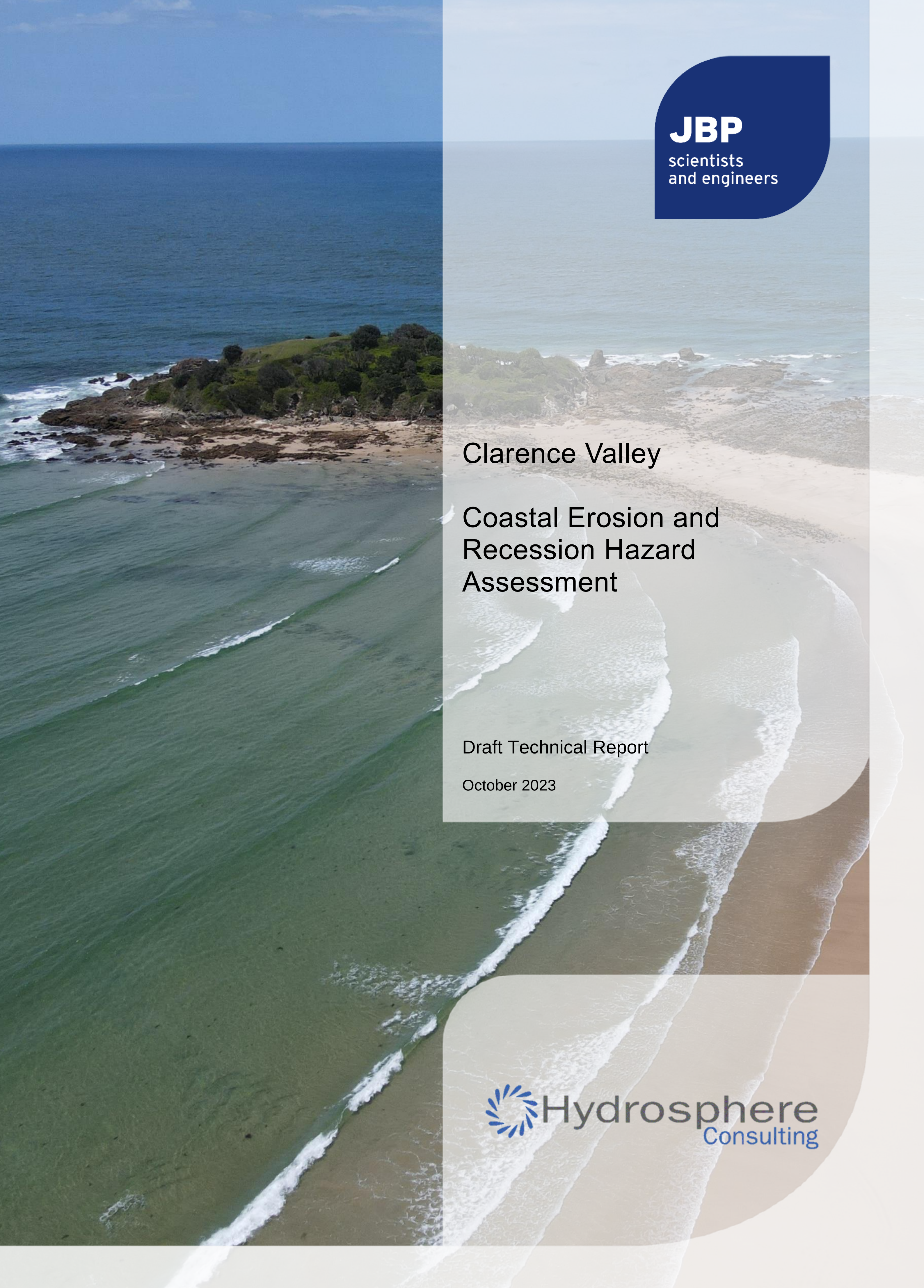

Clarence Valley

Coastal Erosion and Recession Hazard Assessment

Draft Technical Report

October 2023

JBP scientists and engineers

Hydrosphere Consulting

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Revision History

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MO-0001 S3-P01 / 23 Sept 2022 Draft for comment	Draft	RC
MO-0001 S3-P03 / 18 August 2023 Draft Report	Updated erosion and recession hazard methodology	RC
MO-0001 S3-P04 / 22 August 2023 Draft Report	Minor comments addressed	RC
MO-0001 S3-P05 / 6 October 2023 Draft Report	Additional comments from CVC and DPE addressed, ZRFC widths extracted	RC

Contract

This report describes work commissioned by Robyn Campbell, on behalf of Hydrosphere Consulting Pty Ltd, by a letter dated 15/09/21. Daniel Rodger, Michael Thomson, Emma Walker, Zoe Nehring, and Callan Schonrock of JBP carried out this work.

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Disclaimer

Jeremy Benn Pacific ("JBP") has prepared this report for the sole use of Hydrosphere Consulting (the "Client") and its appointed agents in accordance with the Agreement under which our services were performed.

A draft coastal erosion and recession assessment was prepared by JB Pacific for Council and Department of Planning and Environment (DPE) review in October 2022. In late December 2022, DPE representatives advised that the Department would conduct an external peer review of the draft coastal erosion/recession assessment. The aim of the peer review was to contribute to a state-wide approach that DPE is developing to ensure a consistent, robust and legally defensible coastal hazard modelling and assessment approach is undertaken by all NSW councils. This is a developing specialist field and DPE is transitioning to a better-defined approach for the coastal hazard assessments. Hydrosphere, JBP and CVC worked with DPE to confirm the approach to be undertaken which is documented in this report.

JBP has no liability regarding the use of this report except to the Client. No other warranty, expressed or implied, is made as to the professional advice included in this report or any other services provided by JBP.

The conclusions contained in this report are based upon information provided by others and upon the assumption that all relevant information has been provided by those parties from whom it has been requested and that such information is accurate. Information obtained by JBP has not been independently verified by JBP, unless otherwise stated in the report.

The methodology adopted and the sources of information used by JBP in providing its services are outlined in this report. The work described in this report was undertaken between January 2022 to October 2023 and is based on the conditions encountered and the information available during this period of time. The scope of this report and the services are accordingly factually limited by these circumstances.

Certain statements made in the report that are not historical facts may constitute estimates, projections or other forward-looking statements, and even though they are based on reasonable assumptions as of the date of the report, such forward-looking statements by their nature involve risks and uncertainties that could cause actual results to differ materially from the results predicted. JBP specifically does not guarantee or warrant any estimate or projections contained in this report.

Acknowledgements

JBP would like to acknowledge the following groups for their support and supply of data for this project: Hydrosphere Consulting, Clarence Valley Council, NSW Department of Planning and Environment and the NSW National Parks and Wildlife Service.

We also acknowledge the traditional custodians of the lands and seas where we work. We pay our respects to Elders past, present, and emerging.

Copyright

Executive Summary

This report was undertaken by JB Pacific (JBP) in partnership with Hydrosphere Consulting to deliver a Coastal Management Program (CMP) for the Clarence Valley Council (CVC). This CMP sets the long-term strategy for the coordinated management of the Clarence Valley coastline, with a focus on achieving the objects and objectives of the NSW Coastal Management Act 2016 (CM Act). The CMP is being delivered in accordance with the NSW Coastal Management Manual (2018). This process includes five stages:

- Stage 1: Identifies the scope of the CMP.
- Stage 2: Determines risks, vulnerabilities, and opportunities.
- Stage 3: Identifies and evaluates options.
- Stage 4: Prepares, exhibits, finalises, and certifies the CMP.
- Stage 5: Implements, monitors, and evaluates the CMP.

This report and associated coastal erosion and recession hazard maps have been developed under Stage 2 of the CMP process, which includes a coastal hazard assessment of beach erosion and shoreline recession. Maps have been developed for present day and future planning horizons of +20 years (2043), + 50 years (2073), and +100 years (2123). Each planning horizon includes combined coastal erosion and recession mapping for a 50% exceedance probability (considered frequent), 10% exceedance probability (considered frequent to rare), 2% exceedance probability (considered rare), and 1% exceedance probability (considered rare to very rare). Future time horizons include allowances for sea level rise and are presented in two scenarios based on Shared Socio-economic Pathways (SSPs), where SSP2 represents the Representative Concentration Pathway (RCP) 4.5 and SSP5 represents RCP 8.5.

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Abbreviations

AEP .... Annual Exceedance Probability
AHD .... Australian Height Datum
ARI .... Annual Recurrence Interval
CAWCR .... Centre for Australian Weather and Climate Research
CM Act .... Coastal Management Act 2016
CMP .... Coastal Management Program
COWCLIP .... Coordinated Ocean Wave Climate Project
CSIRO............................. Commonwealth Scientific and Industrial Research Organisation
CVC .... Clarence Valley Council
DEA................................. Digital Earth Australia
DECCW .... NSW Department of Environment, Climate Change and Water
DEM .... Depth Elevation Model
DoC................................. Depth of Closure
DSAS .... Digital Shoreline Analysis System
ECL .... East Coast Low
ENSO.............................. El Niño Southern Oscillation
EVA................................. Extreme Value Analysis
GA................................... Geoscience Australia
GPD .... Generalised Pareto Distribution
HAT................................. Highest Astronomical Tide
HHWSS........................... Higher High Water Solstice Spring
ICOLL.............................. Intermittently Closed and Open Lakes and Lagoons
IPCC .... Intergovernmental Panel on Climate Change
JBEM .... JBP Beach Evolution Model
LGA................................. Local Government Area
LiDAR.............................. Light Detection and Ranging
LST .... Longshore Sediment Transport
MHL .... Manly Hydraulics Laboratory
NPWS .... National Parks and Wildlife Service
NSW................................ New South Whales
OEH .... NSW Office of Environment and Heritage
POT................................. Peak Over Threshold
RCP .... Representative Concentration Pathway
SIMP .... Solitary Islands Marine Park
SLR .... Sea Level Rise
SSP................................. Shared Socio-economic Pathway
SWAN .... Simulating Waves Nearshore
TIN .... Triangular Irregular Network
WRL .... NSW Water Research Laboratory
ZRFC .... Zone of Reduced Foundation Capacity

Definitions

Within this report the following definitions have been used:

- Beach erosion – refers to landward movement of the shoreline and/or a reduction in beach volume, usually associated with storm events or a series of events, which occurs within the beach fluctuation zone. Beach erosion occurs due to one or more process drivers; wind, waves, tides, currents, ocean water level, and downslope movement of material due to gravity.
- Recession – a continuing landward movement of the shoreline; or a net landward movement of the shoreline over a specified time.

1 Introduction

This study was completed by JB Pacific (JBP) in association with Hydrosphere Consulting on behalf of the Clarence Valley Council (CVC). It has been prepared to support the Coastal Management Program (CMP) for the Clarence Valley coastline and estuaries, spanning the area shown in Figure 1-1. This program sets the long-term strategy for the coordinated management of the Clarence Valley coastline, with a focus on achieving the objects and objectives of the Coastal Management Act 2016 (CM Act). The CMP is being delivered in accordance with the Coastal Management Manual (2018). This includes the following five stages:

- **Stage 1:** Identifies the scope of the CMP.
- **Stage 2:** Determines risks, vulnerabilities, and opportunities.
- **Stage 3:** Identifies and evaluates options.
- **Stage 4:** Prepares, exhibits, finalises, and certifies the CMP.
- **Stage 5:** Implements, monitors, and evaluates the CMP.

