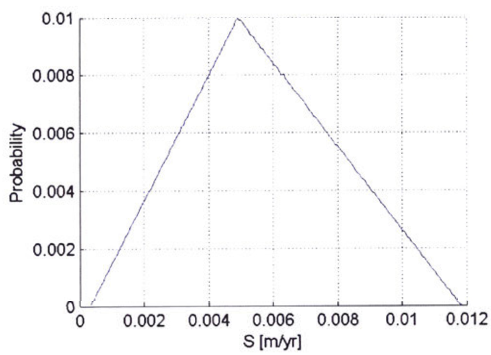

Avoca North: Contributions to Recession (2100)
Total
Sea level Rise
Shells
Loss to lagoon
Mega-rips
Overwash
Cumulative Probability
Recession [m]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-10
0
10
20
30
40
50
60

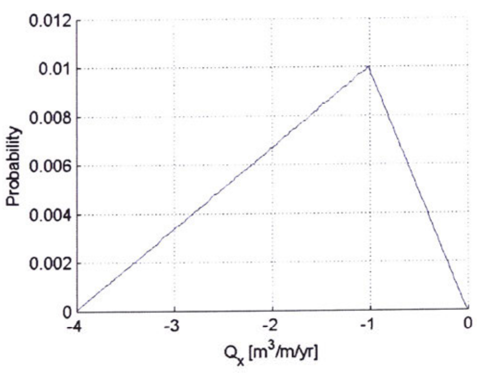

Avoca South: Contributions to Recession (2100)
Total
Sea level Rise
Shells
Loss to lagoon
Mega-rips
Overwash
Cumulative Probability
Recession [m]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-10
0
10
20
30
40
50
60
70

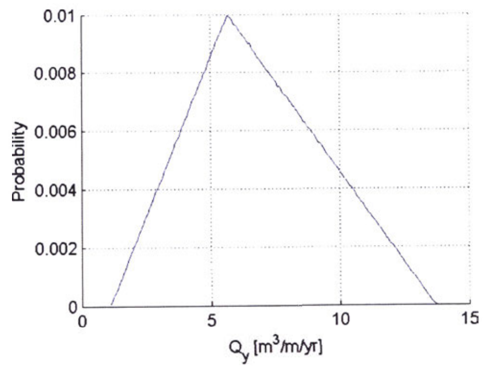

Total Recession at Avoca Sites
Cumulative Distribution
Avoca North
Avoca South
Cumulative Probability
Recession [m]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70

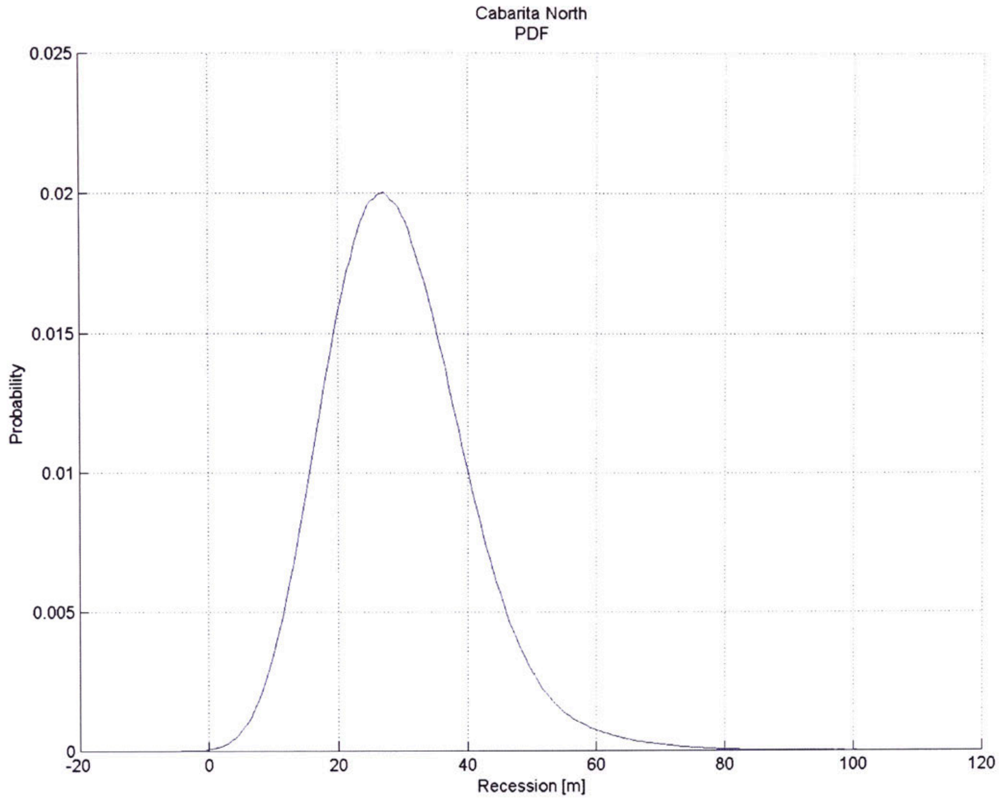

Cabarita North
Cabarita Centre
Cabarita South
Elevation [m AHD]
Distance [m]
20
10
0
-10
-20
-30
-40
-1000
0
1000
2000
3000
4000
5000

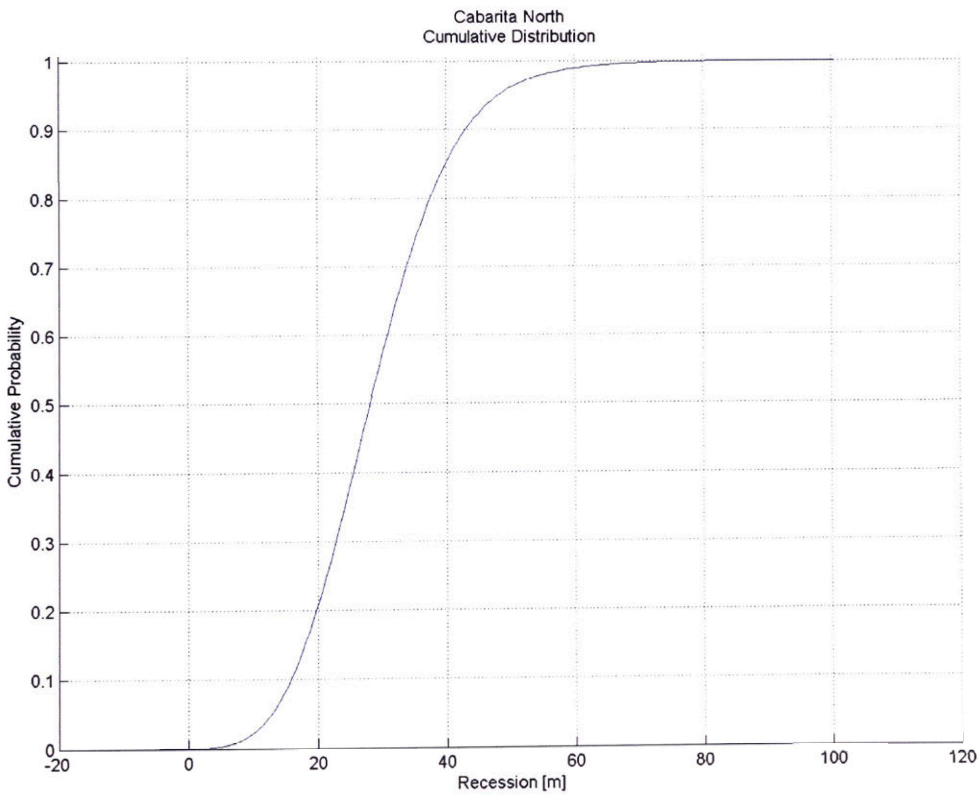

Probability
h, [m]
0.01
0.008
0.006
0.004
0.002
0
10
15
20
25
30
35

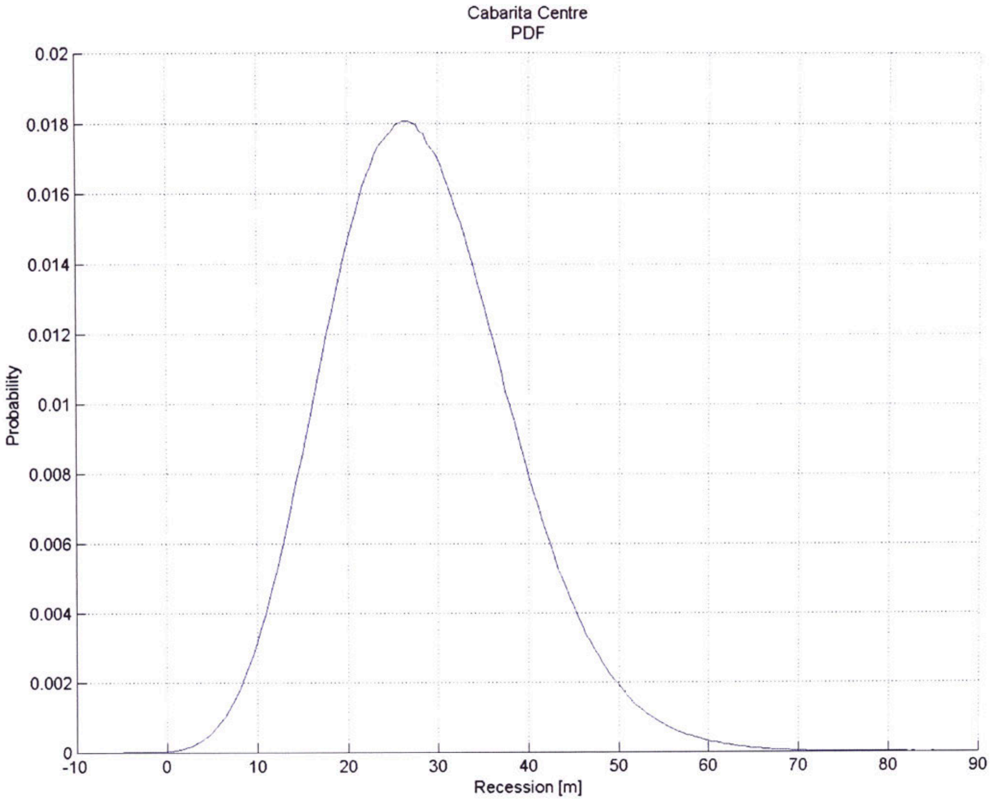

Probability
S [m/yr]
0.01
0.008
0.006
0.004
0.002
0
0
0.002
0.004
0.006
0.008
0.01
0.012

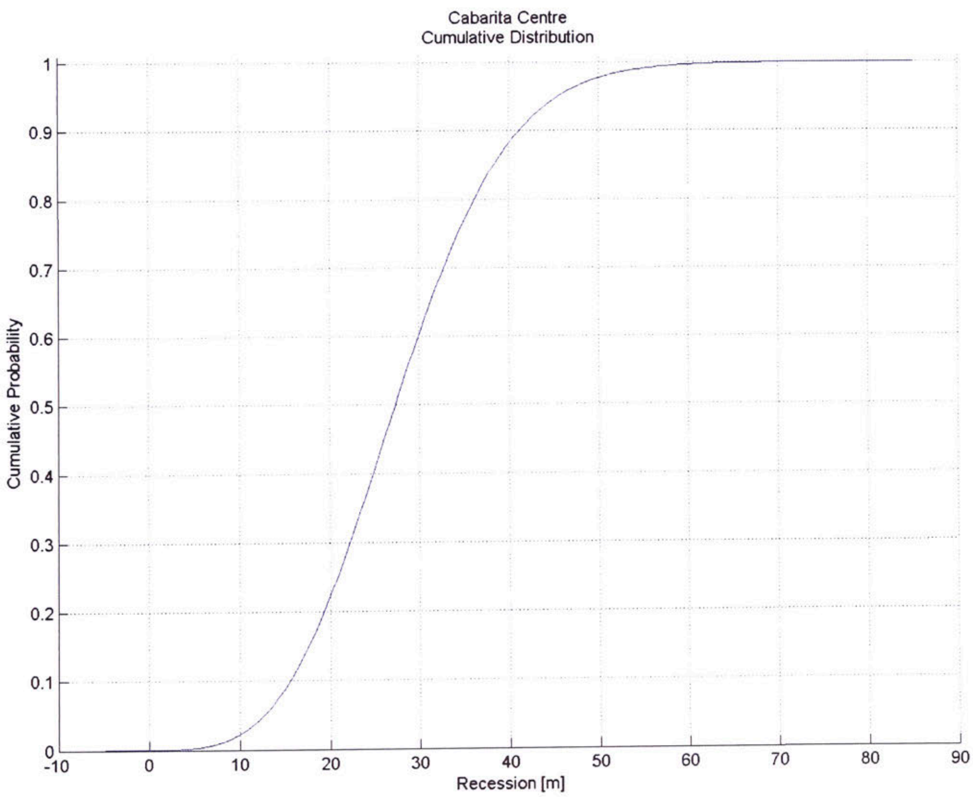

Probability
Q_x [m³/m/yr]
0.012
0.01
0.008
0.006
0.004
0.002
0
-4
-3
-2
-1
0

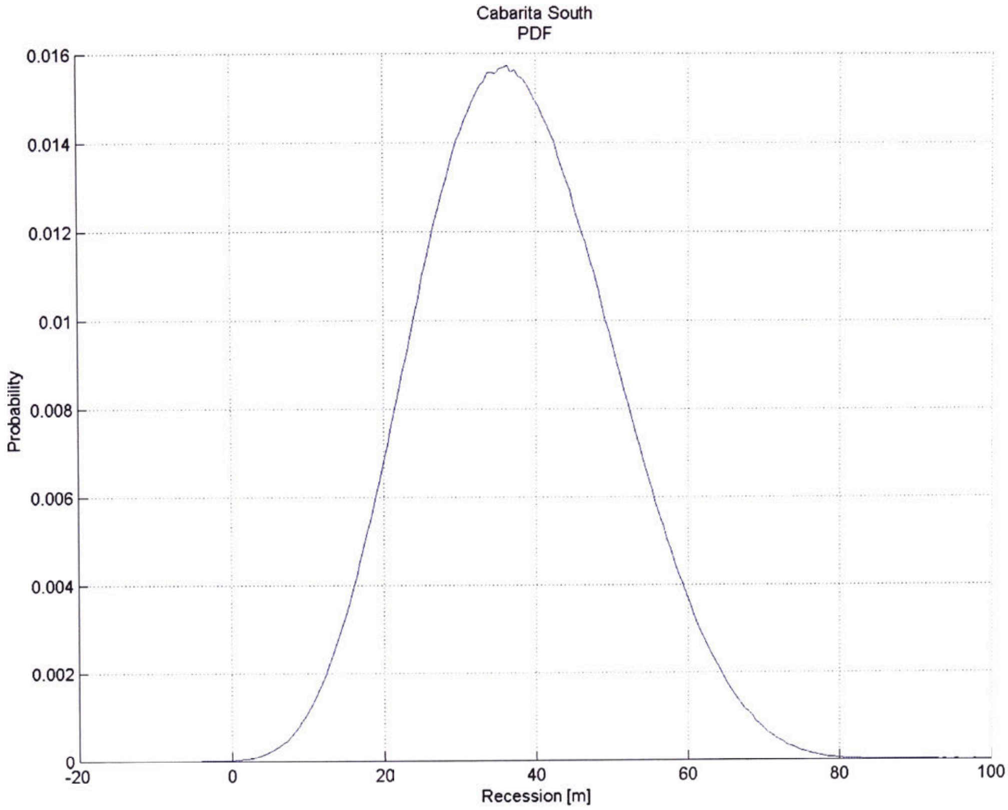

Probability
Qy [m3/m/yr]
0.01
0.008
0.006
0.004
0.002
0
0
5
10
15

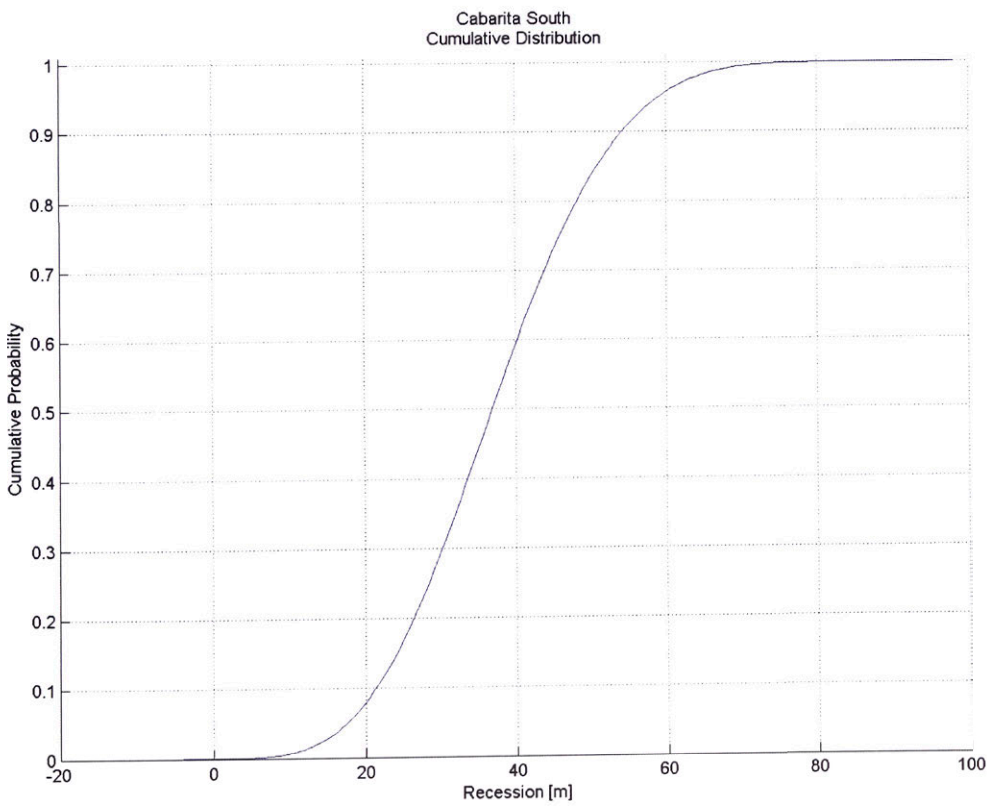

Cabarita North
PDF
0.025
0.02
0.015
0.01
0.005
0
Probability
-20
0
20
40
60
80
100
120
Recession [m]

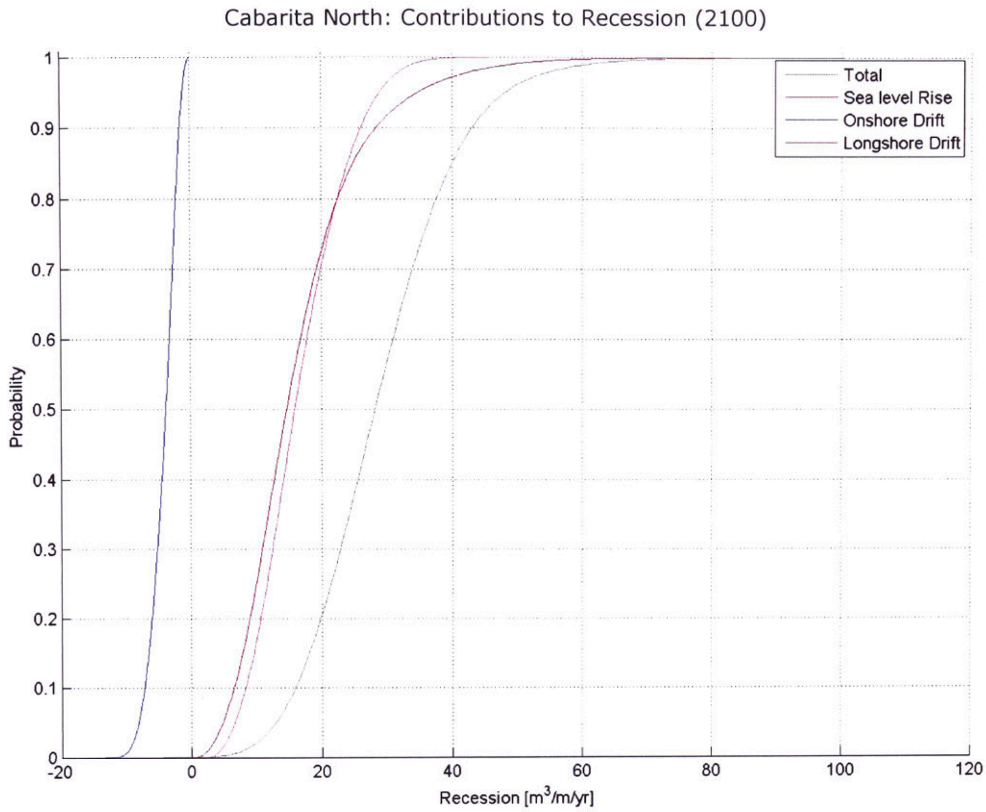

Cabarita North
Cumulative Distribution
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cumulative Probability
-20
0
20
40
60
80
100
120
Recession [m]

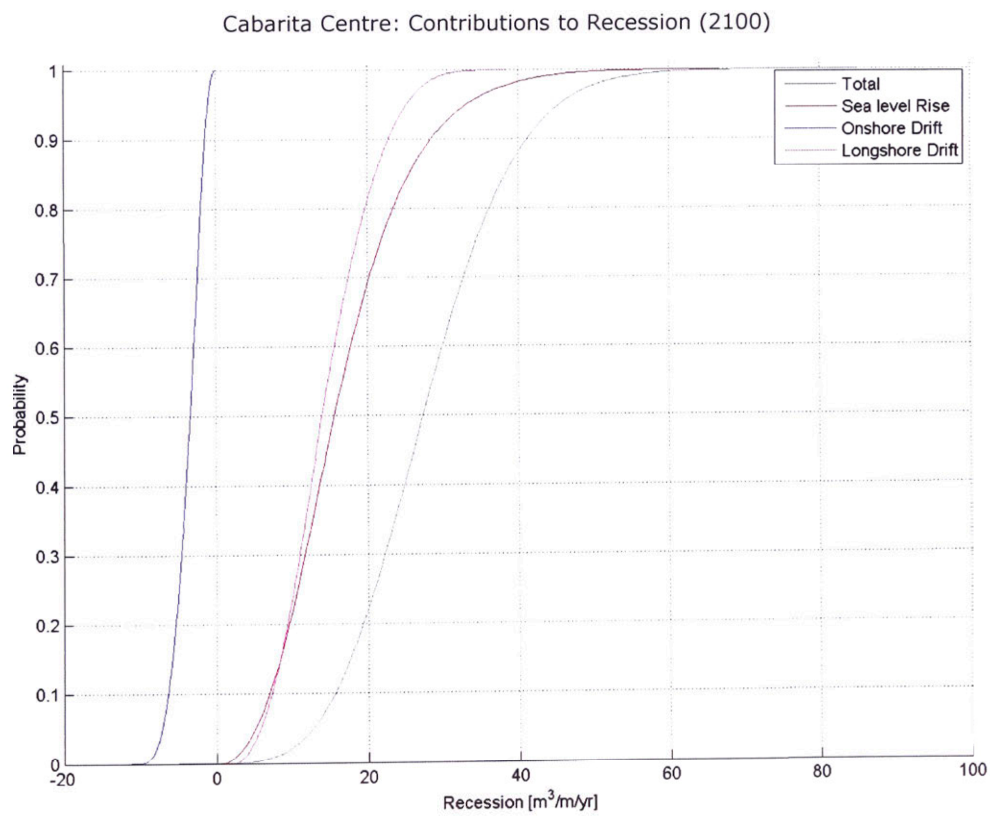

Cabarita Centre
PDF
Probability
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-10
0
10
20
30
40
50
60
70
80
90
Recession [m]