This study supports Stage 2 of the Clarence Coastline CMP. It should be read in conjunction with the Stage 1 Scoping Study[1], which provides additional background information to the coastline, including the purpose of the CMP, stakeholder engagement, strategic context, and the statutory and planning context.

Detailed coastal erosion and recession hazard mapping is not currently available for the entire Clarence Valley coastline. Available studies include the high-level NSW-wide erosion assessment, which spans all beaches, however any detailed studies are limited to individual beaches. To support Stage 2 of the CMP, this study provides a detailed erosion and recession assessment for a larger number of beaches. These are based on the recommendations from the CMP Stage 1 Scoping Study which identified locations that would benefit from a detailed review; Shark Bay, Woody Bay, Yamba Main Beach, Whiting Beach, Brooms Head beach, Sandon campground and village, and Wooli. Following further review, an additional five coastal locations were added to the project scope: Convent Beach and Pippi Beach, Angourie (Spooky Beach), Minnie Water, and Diggers Camp.

Following an initial assessment, Yamba Main Beach and Convent Beach were not modelled using the probabilistic erosion assessment methodology described in this report as the primary hazard at these locations is the instability of high-crested cliffs which are to be assessed in separate geotechnical investigations.

Through detailed analysis of coastal processes, new open coast erosion hazard mapping has been developed for present day and future planning horizons of +20 years (2043), + 50 years (2073), and +100 years (2123). Each planning horizon includes combined coastal erosion and recession mapping for a 50% exceedance probability (considered frequent), 10% exceedance probability (considered frequent to rare), 2% exceedance probability (considered rare), and 1% exceedance probability (considered rare to very rare).

In addition to this introductory section, this report includes the following chapters:

- **Section 2:** Coastal processes, hazards, and available data
- **Section 3:** Erosion and recession analysis
- **Section 4:** Mapping methodology
- **Section 5 to 14:** Erosion and recession assessment summary for Shark Bay, Woody Bay, Yamba beaches, Whiting Beach, Brooms Head, Sandon, Wooli, Pippi Beach, Spooky Beach, Minnie Water, and Diggers Camp.
- **Section 15:** Modelling limitations
- **Appendices:**
  - **Appendix A:** Additional detail on the probabilistic erosion analysis
  - **Appendix B:** Additional detail on erosion and recession data
  - **Appendix C:** Erosion and recession hazard maps for all return periods and climate scenarios.

1 Hydrosphere (2021) Clarence Valley Coastline and Estuaries, Coastal Management Program Stage 1: Scoping Study

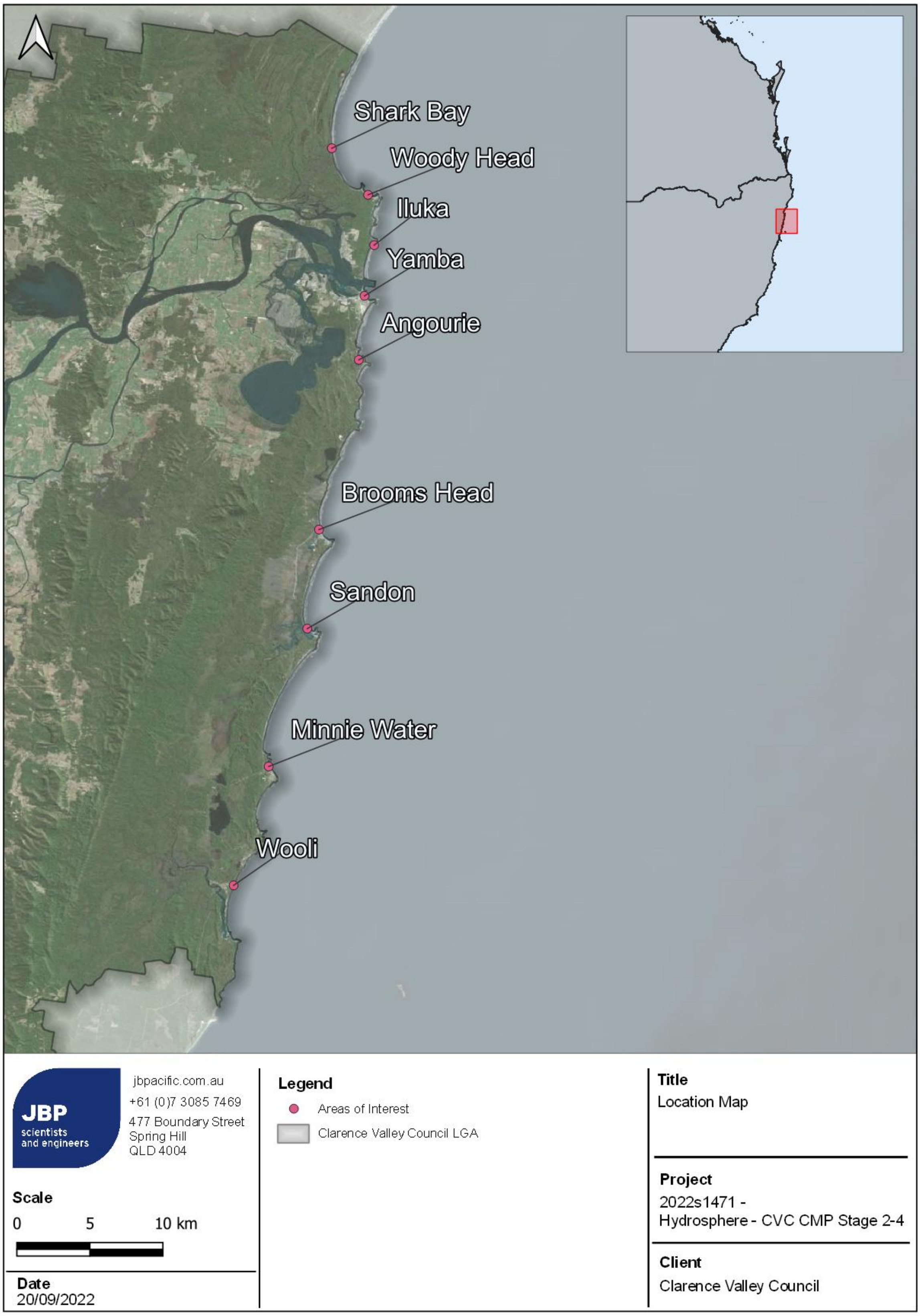


Figure 1-1: Location map

2 Coastal processes, hazards, and available data

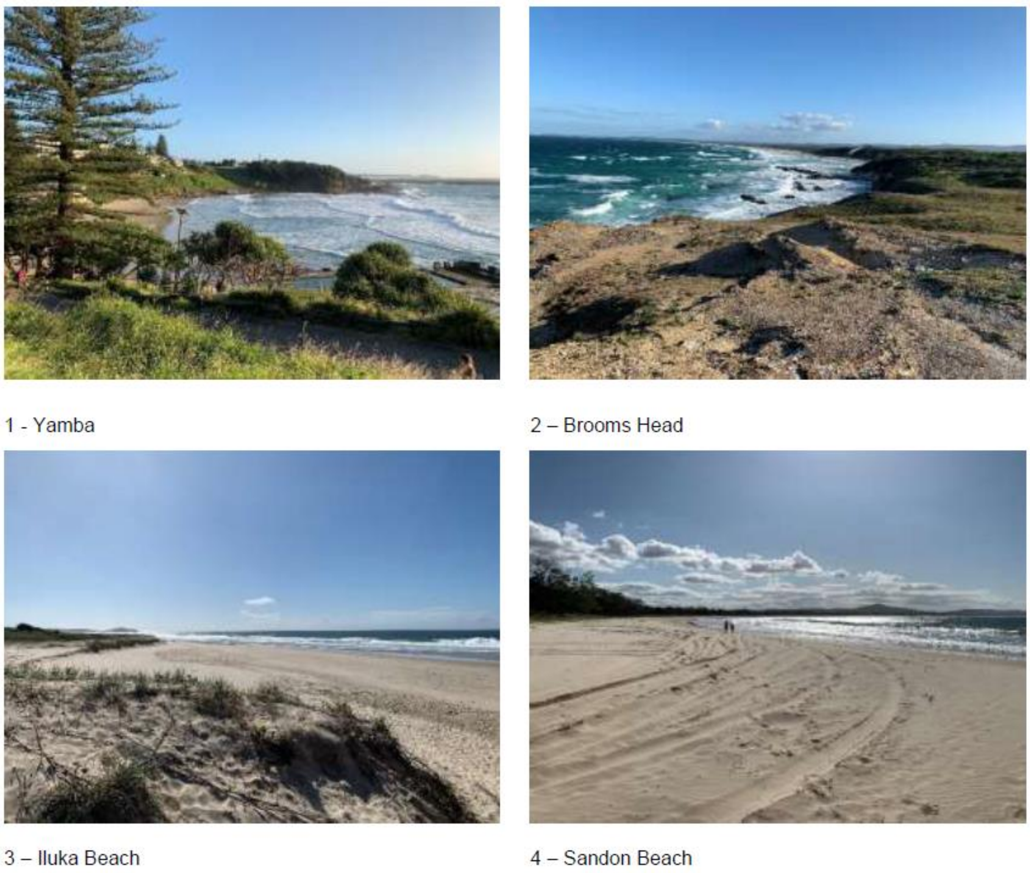
2.1 Regional context

The Stage 1 CMP Scoping Study provides a review of the geographical and coastal drivers throughout the coastline. The study area falls within the southern area of the Clarence Basin. The coastal zone throughout the study area is dominated by quaternary sand beach barrier systems and coastal plains which overlay the Clarence Basin material. Bedrock outcrops (typically sandstone and siltstone) occur as headlands punctuating the beach system.

Sediment compartments are used to compartmentalise sections of the Australian coastline with similar characteristics and processes. A sediment compartment is a section of coast which shares a common sediment resource with clearly defined physical boundaries[2]. A compartment may be open, leaky or closed at either or both boundaries and the sediment budget may be positive, stable or negative.

The sediment compartment concept uses a hierarchy classification including province, division, region, primary and secondary. The Clarence Valley coastline lies within the temperate province, south-east division and central eastern region and spans over two primary coastal sediment compartments, Clarence River to Point Danger (Tweed Heads) and Yamba Heads to Bare Bluff (Sapphire Beach). The secondary sediment compartments within the study area are Bundjalung, Yuraygir and Woolgoolga.

Based on the sediment compartment framework the majority of the Clarence coastline is dominated by sediment compartments that are characterised by rocky headlands, zeta form bays and sandy beaches (Figure 2-1) and the majority of the coast consists of shorelines that do not show evidence of long-term recession but are likely to begin receding with continuing sea-level rise. However, there are several sections where shoreline recession is currently occurring and is likely to continue.