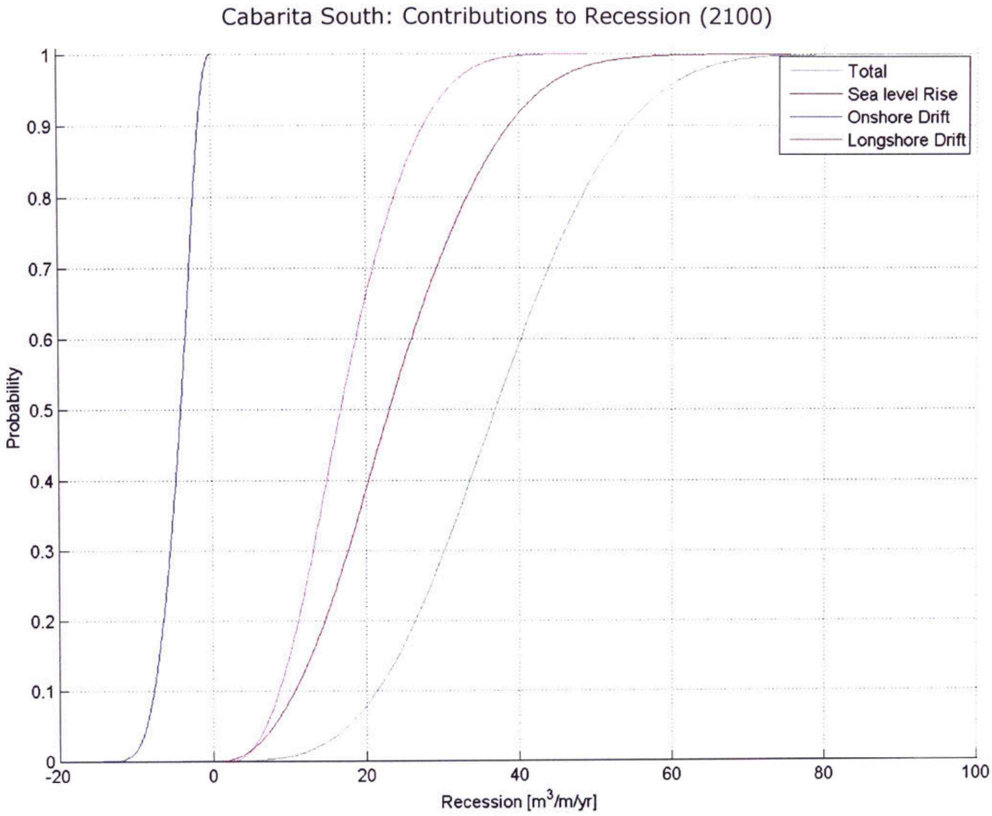

Cabarita Centre
Cumulative Distribution
Cumulative Probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-10
0
10
20
30
40
50
60
70
80
90
Recession [m]

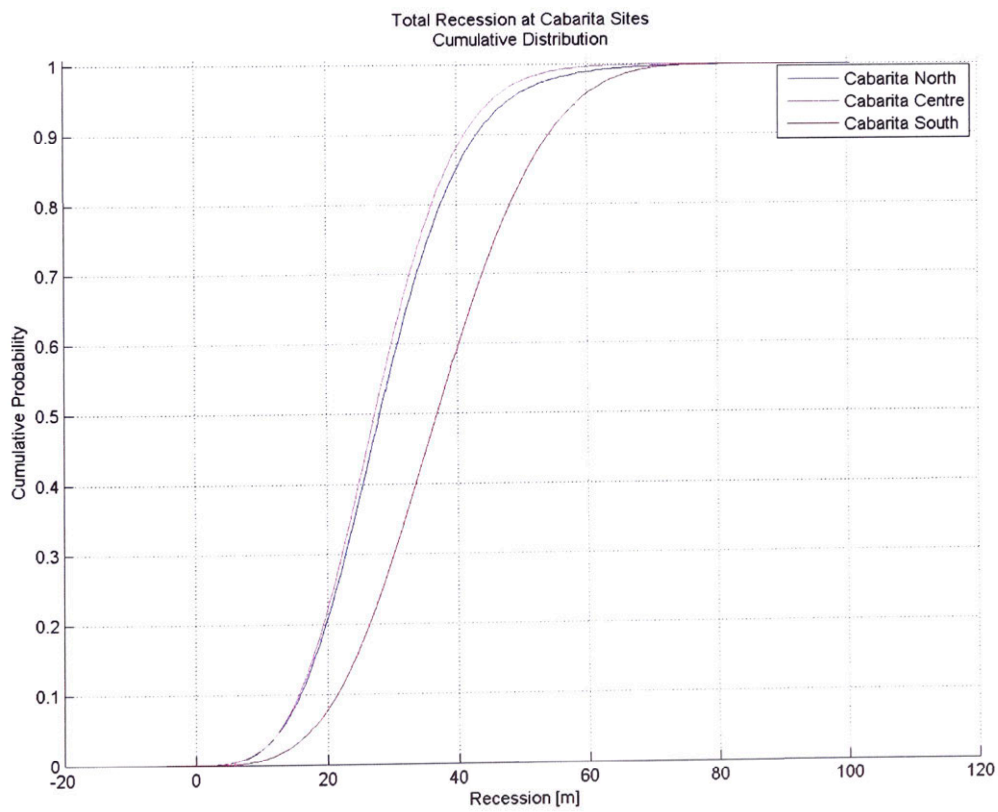

Cabarita South
PDF
Probability
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-20
0
20
40
60
80
100
Recession [m]


Cabarita South
Cumulative Distribution
Cumulative Probability
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-20
0
20
40
60
80
100
Recession [m]

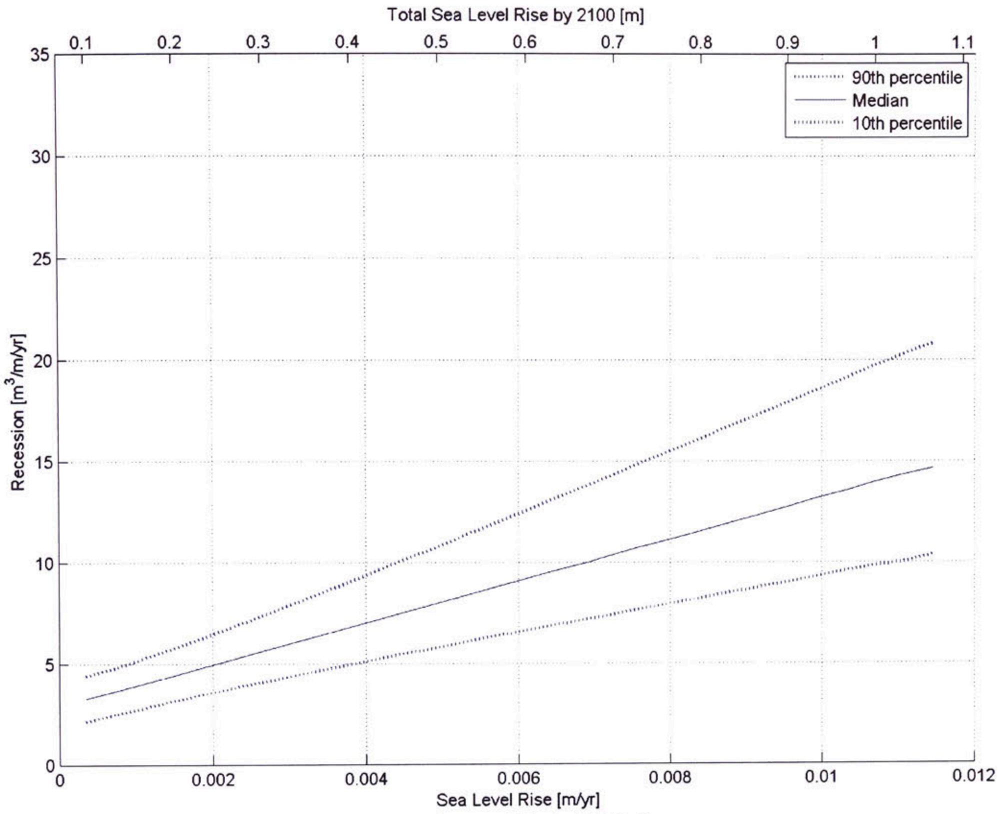

Cabarita North: Contributions to Recession (2100)
Total
Sea level Rise
Onshore Drift
Longshore Drift
Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20
0
20
40
60
80
100
120
Recession [m³/m/yr]

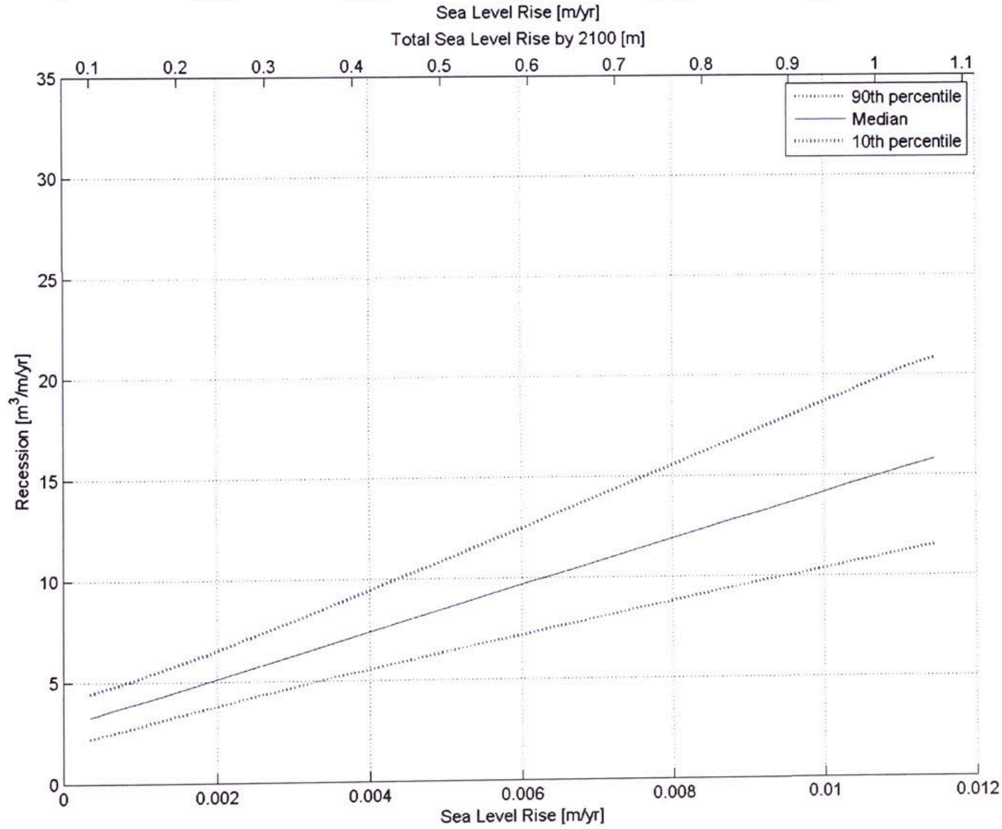

Cabarita Centre: Contributions to Recession (2100)
Total
Sea level Rise
Onshore Drift
Longshore Drift
Probability
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20
0
20
40
60
80
100
Recession [m³/m/yr]


Cabarita South: Contributions to Recession (2100)
Total
Sea level Rise
Onshore Drift
Longshore Drift
Probability
Recession [m^3/m/yr]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20
0
20
40
60
80
100

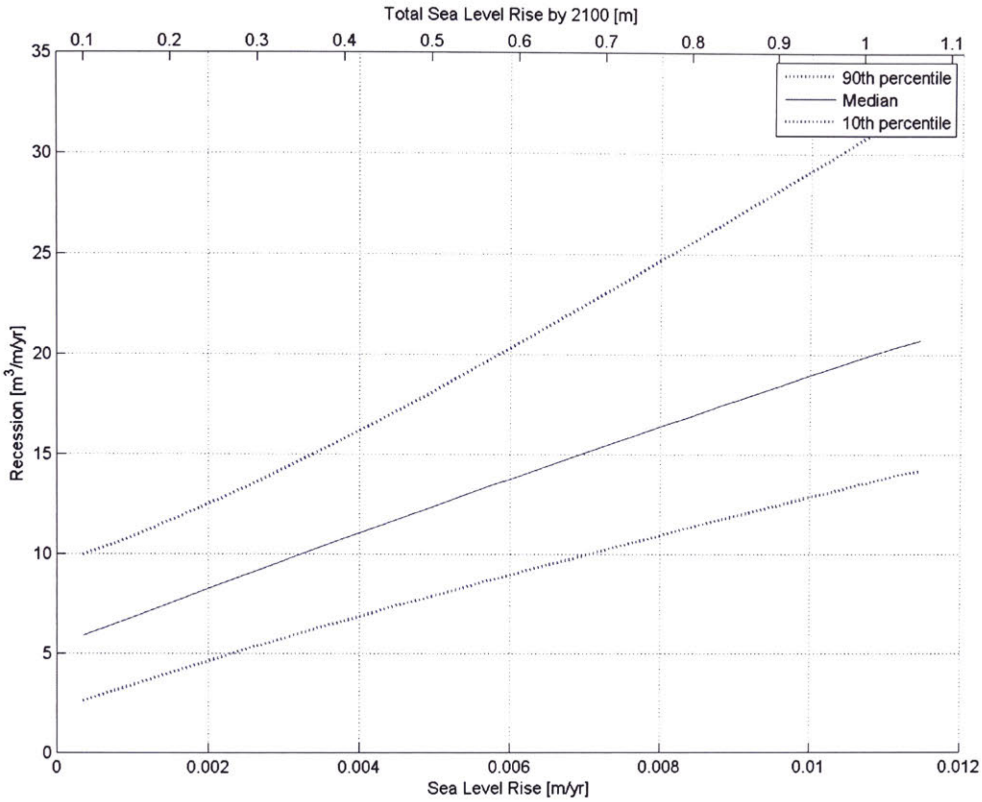

Total Recession at Cabarita Sites
Cumulative Distribution
Cabarita North
Cabarita Centre
Cabarita South
Cumulative Probability
Recession [m]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
-20
0
20
40
60
80
100
120

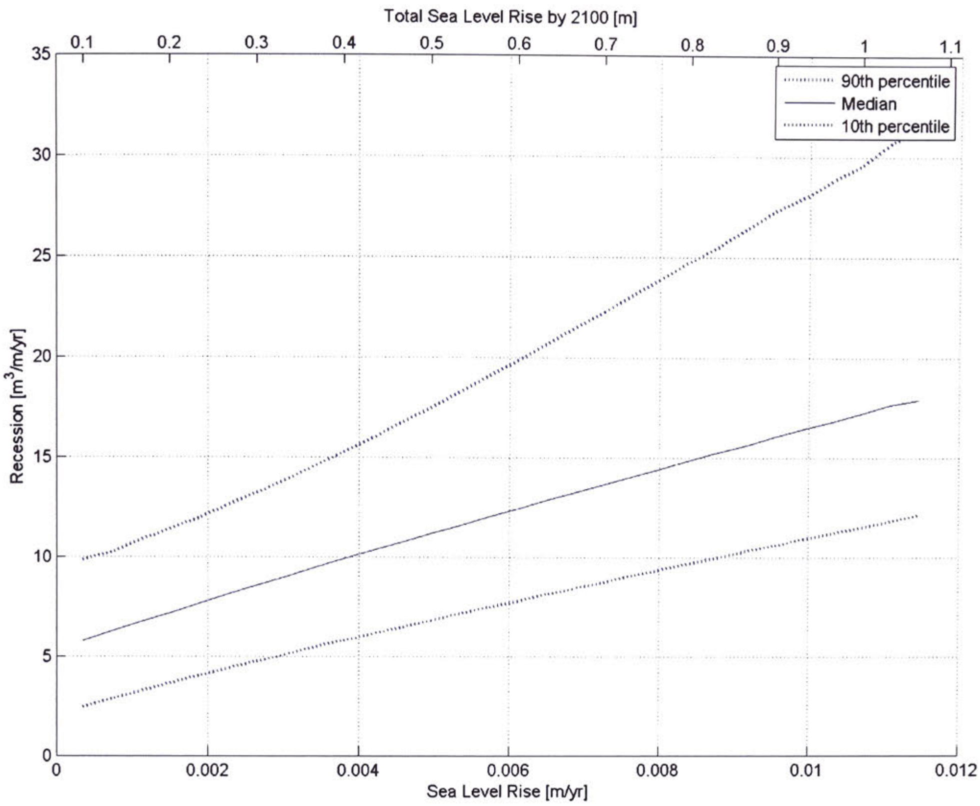
Avoca North (upper plot) and South (lower plot): Recession Against SLR scenario

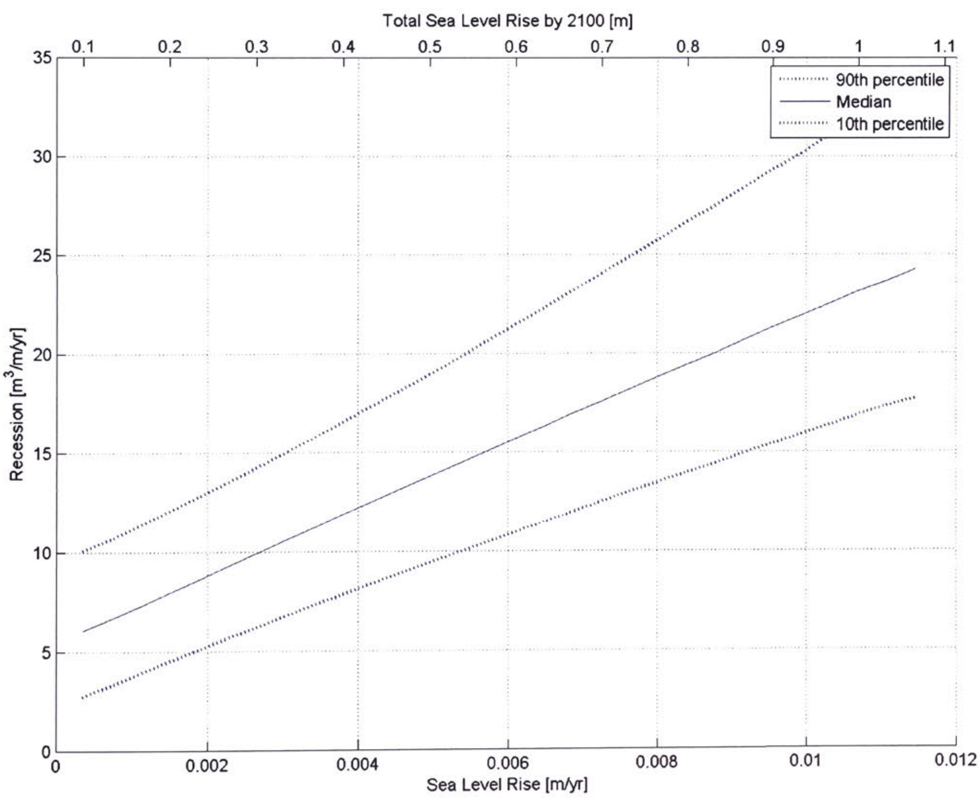




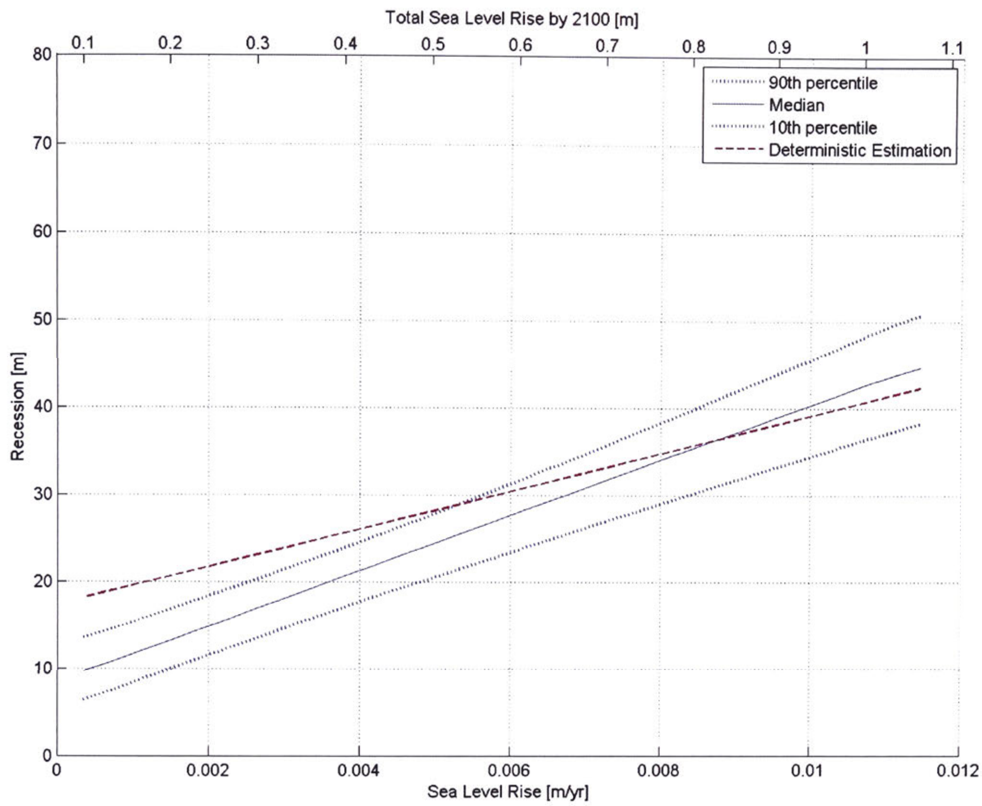
Cabarita Centre, North and South: Recession Against SLR scenario