1 - Yamba

2 – Brooms Head

3 – Iluka Beach

4 – Sandon Beach

Figure 2-1: Study area coastline (CMP Stage 1 Scoping Study; Hydrosphere, 2021)

2 Short (2020) Australian Coastal Systems, Beaches, Barriers and Sediment Compartments, School of Geosciences, University of Sydney, Sydney, NSW, Australia

2.1.1 Coastal drivers

The Clarence Valley coastline has a moderate tidal influence, with an approximate 2m spring tidal range. It is predominantly wave dominated with a moderate to high energy wave climate which has formed multiple crenulate shaped embayments (See Figure 2-2, top left). The region experiences a varying wave climate, which will shift under seasonal changes causing embayment and beach rotation. Whilst the Clarence Valley region does not have a wave buoy, information from the long-term wave monitoring programme offshore of Coffs Harbour is relevant for the region. This is positioned at approximately 70m depth and has captured a mean significant wave height (Hs) of 1.58m between 1976-2021, with the conditions peaking between June and July.

The coastline can be influenced by larger climatic patterns such as the El Niño Southern Oscillation (ENSO). The coast is susceptible to East Coast Lows (ECLs) which can generate large waves and storm surges and cause beach erosion. Recent events in March 2022 led to widespread erosion along the exposed coastlines (Figure 2-2, top right). At a local scale, shoreline variability is also impacted be seasonal rainfall and runoff patterns, which will influence estuary banks, spits and any intermittently closed and open lakes and lagoons (ICOLLS). A range of coastal management actions have been implemented throughout the coastline. This includes beach nourishment and revegetation and the construction of coastal defences (i.e. seawalls, revetments etc).

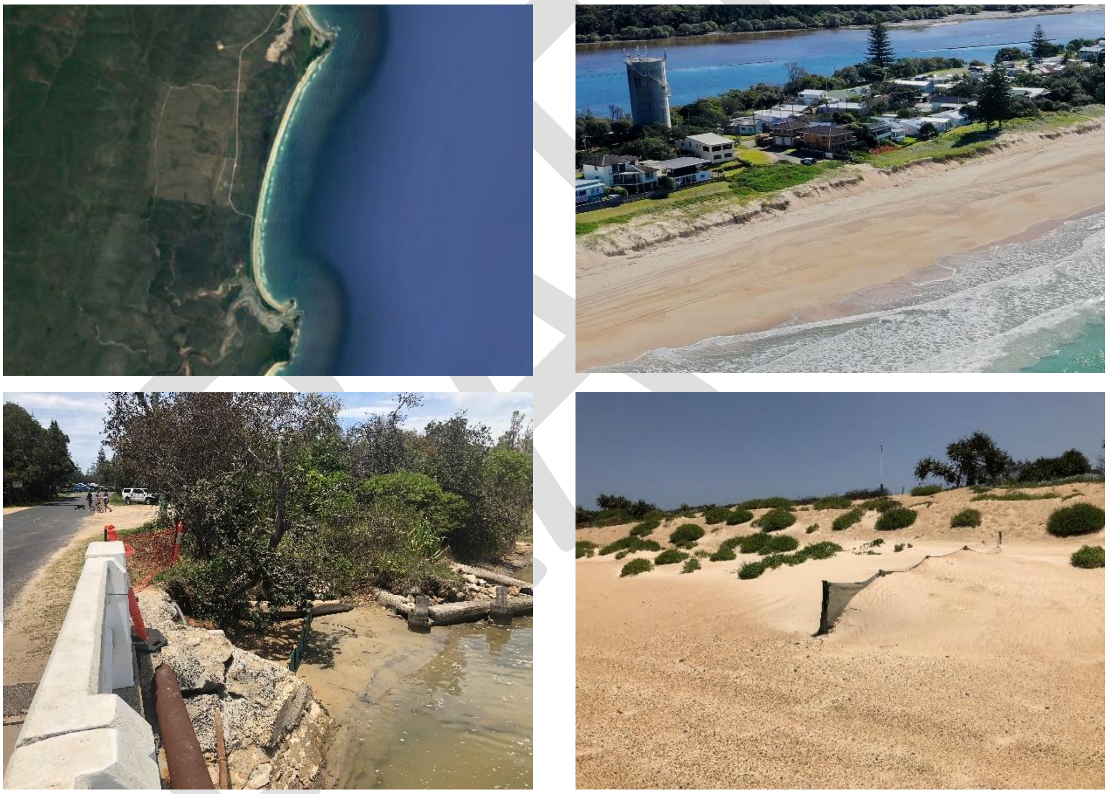


Figure 2-2: Example coastal processes. Clockwise from top left: Crenulate shaped beach at Sandon, erosion at Wooli, nourished dune at Wooli, scour at Lake Cakora bridge abutment.

2.1.2 Previous studies

A range of studies have been completed along the coastline, which can be defined by their northern or southern sediment compartment. These are summarised below and referenced further within the Section 3.3.2 (sediment budget) and within the description of each coastal beach block.

North of the Clarence River (Clarence River to Point Danger)

Coastal processes north of the Clarence River have been studied extensively over the last 40 years, with studies including the following:

- Walsh and Roy (1983)[3] established the geology and coastal evolution of the coast.
- PWD (1993) undertook photogrammetric analysis of Woody Bay.
- Manly Hydraulics Laboratory (MHL) (2000)[4] completed a coastal processes and hazard definition study of Woody Head.
- Goodwin et al. (2006) [5] established a sand budget and described the coastal evolution for the Iluka- Woody Bay coast.
- DECCW (2012)[6] provides coastal processes and hazards information for Woody Bay.
- Doyle et al. (2019)[7] provides updated recession rates for Woody Bay.

Regional scale processes can be summarised for the wide, open beaches and southern headlands within the compartment. The region is part of the Clarence-Moreton Basin, where softer sedimentary rocks have been eroded to form broader valleys, typically with longer beaches and fewer headlands than experienced along the south of the Clarence LGA. At the southern end of the compartment (our study site) the Iluka-Woody bay coastline is considered a progradational Holocene barrier. The coastline has prograded overall over the last 1,500 years however has experienced recession events within this timeframe. Sand is supplied to the beaches by longshore drift, with sand pulses around headlands a key mechanism for the longshore transport. Since 1942, the Iluka Beach compartment has prograded, whilst Back Beach and Bluff Beach have remained relatively stable. During this time Woody Bay and Shark Bay have experienced ongoing erosion and recession, with two mechanisms proposed:

1. Within the Coastal Processes and Hazard Definition Study (MHL 2000), recession is considered to be caused by the bedrock reef extending offshore to the north of Woody Head, which acts as a barrier to sand being transported into the bay.
2. Alternatively, Goodwin et al (2006) proposes that sand bypassing does occur at Woody Head (albeit at a small rate). However, a shift in the dominant wave direction along the NSW coast is primarily responsible for the recession trends experienced in Woody Bay

3 Walsh, I.L., Roy, P.S., 1983. Late Quaternary geology and coastal evolution near Yamba, North Coast of NSW. Geological Survey of New South Wales Report No GS1982/420, Department of Mineral Resources.

4 MHL. 2000. Woody Head Erosion Mitigation Coastal Processes Hazard Definition Management Study and Management Plan.

5 Goodwin, I. D., Stables, M. A. and Olley, J. M. 2006. Wave climate, sand budget and shoreline alignment evolution of the Iluka-Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Marine Geology, 226, 127-144

6 DECCW (2012) Woody Bay Coastal Hazard Review

7 Doyle, T.B.; Short, A.D.; Ruggiero, P.; Woodroffe, C.D. Interdecadal Foredune Changes along the Southeast Australian Coastline: 1942–2014. J. Mar. Sci. Eng. 2019, 7, 177. https://doi.org/10.3390/jmse7060177

Figure 2-3: Ongoing shoreline recession at Woody Bay (Hydrosphere - May 2022)

South of the Clarence River (Clarence River to Wooli)

The majority of coastal processes assessments within the southern compartment have been undertaken at a local beach-scale. These have been completed at various timeframes over the last ten years, and include:

- Coastal Hazard Study for Pippi Beach, Yamba (Royal Haskoning DHV, 2016)
- Brooms Head Beach Coastal Processes and Hazard Study (SMEC, 2013)
- Sandon River Estuary Processes Study (GHD, 2011)
- Wooli Beach Village Review of Coastal Hazards (Worley Parsons, 2010)
- Wooli Beach Management Strategy (Royal Haskoning DHV, 2021)

Wider studies include the Australian Coastal Systems review by Short (2020)[8], which describe the region as being part of the New England Fold Belt whose resilient sedimentary and metasedimentary rocks dominate the rocky sections of coast between Yamba to South West Rocks. This coastline is characterised by its moderately long sandy beaches, separated by rocky outcrops and headlands, most notably at Yamba, around Minnie Waters and just south of the study site between Woolgoolga and Coffs Harbour. Throughout the northern coastline, the presence of exposed Pleistocene dunes suggest a slowly receding coast. One mechanism is the potential for the rocky headlands to interrupt longshore sediment transport, however no recent detailed studies have been completed on the impact of the rocky shoreline sections between Coffs Harbour and Sandy Beach on coastal recession.

2.2 Background to coastal processes

Before undertaking any calculations or modelling of coastal and estuarine processes it is first important to understand the processes that are driving coastal risk at the location. Coastal erosion and inundation are complicated processes, affected by a number of wave, hydrodynamic and morphologic processes. For any coastal hazard investigations, it is also important to consider how any local engineered structures will interact with these processes, such as seawalls. At present there is no single numerical model capable of simulating all these processes, and instead a suite of numerical models is typically used to create hazard maps.

The way in which different coastal processes interact will determine the tide, wave, inundation and erosion conditions experienced at any location. These may include the following:

- Astronomical tide: This is the regular periodic variation in water levels due to the gravitational effects of the moon and sun, which can be predicted with generally very high accuracy at any point in time (past and present) if sufficient measurements are available.

8 Short (2020) Australian Coastal Systems, Beaches, Barriers and Sediment Compartments, School of Geosciences, University of Sydney, Sydney, NSW, Australia

The highest expected tide level at any location is termed the Highest Astronomical Tide (HAT) and occurs once every 18.6 year period, although in northern NSW a common peak tide level is the Higher High Water Solstice Spring (HHWSS).

- Storm surge: This is the combined result of the severe atmospheric pressure gradients and wind shear stress of the storm acting on the underlying ocean. The storm surge is a long period “wave” capable of sustaining above-normal water levels over several hours or even days. The wave travels with and ahead of the storm and may be amplified as it progresses into shallow waters or is confined by coastal features. The magnitude of the surge is affected by several factors such as storm intensity, size, speed, and angle of approach to the coast and the coastal bathymetry.
- Wind-driven waves: winds blowing across a water surface apply a shear stress which is converted to wave energy. The height (and energy) of a wave train is directly related to the speed of the blowing wind, the linear distance of water over which the wind is applied, and the duration that the wind is blowing. Within estuaries, the distance and duration of wind stress, and hence the size of waves, is limited by the size of the estuary.
- Wave setup: As waves break, they create a localised effect to increase the water level, known as breaking wave setup. It predominately occurs at a sloping beach or structure and becomes less significant within river mouths or protected low-lying mangrove or swampy land.
- Wave runup and overtopping: If broken waves reach the shoreline any residual energy may intermittently run up and down the beach face, known as wave runup. This may cause localised impacts as waves can reach elevations higher than the underlying extreme sea level. The vertical elevation the waves may reach will be dependent on the slope of the shoreline, the porosity, vegetation and the coastal (wave and sea) conditions. In extreme cases, wave impact and runup can lead to overtopping of the frontal dune or barrier structure, leading to coastal inundation.