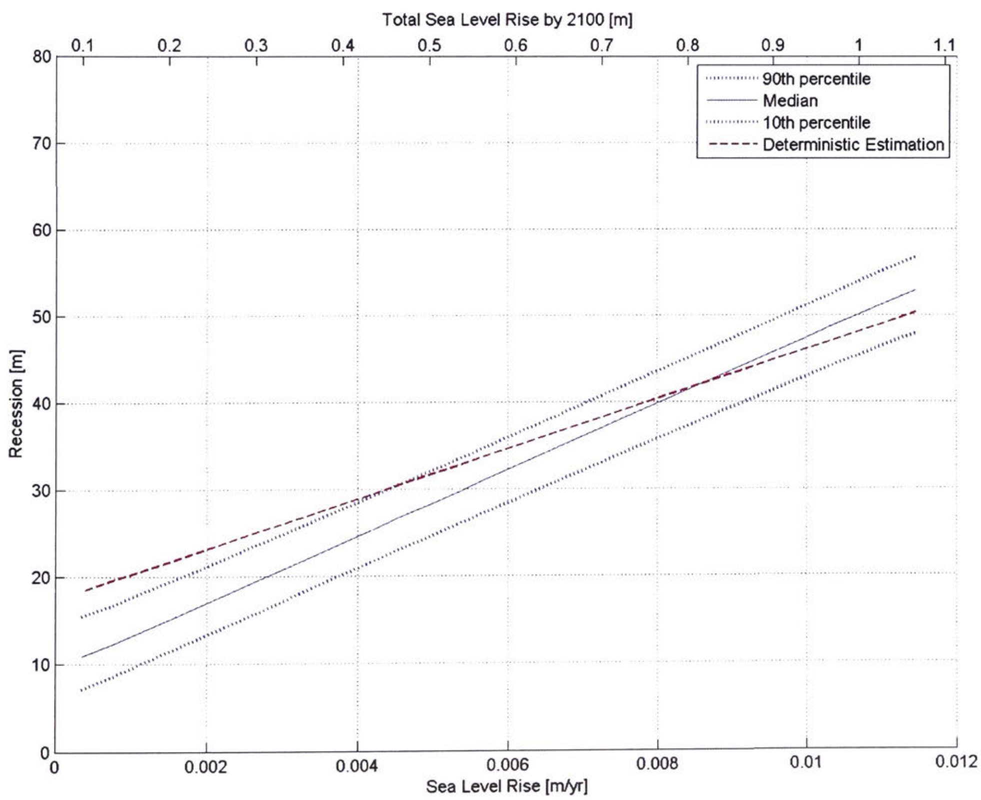



Total Sea Level Rise by 2100 [m]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
90th percentile
Median
10th percentile
Recession [m^3/m/yr]
0
5
10
15
20
25
30
35
0
0.002
0.004
0.006
0.008
0.01
0.012
Sea Level Rise [m/yr]

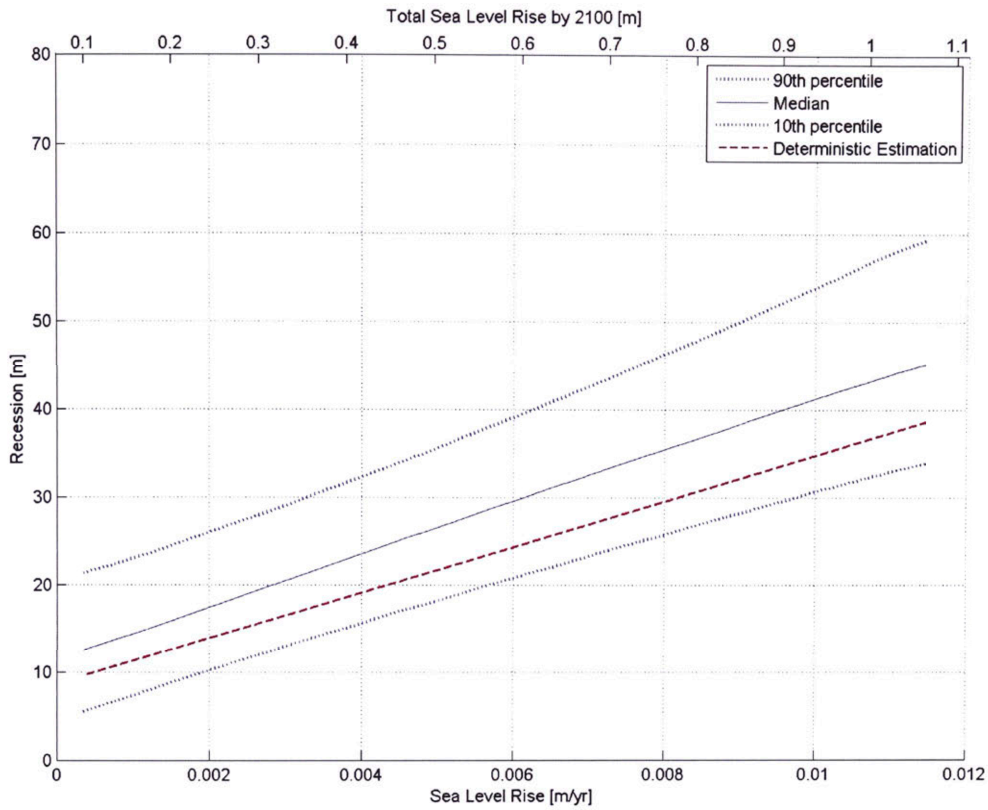

Total Sea Level Rise by 2100 [m]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
90th percentile
Median
10th percentile
Recession [m^3/m/yr]
0
5
10
15
20
25
30
35
0
0.002
0.004
0.006
0.008
0.01
0.012
Sea Level Rise [m/yr]

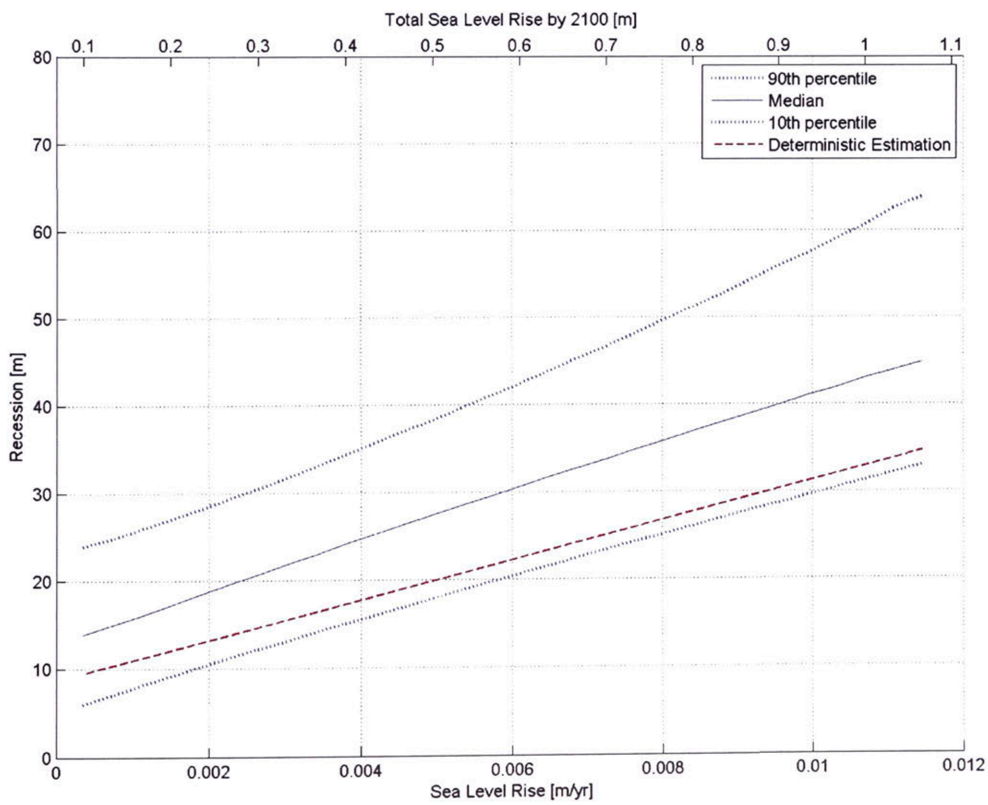
Avoca North and South: Probabilistic Vs Deterministic

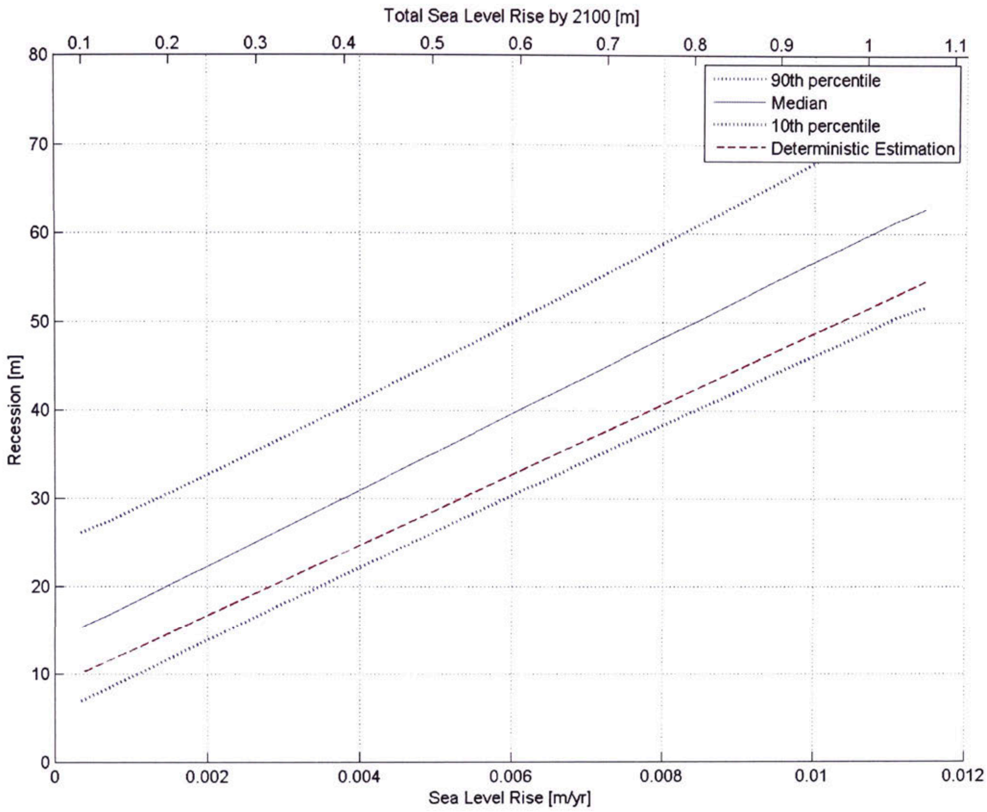




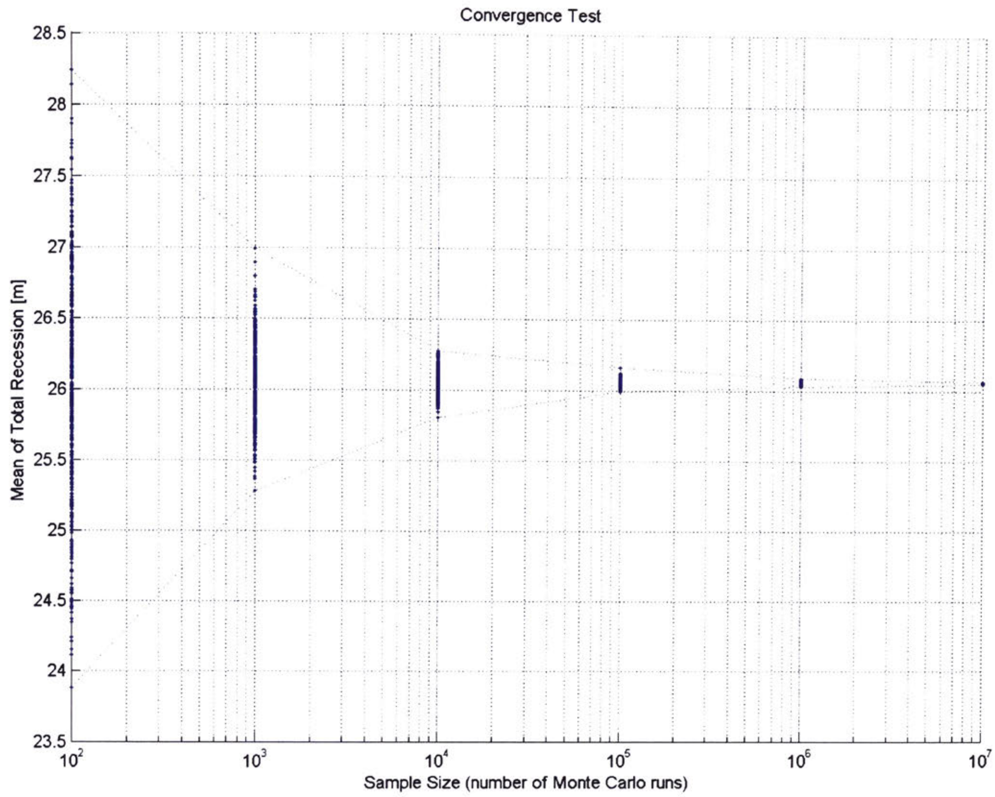
Cabarita Centre, North and South: Probabilistic Vs Deterministic