In addition to hydrodynamic processes, sediment transport will influence a beach and coastline. This includes the presence of any regional sediment sources and sinks, the sediment type (e.g. cohesive silts vs non-cohesive sands), sediment properties, and any interruptions to littoral drift due to headlands and structures. Due to the complexity of these factors, there are several ways sediment can be mobilised, eroded, transported or deposited, as shown in Figure 2-4. This itself can be divided into several processes, including:

- Longshore sediment transport, which is the transport of sediment along the coastline due to the arrival of waves at an oblique angle. This process, when combined with rocky headlands, can create a characteristic curvilinear shoreline, such as a crenulate or zeta-shaped bays[9]
- Cross shore sediment transport, which is the on- and offshore movement between the nearshore zone and any beach/dune system. This process will lead to erosion after large storms and beach accretion/recovery between storms. This beach accretion process can be undertaken mechanically through beach nourishment.
- Suspended and bedload sediment transport, which is typically considered to be the through transport of sediment under tidally driven currents, that can flow along a shoreline and within estuaries, or flows, for instance freshwater inflows entering an estuary.

9 Hsu and Silvester (1991), Parabolic Model

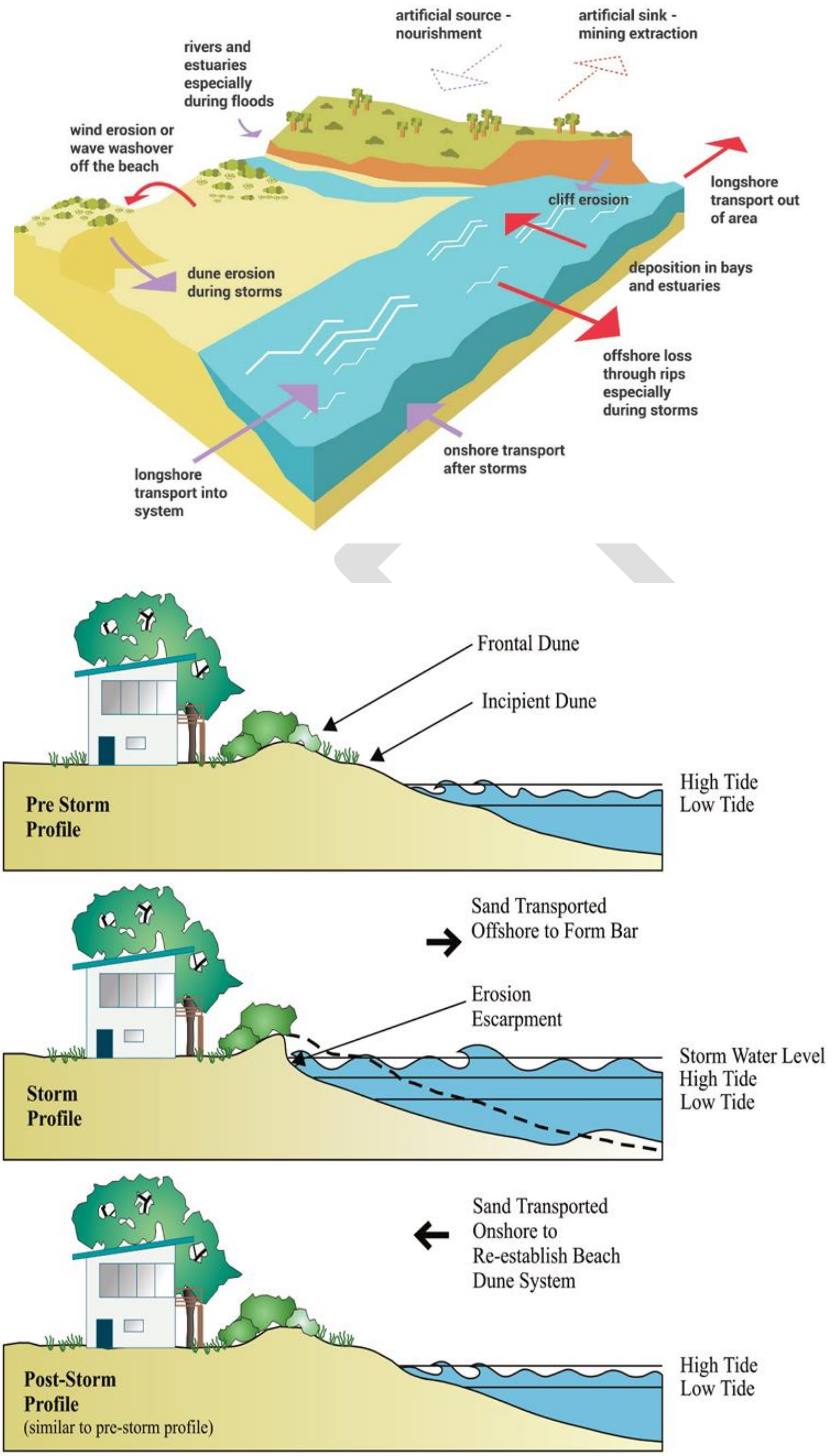


Figure 2-4: Top: Components of the coastal sediment budget (Source from: Coastal Dune Management, NSW Department of Land and Water Conservation, 2001). Bottom: Beach erosion and recovery phases (Source from: NSW Coastal Management Manual, NSW Office of Environment and Heritage, 2019).

2.3 Available Data

A range of studies and datasets are available at a regional scale throughout the study area. These provide information on tides, extreme water levels, waves, bathymetric and topographic data, hydrology, and spatial characteristics.

2.3.1 Datums and conventions

Datums and naming conventions remain a significant source of uncertainty in any coastal study. The definitions used throughout this report are listed below.

- All vertical elevations have been measured from the Australian Height Datum (AHD), which normally approximates mean sea level within a range of several centimetres.
- Winds and waves are designated by the direction they come from. Both a south-easterly wind and wave originates from the southeast.
- Currents are designated by the direction in which they are going. A northerly current is flowing from south to north.
- Longshore sediment transport is the movement of sand parallel to a beach. When standing on a beach facing the ocean, the convention is typically that 'leftward' directed transport is considered negative. This can cause confusion along Australia's east coast, which has a large northward transport rate (therefore a negative rate). In this report the direction of any transport is stated to avoid confusion.
- When referencing changes to a beach profile, a negative shoreline change indicates landward movements (erosion, recession) and positive shoreline change indicates a seaward movement (accretion).

2.3.2 Event Frequencies

Coastal hazards may be defined in terms of a likelihood or event frequency. Standard industry practice is to use statistical definitions, based on an Annual Exceedance Probability (AEP). However, future erosion and recession hazard projections are a combination of short-term and long-term probabilistic components, therefore maps are provided in terms of likely exceedance probability (EP). That is, for a given planning horizon, maps indicate the probability that the hazard extent will be exceeded (e.g., 1% EP). This should not be confused with the concept of AEP which is the probability that a particular event (i.e., storm, flood, erosion) will be exceeded in a given year.

An event likelihood can be used as a qualitative description, useful to aid community and stakeholder understanding of risk. The event frequency is consistent with the terminology used in flood management planning[10]. The exceedance probability is used in preference within this report, however both approaches are described below. The following exceedances have been assessed for each planning period:

- 50% exceedance probability (considered frequent),
- 10% exceedance probability (considered frequent to rare),
- 2% exceedance probability (considered rare),
- 1% exceedance probability (considered rare to very rare).

10 Ball J, Babister M, Nathan R, Weeks W, Weinmann E, Retallick M, Testoni I, (Editors) Australian Rainfall and Runoff - A Guide to Flood Estimation, © Commonwealth of Australia (Geoscience Australia), 2019.

2.3.3 Topography

Several sets of topographic and bathymetric information were used throughout the study.

- Topographic Data: Elevation data above mean sea level (MSL) is available through a 1 Metre LiDAR Grid from Geoscience Australia[11]. This has been produced using a TIN (Triangular Irregular Network) method of averaging ground heights to formulate a regular grid. The data used to create this DEM has an accuracy of 0.3m (95% Confidence Interval) vertical and 0.8m (95% Confidence Interval) horizontal.
- Topo-Bathymetric Data: 5m resolution NSW Bathymetry data was obtained from the NSW SEED portal[12]. This bathymetric data was prioritized below 0mAHD and merged with the topographic data with smoothing performed at the data intersection. This bathymetry is based on LiDAR and limited survey.

2.3.4 Tides

Tidal conditions have been based on the ten-year analysis undertaken by the then Office of Environment and Heritage (OEH)[13], now Department of Planning and Environment (DPE) between 1990 and 2010. Within the analysis, tidal planes are published for Ballina, Yamba and Wooli. No tidal planes or water level gauges are available for other target locations, i.e. Woody Head, Brooms Head, Sandon etc. At these locations tide levels have been estimated through a linear interpolation of published values at Ballina, Yamba and Wooli. These are considered estimates only and may not match local tide conditions, which has the potential to influence model results. The derived tidal planes are shown in Table 2-1.

- HHWSS: Higher High Water Solstice Springs
- MHWS: Mean High Water Springs
- MHW: Mean High Water
- MHWN: Mean High Water Neaps
- MSL: Mean Sea Level
- MLWN: Mean Low Water Neaps
- MLW: Mean Low Water
- MLWS: Mean Low Water Springs
- ISLW: Indian Spring Low Water

Table 2-1: Interpolated tidal planes (mAHD) based on OEH 2012.

	Shark Bay	Woody Head	Iluka	Yamba Offshore	Brooms Head	Sandon	Wooli River Entrance
HHWSS	1.06	1.06	1.06	1.073	1.02	0.97	0.923
MHWS	0.66	0.66	0.66	0.674	0.64	0.60	0.572
MHW	0.51	0.51	0.51	0.524	0.50	0.47	0.45
MHWN	0.36	0.36	0.37	0.375	0.36	0.34	0.328
MSL	-0.01	-0.01	-0.01	-0.006	-0.01	-0.01	-0.006
MLWN	-0.39	-0.39	-0.39	-0.387	-0.37	-0.35	-0.34
MLW	-0.54	-0.54	-0.54	-0.537	-0.51	-0.48	-0.462
MLWS	-0.68	-0.68	-0.68	-0.687	-0.65	-0.62	-0.585
ISLW	-0.97	-0.97	-0.97	-0.971	-0.92	-0.88	-0.835

11 Geoscience Australia, Elevation Information System (ELVIS). 1m Digital Elevation Model (DEM). Produced for the NSW Foundation Spatial Data Framework (FSDF).

12 NSW DPE (2018). NSW Marine LiDAR Topo-Bathy 2018 Geotiff. Accessed from: https://datasets.seed.nsw.gov.au/dataset/marine-lidar-topo-bathy-2018

13 OEH (2012) NSW tidal planes analysis 1990-2010 harmonic analysis report mhl 2053, October 2012

2.3.5 Water level data

Recorded water level data has been sourced from the water level gauges at Coffs Harbour outer jetty for 1983-1996 (now decommissioned) and Inner jetty for 1996- present day. Water level data has been sourced from this gauge due to its proximity to recorded wave data at the Coffs Harbour wave buoy. This proximity is necessary for identifying coincident surge and wave events, as described further in Appendix A). Astronomical tide data is not available for the entire gauge record, therefore the Utide python-based tool has been used to reconstruct the astronomical tidal series from the recorded data. Utide derives the principle tidal constituents from the recorded signal and hindcasts the astronomical series. The tool can also be used to predict astronomical tides in the future[14]. Figure 2-5 shows an example of tidal data at Coffs Harbour in August 2016, during an east coast low system. Residual surge (shown in green) has been determined as the anomaly between the recorded water level and the astronomical tide hindcast.

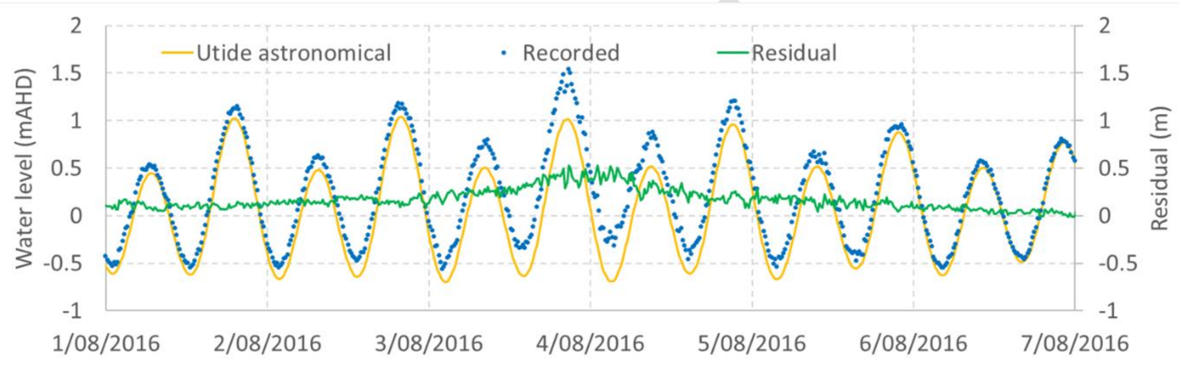


Figure 2-5: Example of recorded, Utide astronomical, and residual water levels at Coffs Harbour

2.3.6 Wave Conditions

Historic wave data for the Clarence region is available from the Coffs Harbour wave buoy, located at the 72m depth contour, approximately 9km offshore of Coffs Harbour. This buoy has recorded data from 1976 to present day. Figure 2-6 shows a predominate south-easterly wave direction for the Coffs Harbour buoy from 1976 to present day. Figure 2-7 shows the monthly fluctuation of wave height across all years in the dataset, with the largest median wave conditions occurring in June and July.

This study uses a probabilistic methodology which does not directly use a single 'deterministic' return period storm scenario. However, extreme wave conditions are estimated here for context. Extreme value analysis (EVA) has been conducted on the historic wave record to estimate extreme wave conditions at the buoy. A peak over threshold (POT) approach has been used to identify extreme events within the recorded data and a Generalised Pareto Distribution (GPD) model has been fit to these extremes to estimate wave heights for more or less frequent events (i.e., greater than the 45 years of data). This analysis produced a range of return periods for extreme wave heights.

14 Codiga, D.L., 2011. Unified Tidal Analysis and Prediction Using the UTide Matlab Functions. Technical Report 2011-01. Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 59pp.

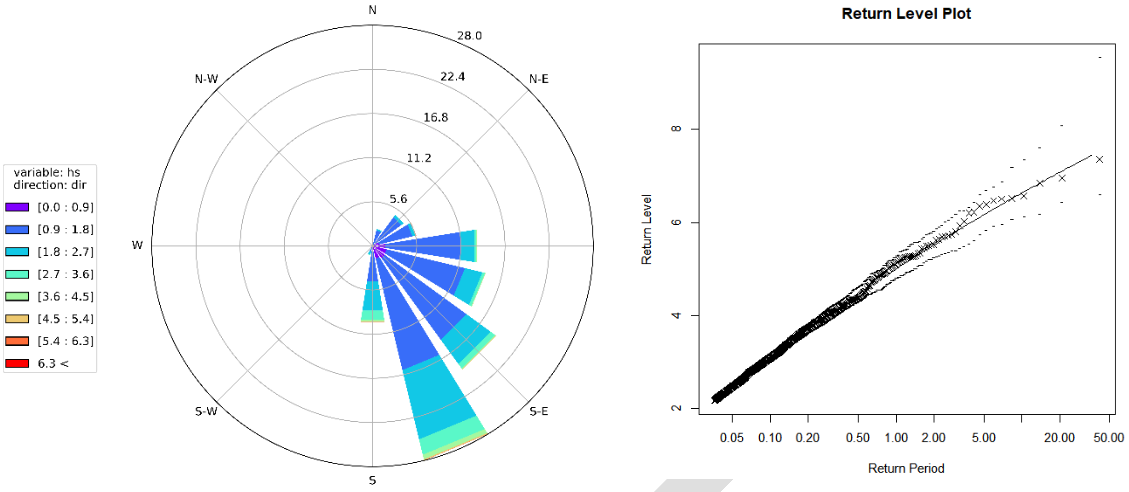


Figure 2-6: Coffs Harbour offshore buoy wave rose (1976 to 2021) (left), and GPD fit to recorded extreme waves (right).

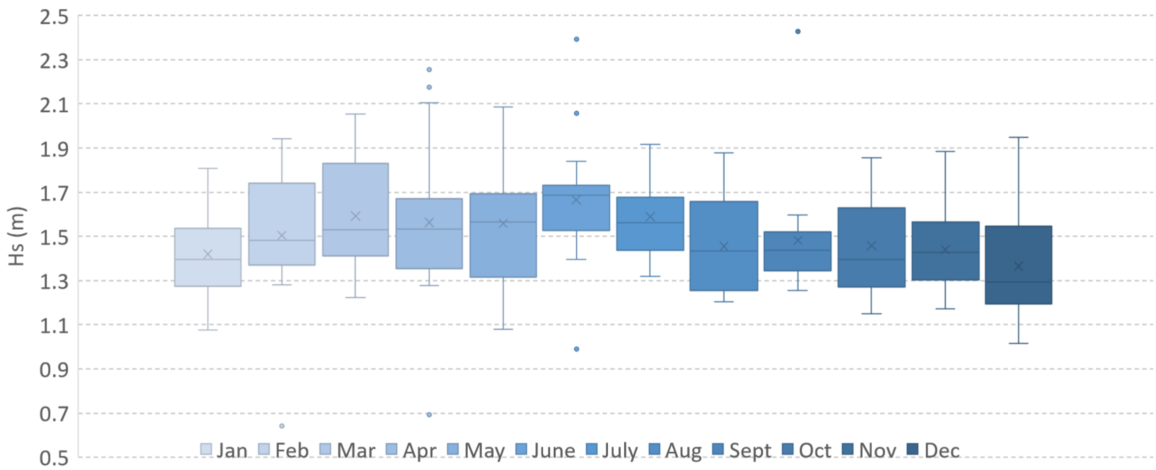


Figure 2-7: Monthly significant wave height at Coffs Harbour wave buoy, crosses show mean monthly wave height across all years in the wave buoy record.

2.3.7 Climate Change Estimates

Planning horizons include present day, +20 years (2043), +50 years (2073), and +100 years (2123) from present, as specified within the NSW Coastal Management Manual[15]. The likelihood scenarios for mapping have been set by the CVC project team in conjunction with State Government feedback and include 50% exceedance scenario (considered frequent), 10% exceedance scenario (considered frequent to rare), 2% exceedance scenario (considered rare), and 1% exceedance scenario (considered rare to very rare).

Two climate change scenarios have been evaluated in this assessment, using predicted changes to water level (sea level rise) as presented by the Intergovernmental Panel on Climate Change (IPCC). The scenarios follow different Shared Socio-economic Pathways (SSP), which consider how socio-economic factors may change over the next century. These include potential changes to population, economic growth, education, urbanisation and the rate of technological development. They are complimentary to Representative Concentration Pathway (RCP) terminology, which

15 State of NSW and NSW Office of Environment and Heritage (2018). Our future on the coast; NSW Coastal Management Manual Part A: Introduction and mandatory requirements for a coastal management program

considers the effect of different levels of greenhouse gases and other radiative forcings. The two climate change scenarios used in this study are:

- SSP2, which represents a pathway where the world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. It considers intermediate greenhouse gas emissions, with carbon dioxide (CO_2) emissions maintaining current levels until 2050, then falling, but not reaching net zero by 2100. It reflects an RCP of 4.5.
- SSP5, which represents the highest level of fossil fuel use, food demand, energy use and greenhouse gas emissions. It includes very high greenhouse gas emissions, where CO_2 emissions triple by 2075. However, it also includes a socio-economic pathway where competitive markets, innovation and participatory societies are able to produce rapid technological progress to achieve sustainable development over the long-term. It reflects an RCP of 8.5.

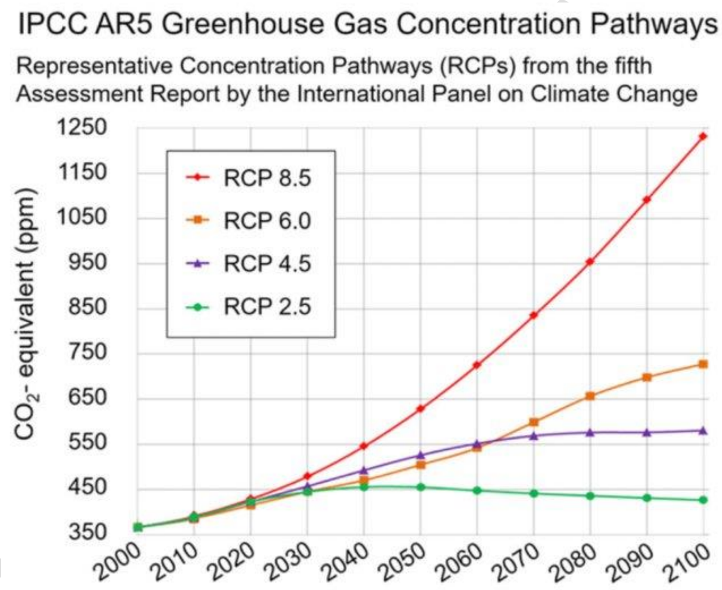


Figure 2-8: Differences in RCPs for future time periods (Hanna, J. W et al. 2020).

Changes to water level

In 2021 CVC commissioned consultants Risk Frontiers (2021[16]) to undertake a climate risk assessment. The highest greenhouse gas scenario is RCP8.5 (SSP5) and represents a worst-case scenario where GHG emissions continue to increase, and global mean temperature increase exceeds 4ºC. RCP4.5 (SSP2) is a 'middle-of-the-road' GHG emission scenario where some mitigation of GHG emissions occurs, and global mean temperature increase is between 2-3ºC. RCP8.5 translates into greater sea level rise compared to RCP4.5. RCP4.5 is considered to be a more realistic future scenario whereas RCP8.5 is currently considered to be less likely. The Risk Frontiers (2021) report was adopted by Council in April 2022.