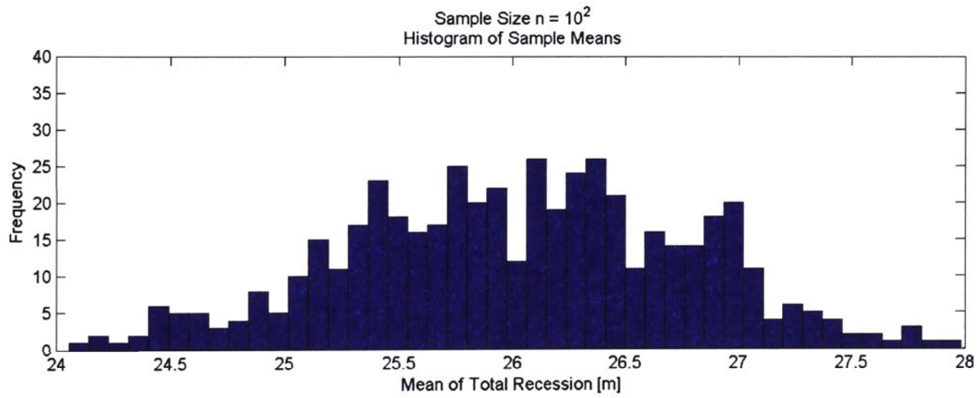



Total Sea Level Rise by 2100 [m]
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
90th percentile
Median
10th percentile
Deterministic Estimation
Recession [m]
0
10
20
30
40
50
60
70
80
0
0.002
0.004
0.006
0.008
0.01
0.012
Sea Level Rise [m/yr]

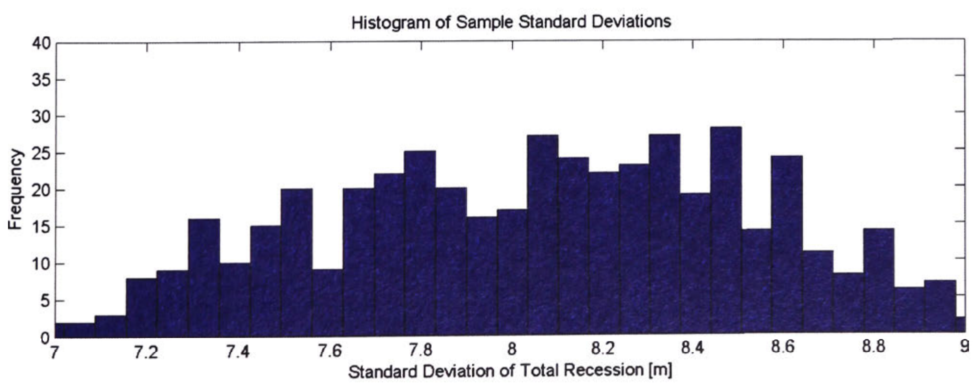
Avoca North



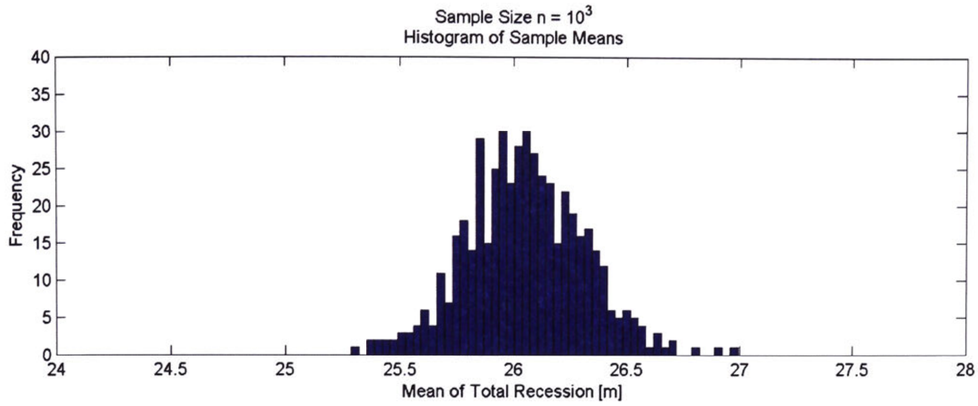
Convergence Test
Mean of Total Recession [m]
Sample Size (number of Monte Carlo runs)

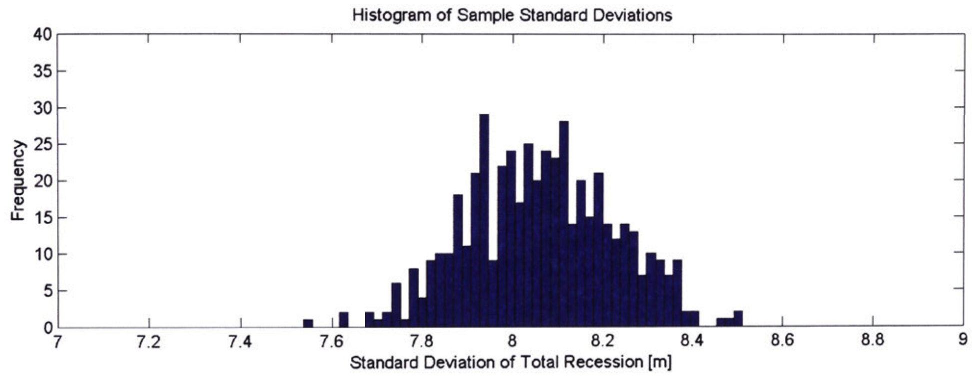


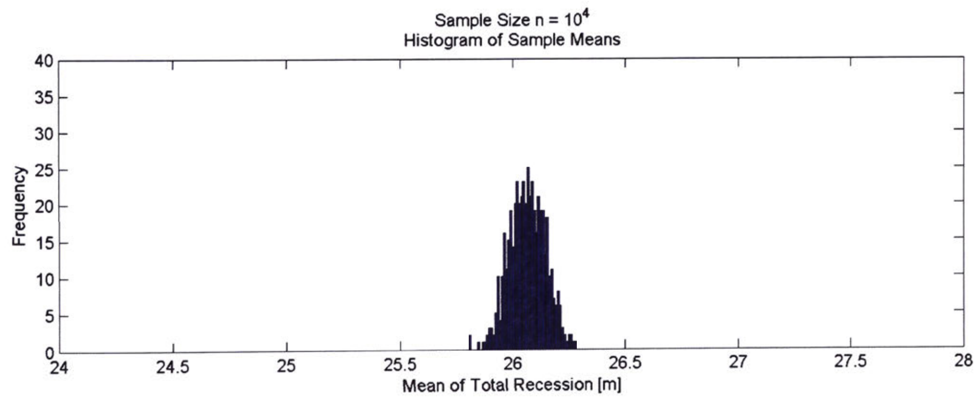
Sample Size n = 10^2
Histogram of Sample Means
Frequency
Mean of Total Recession [m]

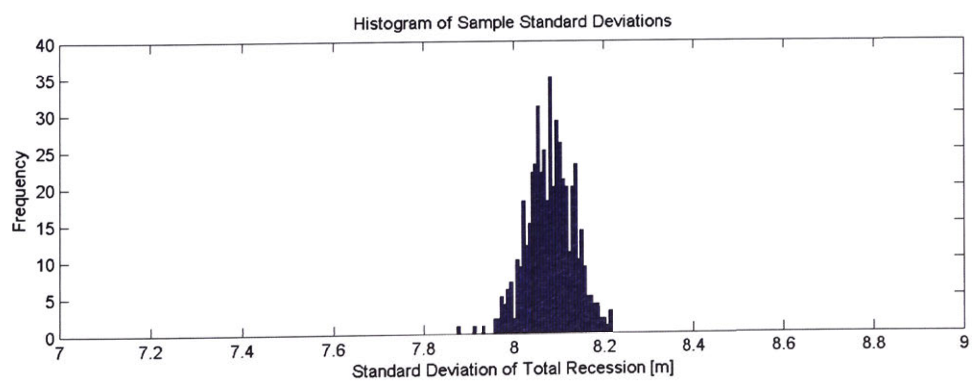


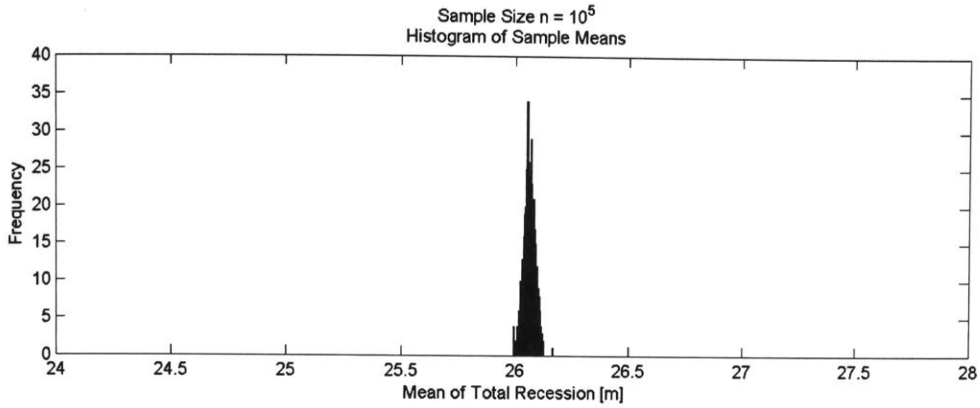
Histogram of Sample Standard Deviations
Frequency
Standard Deviation of Total Recession [m]

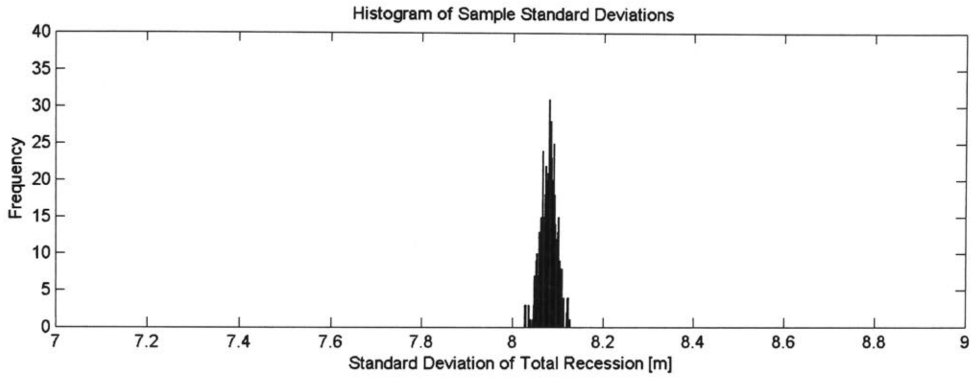

Sample Size n = 10^3
Histogram of Sample Means
Frequency
Mean of Total Recession [m]

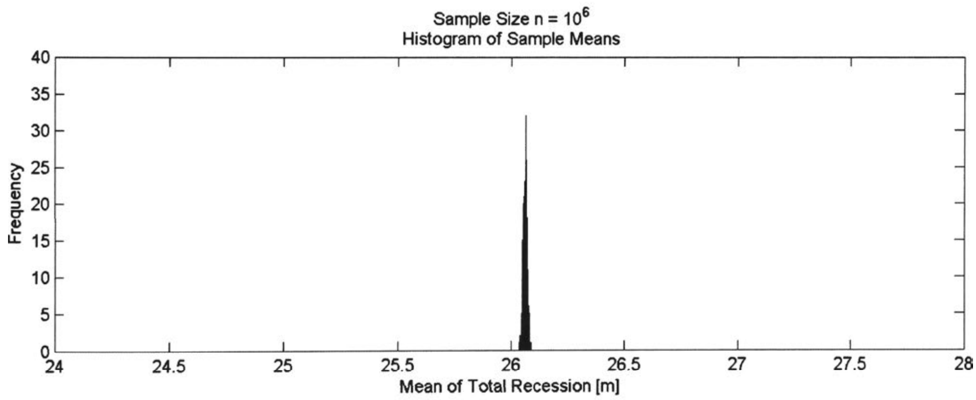

Histogram of Sample Standard Deviations
Frequency
Standard Deviation of Total Recession [m]