Sea level rise estimates for each planning horizon were based on the IPCC Assessment Report 6 (AR6), derived from the NASA Sea Level Projection Tool[17]. Sea level rise projections for SSP2 and SSP5 are shown in Table 2-3, which are provided for 5th, 50th, 95th percentiles. Sea level rise estimates for planning horizons 2043, 2073, and 2123 are shown in Table 2-2, and were obtained by linearly interpolating the values (to the full range, 0-100%) from Table 2-3 to the adopted planning horizons.

16 Risk Frontiers (2021) *Physical Climate Risk Assessment - Coastal Flood and Sea Level Rise, Supplementary Report S6*
17 Available at: https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool?psmsl_id=310

Table 2-2: Interpolated mean sea level rise estimates for 2043, 2073, and 2123.

Year	SSP2 (RCP 4.5) (m)			SSP5 (RCP 8.5) (m)		
	5th percentile	50th percentile	95th percentile	5th percentile	50th percentile	95th percentile
2043	0.10	0.17	0.27	0.12	0.19	0.30
2073	0.23	0.37	0.62	0.30	0.46	0.76
2123	0.43	0.76	1.34	0.63	1.09	1.89

Table 2-3: Mean sea level rise estimates (IPCC, 2021)

Year	SSP2 (RCP 4.5) (m)			SSP 5 (RCP 8.5) (m)		
	5th percentile	50th percentile	95th percentile	5th percentile	50th percentile	95th percentile
2020	0.01	0.05	0.10	0.02	0.06	0.10
2030	0.05	0.10	0.17	0.06	0.11	0.18
2040	0.09	0.15	0.24	0.10	0.17	0.27
2050	0.12	0.21	0.35	0.16	0.25	0.39
2060	0.16	0.27	0.46	0.21	0.33	0.53
2070	0.21	0.35	0.58	0.28	0.43	0.70
2080	0.26	0.42	0.71	0.36	0.54	0.89
2090	0.30	0.50	0.85	0.46	0.68	1.11
2100	0.35	0.57	1.00	0.53	0.82	1.35
2110	0.37	0.66	1.15	0.53	0.92	1.59
2120	0.42	0.73	1.30	0.61	1.05	1.82
2130	0.45	0.81	1.44	0.68	1.18	2.05
2140	0.49	0.89	1.59	0.75	1.30	2.28
2150	0.53	0.96	1.73	0.82	1.41	2.50

Changes to wave conditions

The future wave climate has been assessed using global wave modelling, the Centre for Australian Weather and Climate Research (CAWCR), and Commonwealth Scientific and Industrial Research Organisation (CSIRO). This used the CAWCR global wind-wave 21st century climate projections and Coordinated Ocean Wave Climate Project (COWCLIP) '218' dataset, which contains a standardised set of global wave model outputs from a variety of modelling centres (referenced here as different 'ensembles'). The standardised COWCLIP data are available for a historical period spanning 1979-2004 and for the projected future period at the end of the 21st century 2081 to 2099. The model outputs from the available COWCLIP2 and CAWCR data contains multiple model simulations (ensembles), which were analysed to identify the projected changes in wave parameters on a monthly and annual basis using the historical and end-of-century datasets for SSP2 and SSP5 scenarios.

Figure 2-9 presents the ensemble model outputs showing the variability (envelope of all ensembles) and mean predictions in future wave conditions. Changes are reported for three parameters:

- Change in Significant Wave Height (Hs), measured as a percentage of present values.
  - The envelope of SSP2 ensembles show a decrease in Hs, with an average of -6% by 2123.
  - There is greater variability within the SSP5 ensembles, some showing a positive and negative change in Hs. Overall, the average result is a small decrease in Hs of -2% by 2123, however this variability should be noted.
- Change in Mean Wave Period (Tm), measured as a percentage of present values.

18 Morim, J., Trenham, C., Hemer, M. et al. A global ensemble of ocean wave climate projections from CMIP5-driven models. Sci Data 7, 105 (2020). https://doi.org/10.1038/s41597-020-0446-2

- The envelope of SSP2 ensembles show only small changes (either positive or negative) from current conditions for the next 50 years. However, by 2123 all ensembles indicate a reduction in Tm, with an average of -2%.
    - Similar trends exist until 2050 for the SSP5 ensembles, after which far greater uncertainty exists. By 2123 different ensembles present both increases or decreases to Tm, with an average +1%.
- Change in Mean Wave Direction (Dm) measured in degrees, where negative is an anticlockwise shift.
    - All ensembles show a mean anticlockwise change in wave direction indicating more northerly waves.
    - By 2123, under SSP2 the average change is -3 degrees. Under SSP5 the change in Dm increases to -7 degrees northward.

Table 2-4: Future changes to wave conditions (mean)

SSP	Year	Hs (%)	Tm (%)	Dm (˚)[1]
SSP2 (RCP 4.5)	2043	-0.40	0.08	-0.71
	2073	-1.75	-0.25	-1.73
	2123	-6.01	-1.96	-3.29
SSP5 (RCP 8.5)	2043	-0.59	0.16	-1.03
	2073	-1.38	0.45	-2.85
	2123	-2.42	1.11	-6.57
[1]Negative is an anticlockwise shift				

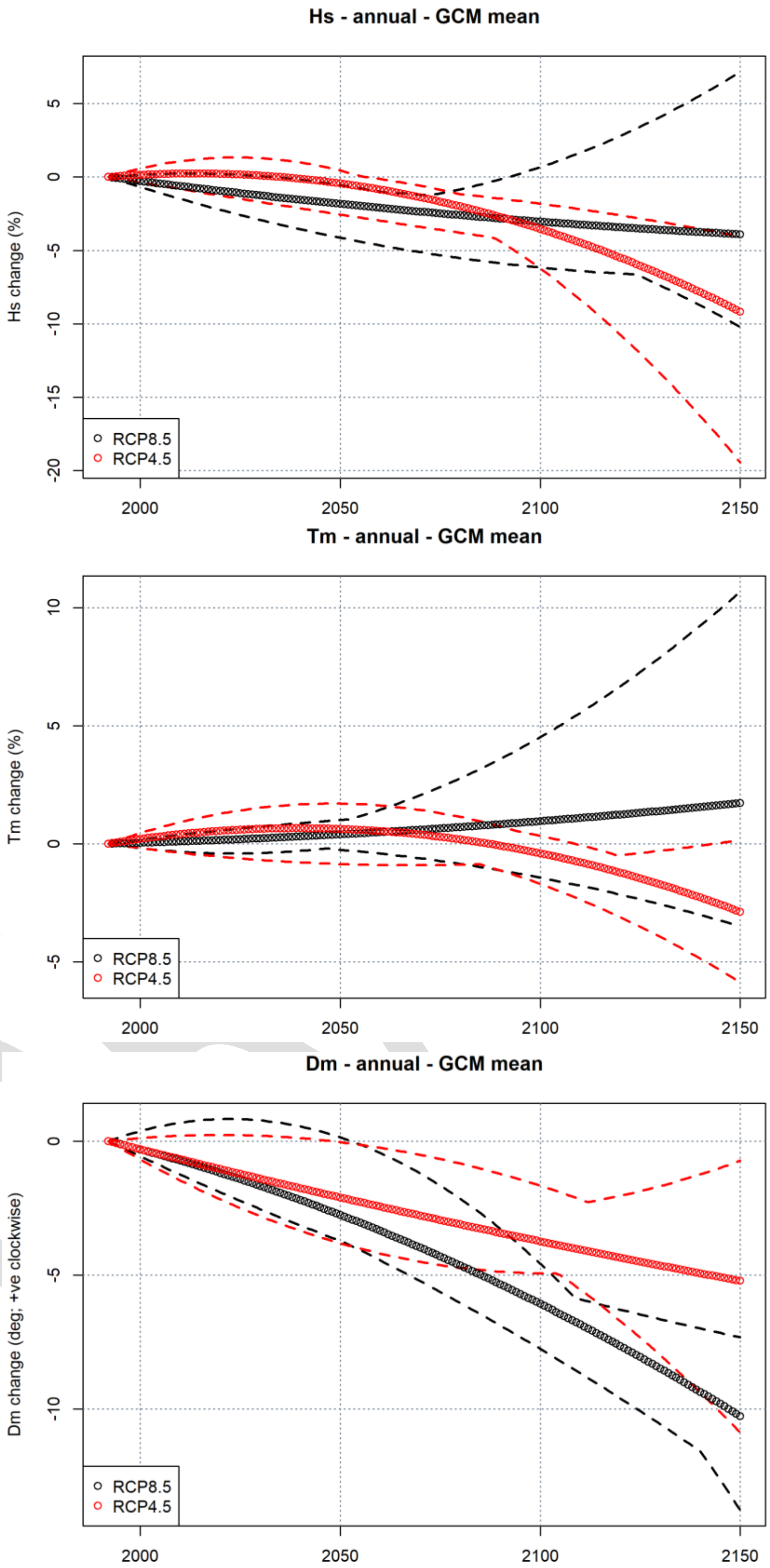


Figure 2-9: Future wave projections. Top: Significant wave height. Middle: Mean wave period. Bottom: Mean Wave Direction.

3 Erosion and recession analysis

3.1 Overview

Beach erosion and recession hazards have been calculated using a probabilistic framework. The study applies a stochastic simulation to evaluate coastal processes, which uses a distribution of values for each parameter to account for expected variation, or uncertainty, rather than single values.

The Coastal Management Manual, which guides the preparation of a CMP and hazard maps, does not specify a required methodology to estimate erosion hazards. However, three alternative analysis methods have been presented by the NSW State Government that can be followed to develop increasingly detailed maps:

1. Proximity analysis (First pass)
2. Regional-scale modelling (Second pass)
3. Local government hazard lines (Third pass)

The First Pass (Proximity analysis) and Second Pass (Regional-scale modelling) assessments have been completed for the NSW coastline, with the latter moving towards a probabilistic framework. This study now provides a detailed erosion and recession assessment for a larger number of beaches, continuing the use of the probabilistic framework and incorporating additional local datasets.

3.1.1 First and second pass assessments

The First Pass assessment used a simple proximity analysis to consider potentially erodible sandy coast featuring properties that may be affected by coastal erosion at present or in the future. This used proximity buffers extending 55, 110 and 220 metres landward from open-coast sandy shorelines. The assessment is considered a useful tool for identifying locations where coastal erosion may be an issue and was referenced within the CMP Phase 1 Scoping Study.

The Second Pass assessment (Kinsela et al. 2017)[19] used a sediment-compartment templating approach to characterise the morphology and sediment budgets of NSW beaches. This was applied through a probabilistic framework to consider uncertainty in model inputs. It used a Volumetric Beach Response model, where the long-term erosion was calculated based on a sediment budget imbalance between sources and sinks. It considered three main components:

$$Erosion = Littoral\ Sediment\ Changes\ + Sinks\ and\ Sea\ Level\ Rise + Sediment\ Cell\ Changes$$

Where:

- Littoral Sediment Changes describe underlying change in the littoral sediment budget as either cross-shore (Qx) or alongshore (Qy) sediment transport processes.
- Sinks and Sea Level Rise describe the response of the shoreface and estuarine flood-tide delta sinks to sea-level rise.
- Sediment Cell Changes describe the annual sediment losses or gains due to aeolian processes, barrier washover, mega-rips, biogenic sediment production, and river supply.

The Volumetric Beach Response model is described in full within Kinsela et. al (2016)[20], which estimates the sediment volume flux per metre of beach (V_T):

$$V_T = C_F(V_F) + C_R\left[(q_x + q_y)t + C_S(V_S) + \left(\frac{A_D.S}{L}\right) + \left(\frac{V_o+V_A+V_M+V_C}{L}\right)t\right]$$

Where:

- q_x = historical shore-normal sediment flux rate

19 Kinsela, M.A., Morris, B.D., Linklater, M. and Hanslow, D.J., 2017. Second-pass assessment of potential exposure to shorlein change in New South Wales, Australia, using a sediment compartments framework. J. Mar. Sci. Eng. 2017, 5, 61; doi:10.3390/jmse5040061

20 Kinsela, M.A., Morris, B.D., Daley, M.J.A. and Hanslow, D.J., 2016. A Flexible Approach to Forecasting Coastline Change on Wave-Dominated Beaches. In: Vila-Concejo, A.; Bruce, E.; Kennedy, D.M., and McCarroll, R.J. (eds.), Proceedings of the 14th International Coastal Symposium (Sydney, Australia). Journal of Coastal Research, Special Issue, No. 75, pp. 952-956. Coconut Creek (Florida), ISSN 0749-0208.

- q_y = historical alongshore sediment flux rate
- V_F = fluctuating erosion from storms and variability
- V_S = theoretical shoreface accommodation volume
- V_O = sediment loss via barrier overwash
- V_A = sediment loss via aeolian transport to dunes
- V_M = sediment loss via mega-rips during storms
- V_C = carbonate sediment dissolution or production
- A_D = surface area of marine (flood-tide) delta
- S = sea level change over forecast period
- L = alongshore length of sediment cell

The resulting coastal hazard maps are available for the NSW coastline, however do not span all time horizons or climate scenarios.

3.1.2 New probabilistic erosion approach

The CVC Coastal Hazards Assessment has incorporated additional local-scale data, regional wave modelling, multiple climate scenarios and new erosion modelling for the open coastline. Each location has been defined by discrete beach blocks, based on the segments contained within the NSW Coastal Profile Database. This allows improved resolution for each coastline, for example, the Sandon coastline has been defined by seven beach blocks. Within each block, the potential zone of erosion and recession has been calculated based on a subset of processes identified within the Kinsela volumetric model, each subject to new analysis. The decision to select key erosion parameters has been made to balance level of detail, number of beaches being assessed, available time and local processes. This includes:

User defined parameters:

- The planning year (present day, 2043, 2073, 2123)
- Return period (50%, 10%, 2%, 1% exceedance probabilty)
- Climate pathway (SSP2, SSP5)

The resulting erosion and recession zone is then calculated based on four statistical, evidence-driven or modelling parameters:

- Historic recession rate
- Future variability in wave climate
- Potential sea level rise impacts
- Storm (event-based) erosion.

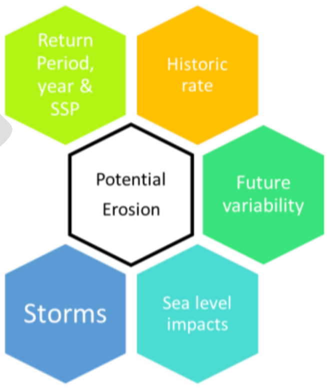


Figure 3-1: CVC probabilistic assessment

These parameters have been combined to calculate the volume of potential coastal erosion and recession hazards. This uses the following equations:

$$E_T = q_x N(1 + q_y) + S + V$$

Where:

- E_T = the estimated erosion at a given planning horizon (m^3)
- q_x = historical shore-normal recession rate (m^3/yr)
- N = number of years to planning horizon
- q_y = factor applied to q_x to account for changes in cross-shore recession deficit due to changes in future wave climate and Longshore Sediment Transport rates
- S = shoreline changes due to erosion from changes in sea level (m^3)
- V = event-based erosion due to storms (m^3)

This volume has been converted to a hazard width for each beach block that is measured landward from the coastline. The four key terms (q_x = historical recession, q_y = changes in longshore sediment transport, S = shoreline changes due to sea level rise, and V = event-based storm erosion) are described in the following sections.

3.2 Historical shore-normal recession rate (q_x)

The historical shore-normal recession rate is calculated using coastal profile data, remote sensing and image analysis. Three datasets were explored for use:

1. Long-term trends of annual shoreline position estimated through the Geoscience Australia (GA) Digital Earth Australia (DEA) dataset.
2. Trends within the NSW Beach Profile Database for a contour above the beach fluctuation zone (e.g. 3 to 4m AHD)
3. Long-term trends of mean sea level variation estimated by CoastSat

This study has adopted the long-term trends captured within the Geoscience Australia Digital Earth Australia (DEA) Coastlines data for the open coastline. DEA Coastlines is a continental dataset along the whole of Australia's coastlines dating back to 1988. It utilises sub-pixel waterline extraction from GA's satellite data in combination with a pixel-based tidal modelling to digitise the annual mean sea level coastlines and rate of change of shoreline positions[21].

The use of the DEA has both advantages and disadvantages when comparing to the NSW Beach Profile Database. The primarily advantage of using the DEA is the greater frequency and length of the available timeseries data which allows an in-depth analysis of the long-term shoreline position. The significant quantity of data is considered beneficial as a broad analysis of annual and seasonal variation and can allow a correlation to climate drivers. The dataset has been corrected to account for tidal fluctuation using an assumed fixed beach slope and presents both annual rates of change and standard deviation.

The drawbacks of the DEA Coastlines data are that it captures mean sea level variation, which is situated within a dynamic part of the beach. The consequences of coastal erosion are typically due to movement of the dune crest, not the mean sea level, which would be best undertaken using the NSW Beach Profile Database for a contour above the beach fluctuation zone (e.g. 3 to 4m AHD). The NSW Beach Profile Database has limitations due to the limited length of beach profiles within the database. A comparison of satellite derived coastline positions (albeit using CoastSat) and detailed photogrammetry has been undertaken in previous investigations at Wooli, with the results showing a degree of correlation between both approaches[22]. Given these factors, the use of the Geoscience Australia DEA Coastlines tool is considered to have the greatest advantages to the study.

An example of historic fluctuations of mean shoreline position using the DEA Coastlines data is shown in Figure 3-2 for Shark Bay and Woody Bay, and recession rates are shown in Figure 3-3 for the CVC coastline.

21 Bishop-Taylor, R., Nanson, R., Sagar, S., Lymburner, L. (2021) Mapping Australia's dynamic coastline at mean sea level using three decades of Landsat imagery, Remote Sensing of Environment, Volume 267. ISSN 0034-4257

22 RHDHV (2020) Wooli Beach Management Strategy, App C - PA2345 Recession Analysis_FINAL.pdf (Section 4.2.2 CoastSat)

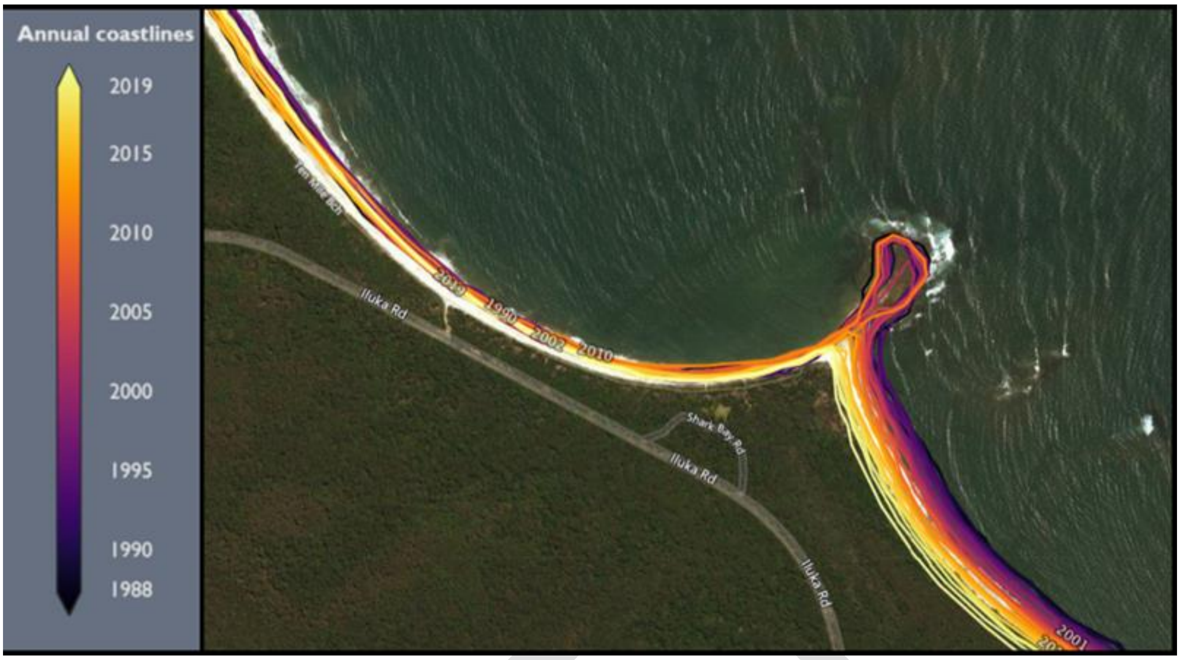


Figure 3-2: Example DEA Coastline data at Shark Bay (source: DEA web interface, https://maps.dea.ga.gov.au/).

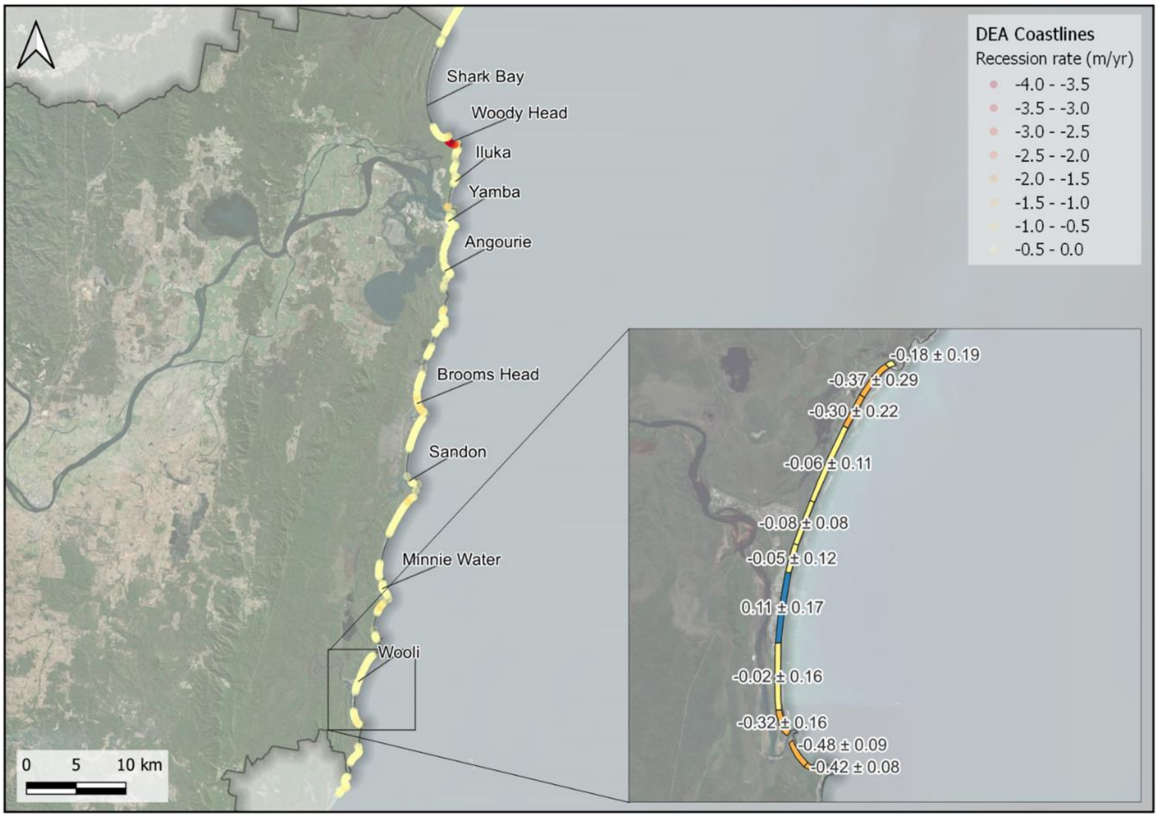


Figure 3-3: DEA Coastlines annual recession rate for Clarence Valley coastline. Annual recession rates have been averaged for each beach block, as shown in the inset map for Wooli