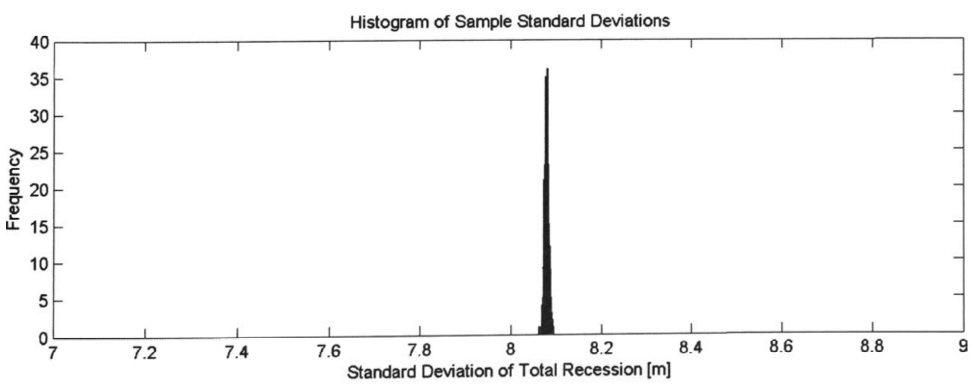

Sample Size n = 10^4
Histogram of Sample Means
Frequency
Mean of Total Recession [m]

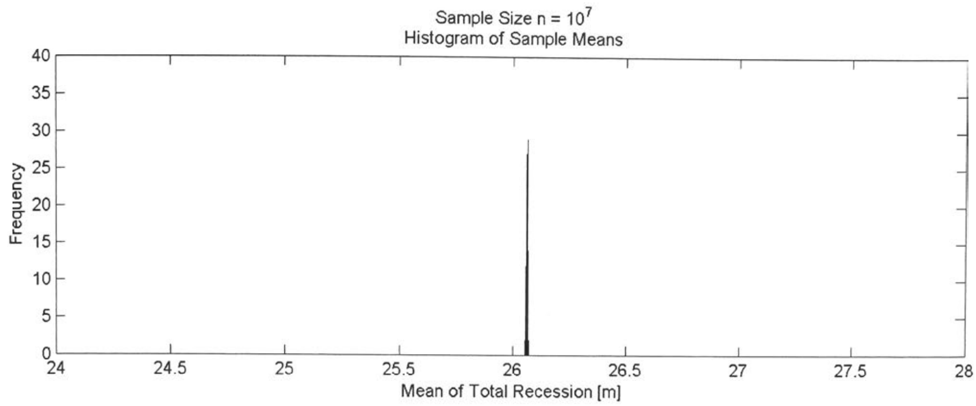

Histogram of Sample Standard Deviations
Frequency
Standard Deviation of Total Recession [m]

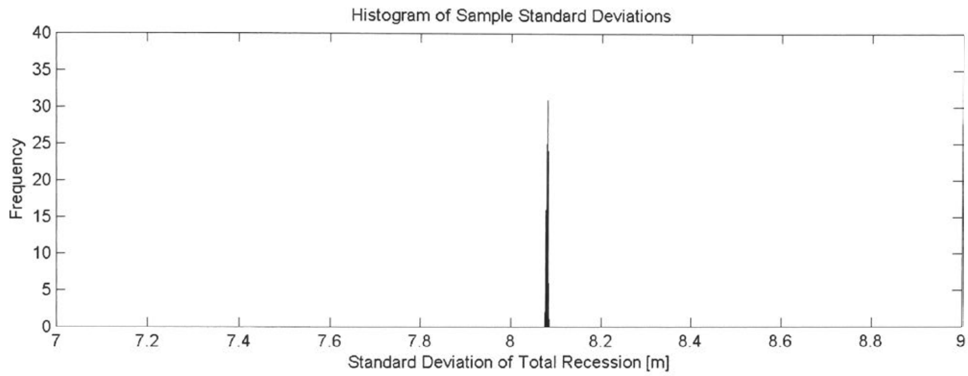

Sample Size n = 10^5
Histogram of Sample Means
Frequency
Mean of Total Recession [m]


Histogram of Sample Standard Deviations
Frequency
Standard Deviation of Total Recession [m]


Sample Size n = 10^6
Histogram of Sample Means
Frequency
Mean of Total Recession [m]


Histogram of Sample Standard Deviations
Frequency
Standard Deviation of Total Recession [m]


Sample Size n = 10^7
Histogram of Sample Means
Frequency
0
5
10
15
20
25
30
35
40
24
24.5
25
25.5
26
26.5
27
27.5
28
Mean of Total Recession [m]


Histogram of Sample Standard Deviations
Frequency
0
5
10
15
20
25
30
35
40
7
7.2
7.4
7.6
7.8
8
8.2
8.4
8.6
8.8
9
Standard Deviation of Total Recession [m]

Appendix D Sensitivity to Changes in Wave Climate

D. Sensitivity to Changes in Wave Climate

D.1. Introduction

The "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering" (Engineers Australia, 2012) list six key environmental variables applicable to coastal engineering:

(i) Mean sea level

(ii) Ocean currents and temperature

(iii) Wind climate

(iv) Wave climate

(v) Rainfall/runoff

(vi) Air temperature

While it is necessary to assess the importance of each variable on a project-by-project basis, generally mean sea level increase, wind climate change and wave climate change are the major concerns for coastal hazards analysis around the Australian coast.

To date, it can be noted that there has been a greater emphasis on the potential impact of sea level rise on the coastal horizon in comparison to change to the wind/wave climate.

It is expected that sea level rise will result in higher water levels on the open coastline which will correspond to an increased rate of shoreline recession. Increased still water levels will also allow land in the lee of low-crested dunes or barriers to be episodically inundated due to wave run-up and overtopping. The threat from tidal inundation around lower-lying estuarine foreshores will be significantly exacerbated with sea level rise.

At present, projections of wind and wave climate changes are not as robust as those developed for mean sea level increases. Climate change may have a direct influence on the frequency, magnitude and direction of local winds from storms.

D.2. Review of predicted medium to long term changes to wind-wave climate

D.2.1. *Wind Climate*

At present, projections of wind and wave climate changes are not as robust as those developed for mean sea level increases. DCC (2009) suggests that extreme wind speeds associated with tropical cycles and mid-latitude lows may increase along with greater variations in air pressure leading to increased storm surge and wave height. However, other studies have predicted for the eastern Australian coast that trade winds may be weaker and that the westerly wind stream may move further south (McInnes *et al.*, 2007, Hemer *et al.*, 2012).

Recent modelling by Hemer *et al.* (2012) tends to display a projected southward shift in the position of the subtropical ridge (STR), associated with a strengthening of the easterly winds north of the STR, and a weakening of the westerly winds south of the STR. Hemer et al. (2012) indicated that the reduced northward extent of the position of the STR during winter months leads to a greater decrease in the influence of the southerly wave systems at the more northerly sites. There is no evidence for any significant change in the circulation patterns that drive the north-easterly wave events in this region. Furthermore, they predicted the trade winds to remain relatively steady near the Australian coast, and that, while not assessed in detail, there is no evidence to suggest changes in frequency, intensity, or tracks of tropical cyclone systems.

The latest consensus view (Knutson et al., 2010) in relation to tropical cyclones in a changed climate is that the most intense tropical cyclones may have the opportunity to develop up to 11 % stronger peak winds by the year 2100 and the relative proportion of the most intense tropical cyclones would likely increase as a result. However, the global frequency of tropical cyclones may decrease by up to 34 % due to a more unfavourable state of environmental shear but the extent of tropical cyclone influence is not expected to greatly change.

D.2.2. ***Wave Climate***

Again, it should be emphasised that the scientific understanding of the projected changes to storminess, and hence wave climate, are still developing (DECCW, 2010). Some assessments have been undertaken on available medium-term wave height data. Young et al. (2011) used satellite altimeter measurements from 1985 to 2008 to investigate global changes in oceanic wind speed and wave height. Young et al. (2011) found some evidence of increase in global monthly mean wave heights (8 % of trends in mean monthly wave height statistically significant) and more pronounced upward trends in the 90 and 99^{th} percentile monthly wave heights (12 % and 47 % statistically significant respectively). However, Shand et al. (2011) argued that agreement with buoy data is questionable. Shand et al. (2011) found that while both Australian East and West coast buoys exhibit upward trends in monthly mean wave height (up to 2 mm/year and 7 mm/year respectively), none exhibited statistical significance and the Australian South coast buoys exhibit non-statistically significant downward trends of -1 to -5 mm/year. Similar non-statistically-significant trends were observed for the 90^{th} and 99^{th} percentile monthly wave height. No statistically significant temporal trends in storm magnitude were found, although one East coast buoy showed a small statistically significant increase in storm frequency.

This absence of consensus in regard to a suggestion of a change to the characteristics of extra tropical storms is further highlighted by the absence of agreements between wind-wave models. High resolution regional climate modelling along the NSW coastline by McInnes et al. (2007) projected increasing mean H_S of approximately 0.1 m and changes in mean wave direction of less than 1° over the XXI century. Such projected changes to mean wave climate (height, direction and period) can be considered reasonably small to negligible. Correspondingly, changes to extreme wave climate and storm surge behaviour were also inconclusive. On the other hand, the more recent wind-wave modelling study by Hemer et al. (2012), project a decrease in mean significant wave height along the south-east Australian coast relative to present conditions. The magnitude of this projected change in mean annual significant wave height is less than 0.2 m by 2100, with larger values north of the region of interest, and is associated with a projected decrease in storm wave energy of 40 % in the region (lower confidence in the projected storm wave climate is reported). An anticlockwise rotation in mean wave direction for NSW of approximately 5° is also projected over the same period.

It should be noted that while DEFRA (Department for Environment, Food and Rural Affairs,UK,2006) specified allowances for sea level rise based on well developed scenarios, only sensitivity ranges for other parameters such as extreme wave height are indicated, because "... *the degree of certainty in the figures is lower as we require further evidence and research to understand local and regional variations, and develop our management of uncertainty."*

Indicative sensitivity ranges from DEFRA (2006) are shown in Table D.1, which include a sensitivity of +5 % in offshore wave height to 2055. It is stressed that these values are for the UK, not Australia, but in the absence of more definite trends are one of the possible options to assess the risk on coastal erosion caused by changing wave climate. Substantial discussion and caveats on the values are contained in DEFRA (2006).

Table D.1 Indicative Sensitivity Range of Climate Change Parameters (from DEFRA, 2006)

Parameter	1990- 2025	2025-2055	2055-2085	2085-2115
Peak rainfall intensity (preferably for small catchments)	+5%	+10%	+20%	+30%
Peak river flow (preferably for larger catchments)	+10%	+20%	+20%	+20%
Offshore wind speed	+5%	+5%	+10%	+10%
Extreme wave height	+5%	+5%	+10%	+10%

D.3. Qualitative analysis of the potential impact wave climatology change to study sites

D.3.1. *Short term erosion (storm demand)*

As introduced in Section 3 of the main report, beach erosion is defined as the erosion of the beach above mean sea level by a single extreme storm event or from several storm events in close succession. Review of the available literature on the potential change to future extreme wave climate showed that there was now clear consensus on the nature of the change (decrease or increase, storm wave direction).

Prediction of a decrease in storm wave energy of 40 % in the region (Hemer et al., 2012) would amount to a decrease of 6 % in the deep offshore wave height, which is about the same magnitude of the suggested increase in wave height by DEFRA (2006). Using SBEACH, a sensitivity analysis was performed for storm demand volumes for a single 100 year ARI event on the central transect of Avoca Beach, with a ±10% change in offshore storm wave height. This analysis showed that due to wave propagation processes, the initial offshore wave height difference became negligible in the nearshore (i.e. at 10 m water depth), resulting in a storm demand volume variability of less than 10% in comparison to storm demand for present day storm wave conditions. Such range of variation in storm demand could be expected at Cabarita Beach due to the nature of the bathymetry.

The second change to wave climate which could have an influence on short term beach erosion is the wave direction. The only available information for this variable for the south-east Australian coastline is provided in Hemer et al. (2012), which reports a predicted maximum 5° anti-clockwise rotation of wave direction by 2100. It should be noted that this change is only reported for ambient wave conditions, and may be less for extreme wave events. Based on the nearshore extreme wave conditions obtained by numerical wave propagation modelling presented in Appendix A, such change in wave direction could only marginally increase wave conditions for the southern end of Avoca Beach as it is exposed predominantly to waves from the east-northeast direction. An anti-clockwise rotation of wave climate would tend to shift the present east wave climate towards the east-north-east and such a change in wave direction could only marginally increase (less than 5 %) wave conditions by 2100. It is expected that such a change would therefore result in a negligible storm demand increase, based on the previous analysis of storm demand for the 10 % wave height increase. Due to the almost constant orientation of Cabarita Beach, it is reasonable to expect that an anti-clockwise rotation in extreme wave direction would not have a significant impact on the present storm demand values, which were derived from a conservative east wave exposure. Note that future changes beyond the projections and ranges presented in this report are possible.

D.3.1. ***Long term Recession (ongoing underlying recession)***

The study site which could potentially be subject to a change in underlying recession associated with wave climate change is Cabarita Beach, as Avoca Beach can be described as a closed coastal compartment.

As for short term erosion, a potential change to wave height and/or wave direction could in theory have an impact on sediment littoral drift and long term erosion. However, it is important to note the mean magnitude of projected change in wave climate height is relatively small (about ± 0.1 m for deep offshore wave conditions). Likewise, the projected change in wave direction of less than 5° for wave conditions in about 100 m water depth is unlikely to have a significant influence on coastal littoral transport processes, due to wave refraction which will decrease the magnitude of this change in the nearshore. The resulting change in sediment transport due to predicted change in wave direction in the nearshore is likely to be within present range of net sediment transport rate differentials explored in Section 4 of the main report (i.e. from 10,000 to 120,000 m^3/year). Note that future changes beyond the projections and ranges presented in this report are possible

References

DEFRA UK (2006), "Coastal Defence Appraisal Guidance FCDPAG3 Economic Appraisal Supplementary Note to Operating Authorities - Climate Change Impacts October 2006" UK Department for Environment, Food and Rural Affairs.

Department of Climate Change (DCC) (2009), "Climate Change Risks to Australia's Coast: A First Pass National Assessment", Canberra, DCC, 172 pp.

Department of Environment, Climate Change and Water (2010), "Coastal Risk Management Guide: Incorporating sea level rise benchmarks in coastal risk assessments", NSW Government.

Engineers Australia (2012), "Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering", Engineers Australia National Committee on Coastal and Ocean Engineering, 3rd ed., ISBN: 9780858259195.

Hemer, M A, McInnes, K L and Ranasinghe, R (2012), "Projections of Climate Change-driven Variations in the Offshore Wave Climate off South Eastern Australia", *International Journal of Climatology* 2012.

Knutson, T R, McBride, J L, Chan, J, Emanuel, K, Holland, G, Landsea, C, Held, I, Kossin, J P, Srivastava, A K and Sugi, M (2010), "Tropical Cyclones and Climate Change", *Nature Geoscience* 21 February 2010.

McInnes, K L, Abbs, D J, O'Farrell, S P, Macadam, I, O'Grady, J and Ranasinghe, R (2007), *Projected Changes in Climatological Forcing for Coastal Erosion in NSW*, CSIRO Report prepared for the NSW Department of Environment and Climate Change.

Shand, T D, Mole, M A, Carley, J T, Peirson, W L and Cox, R J (2011), *Coastal Storm Data Analysis: Provision of Extreme Wave Data for Adaptation Planning*, WRL Research Report 242.

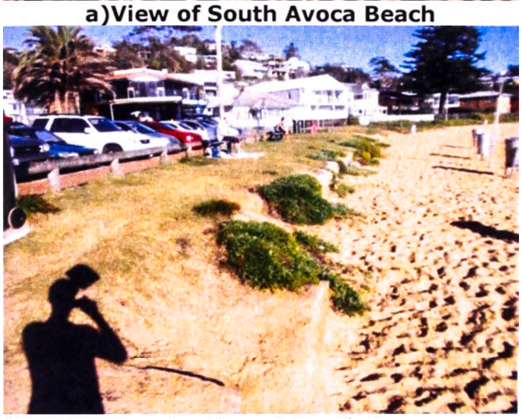
Young, I R, Zieger, S and Babanin, A V (2011), Global Trends in Wind Speed and Wave Height, *Science*, 332(6028), 451-455.

Appendix E Site Inspections

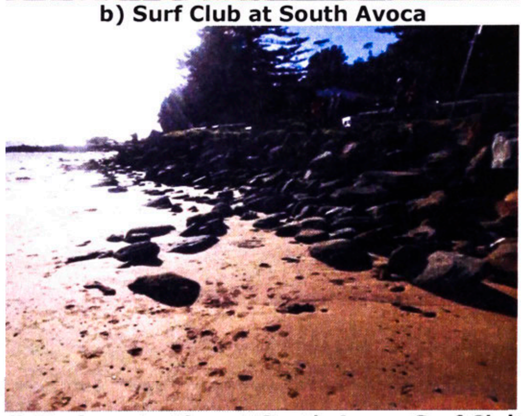
E. Avoca Beach

a)View of South Avoca Beach

b) Surf Club at South Avoca

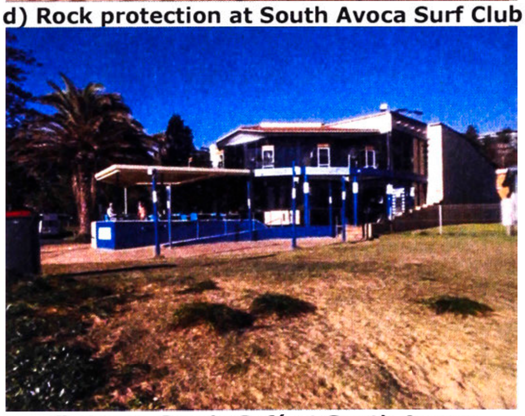


c) Low dune protection at South Avoca car park

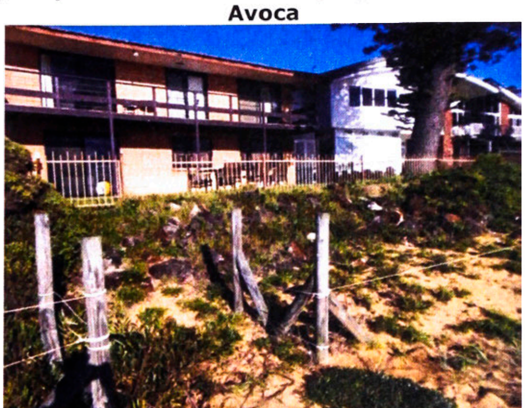


d) Rock protection at South Avoca Surf Club

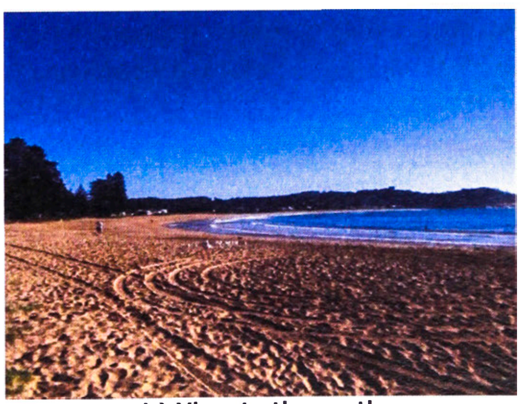
e) Very low dune in front of properties at South Avoca



f) Avoca Sands Café at South Avoca



g) Ad hoc property protection at South Avoca

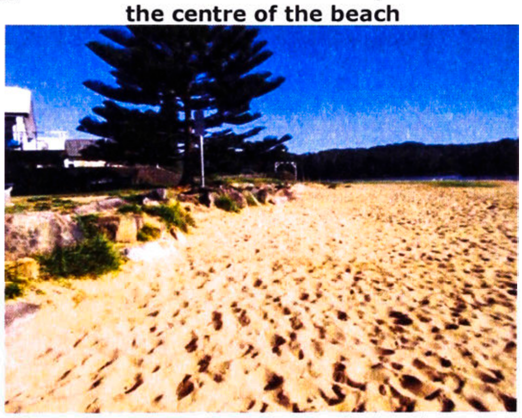


h) View to the north

i) Pedestrian access way in the centre of the beach

j) Stormwater outlet and scour protection in the centre of the beach

k) Moderate dune height in the centre of the beach and cliffs backing the dunes

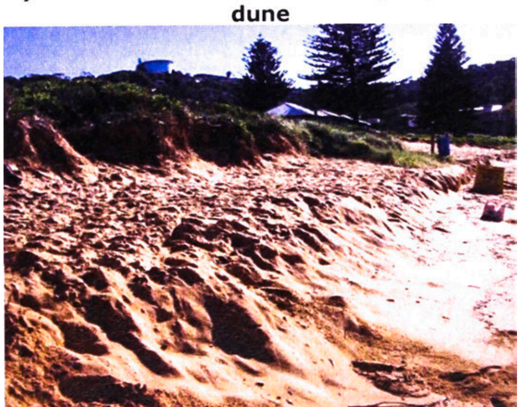


l) Bank scour protection at Avoca Lagoon

m) Avoca Lagoon entrance

n) View of North Avoca showing vegetated dune

o) North Avoca Surf Club

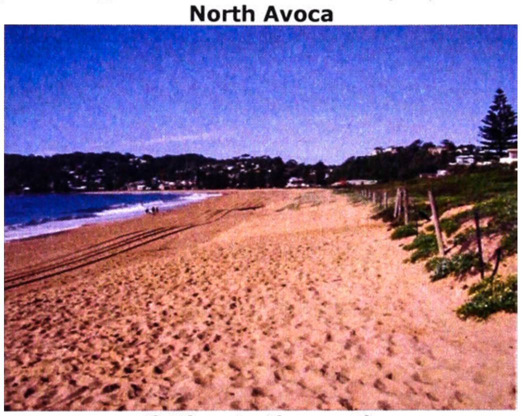


p) Eroded dune scarp at North Avoca

q) Creek outlet at North Avoca

r) Well vegetated dune in front of properties at North Avoca

s) Rock outcrop at North Avoca



t) View to the south

Cabarita Casuarina/Salt Beach

a) Overview of Cabarita Beach (from Lions Park)

b) Beach access from Cabarita SLSC

c) From Cabarita SLSC beach access looking north

d) From Cabarita SLSC beach access looking south

e) Casuarina/Salt dune escarpment looking north

f) Casuarina/Salt dune scarp looking south

g) Casuarina/Salt foredune

h) Beach access at Salt SLSC

i) Patrolled area at Salt SLSC

j) Bicycle path along the back of the frontal dune system

k) Well vegetated dune system

Water Research Laboratory
110 King St, Manly Vale, NSW, 2093, Australia
Tel: +61 (2) 8071 9800 Fax: +61 (2) 9949 4188
www.wrl.unsw.edu.au

Quality system certified to AS/NZS ISO 9001:2008

Expertise, research and training for industry and government since 1959