3.2.1 Probabilistic inputs for historic recession rate (qx)

Historic recession has been expressed in probabilistic terms. The method to process historic recession has been to:

- Extract the annual recession rate for all points from the GA DEA dataset. These are typically available at a 2km chainage within each beach block.
- For each block, an average value of the mean recession rate (m/yr) and standard deviation was calculated.
- These linear rates have been converted to volumes on each beach block by assuming a triangular loss of sediment, as described in Section 3.3.2.
- Future planning period volume loss is estimated by multiplying current loss by N number of years.
- For each planning period, recession (or accretion) volume is represented as a normal distribution

Table 3-1: Example probabilistic input table for q_x - Annual mean historic recession

Parameter	Units	Distribution	Mean (m^3/yr)	Standard deviation
qx - Annual mean historic recession[1]	m^3	Normal	16.1	15.5
[1]Example for one beach, Wooli Beach Block 7, for 2043 planning period. Appendix B contains detailed data.				

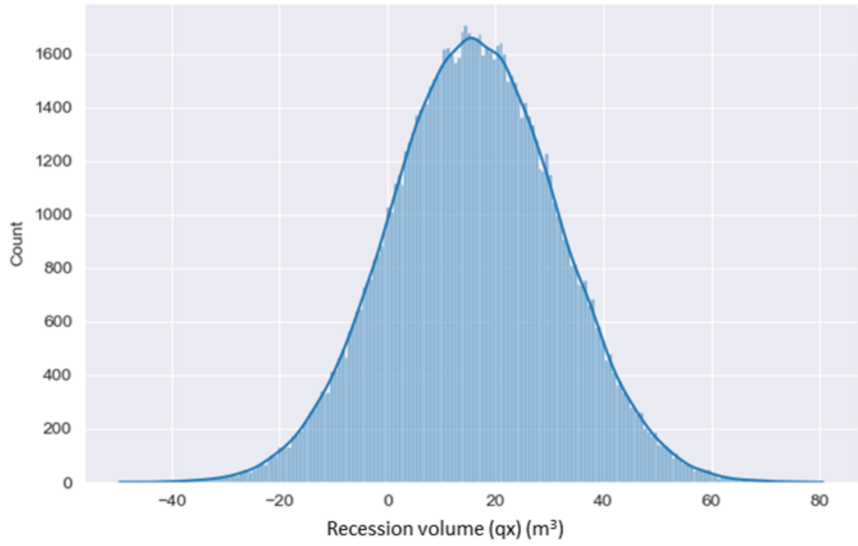


Figure 3-4: Example distribution of recession volume, for Wooli Block 7, 2043 planning period.

3.3 Recession changes due to future alongshore sediment flux (q_y)

A gradient in Longshore Sediment Transport (LST) is a driver of long-term recession. Future changes to wave conditions will alter the LST rate and is therefore expected to alter the historic recession rates. The magnitude of this change has been explored by considering the present day and future sediment budget.

3.3.1 Background

No detailed sediment budgets exist for this section of the northern NSW coastline; however, a range of literature is available that summarises the key LST processes.

Available descriptions, whilst not based on contemporary numerical modelling approaches, describes two different LST trends which are split at the Clarence River training walls. To the south, LST rates entering the compartment from Coffs Harbour equal those at Yamba, although some interruption and leakage is assumed around headlands. To the north, LST rates begin to increase, with more leaving each cell than being restored. LST estimates are shown in Table 3-2 and summarised below by Short (2020)[23].

- Compartment NSW01.01 Clarence River to Point Danger

  This long sediment compartment spans north of the Clarence River and continues beyond Ten Mile Beach to the north. It is comprised of drift-aligned sandy beaches, with some rocky headlands. The entire 170 km long system is part of a major continuous transport system that increases in volume from 250,000 m^3/year at the Clarence River to 500,000 m^3/year at Tweed Heads. This differential in LST provides a gradient that can drive long-term recession.

- Compartment NSW01.02 Yamba to South West Rocks

  Spanning south of the Clarence River, this sediment compartment has predominately sandy shorelines which are bounded by frequent rocky headlands and trained river mouths. Various LST estimates exist to the south of the cell, with expected bypassing of the Coffs Harbour training walls now estimated between 60,000 to 75,000 m^3/year heading northwards. No recent detailed studies have been completed for the rocky section of headlands between Coffs Harbour/Sandy Beach (Bare Bluff) and Wooli (Barcoongere headland), which extends into the CVC study area. Previous work suggests the deeply embayed coastlines, headlands and reefs will have some degree of interruption to LST, with some sediment also lost from the shelf sand body. Rates within embayments will be lower than the seaward littoral pathway, for example, estimates within the Wooli embayment are between 10,000 and 30,000 m^3 (RHDHV, 2017)[24]. Based on the presence of exposed Pleistocene dunes, previous studies concluded the coast is slowly receding, although most sand remains in transit through the system. The primary sediment pathway is moving along the beaches and bypassing the headlands, which Chapman et al. (1982)[25] suggests are only a partial obstacle to sand transport. The result is that the net LST rate is maintained, with 75,000 m^3/year[26,27] estimated to reach the Clarence River.

Table 3-2: Estimated rates of longshore sand transport through study site (from Short, 2020)

Location	LST Rate (m^3/yr)	Reference
Shark Bay	250,000	Patterson (2007b)[28]
Clarence River (N)	200,000	Thom et al. (2018)[29]
Clarence River	150–200,000	BMT WBM (2013b)[30]
Clarence River (S)	75,000	Floyd and Druery (1976) and Goodwin et al. (2006)
Wooli	10–30,000	RH DHV (2017)
Coffs Harbour	75,000	Lord and Van Kerkvoort (1981a, 1981b)[31] [32] and Gordon (1987) [33]

23 Short (2020) Australian Coastal Systems, Beaches, Barriers and Sediment Compartments, School of Geosciences, University of Sydney, Sydney, NSW, Australia

24 Royal Haskoning DHV (2017) Surfers paradise sand backpassing: forward planning report. Prepared for Gold Coast City Council, M&APA102R001F04, Royal Haskoning DHV, Burleigh Heads, 84 p plus appendices

25 Chapman DM, Geary M, Roy PS, Thom BG (1982) Coastal evolution and coastal Erosion in New South Wales. Coastal Council New South Wales, Sydney, 341 pp

26 Floyd CD, Druery BM (1976) Results of river mouth training on the Clarence bar, NSW, Australia. In: 15th international coastal engineering conference, Honolulu, American Society of Civil Engineers

27 Goodwin ID, Stables MA, Olley JM (2006) Wave climate, sand budget and shoreline alignment evolution of the Iluka–Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Mar Geol 226:127–144. https://doi.org/10.1016/j.margeo.2005.09.013

28 Patterson D.C. (2007b). Sand transport and shoreline evolution, northern Gold Coast, Australia. Journal of Coastal Research, Special Issue 50.

29 Thom, Bruce G.; Eliot, I G; Eliot, M; Harvey, Nicholas; Rissik, David; Sharples, Chris; Short, Andrew D.; and Woodroffe, Colin D., "National sediment compartment framework for Australian coastal management" (2018). Faculty of Science, Medicine and Health - Papers: part A. 5215.

30 BMT WBM (2013). Byron Shire Coastline Hazards Assessment Update. Prepared for Byron Shire Council

31 Lord & van Kerkvoort (1981a):A Coastal Process Investigation, Coffs Harbour, NSW. 5thAust. Conf.on Coastal and Ocean Engg., IEAust., Perth, 150-154.

32 Lord, D., & Kerkvoort, A.V. (1981b). The Effects of a Major Harbour Construction on Longshore Sediment Movement - Coffs Harbour, New South Wales.

33 Gordon, A.D., 1987. Beach fluctuations and shoreline change - NSW, 8th Australasian Conference on Coastal and Ocean Engineering, Launceston, p. 5

3.3.2 Sediment budget

A new regional sediment budget has been developed by JBP using the Geoscience Australia DEA Coastlines data and the processed annual mean historic recession rate (q_x) for each beach block. This included the following steps:

1. The average long-term linear recession rate (m/yr/block) is converted to a volumetric rate
2. The elevation of the most seaward dune crest was identified from LiDAR for each beach block (e.g. 3m AHD)
3. The change in beach volume was estimated as:
    - *Elevation of dune crest x linear recession rate (m/yr) at MSL x 0.5*
4. The 0.5 factor has been used to create a triangular beach cross section, which assumes the crest is relatively stable (Figure 3-5). This is acknowledged as an approximation only.
5. The volumetric change is multiplied by the beach block length and summed to get a regional sediment budget.

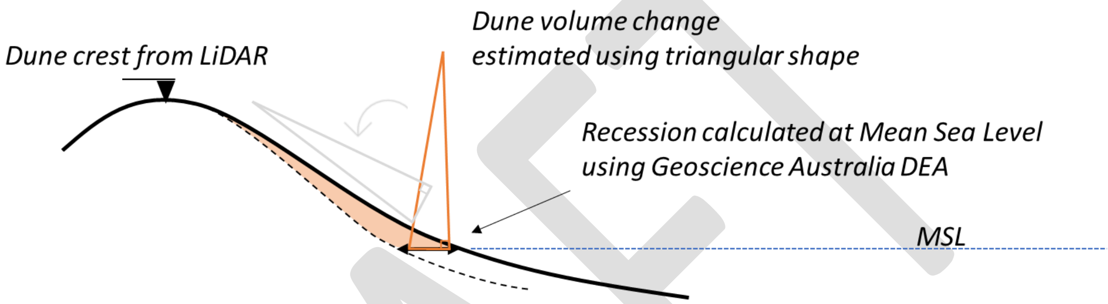


Figure 3-5: Dune volume change approach for sediment budget

The calculated total annual volumetric sediment change of the southern LGA between Wooli and Yamba was approximately -8,752 m^3/year (net recession). A summary of all main beaches is shown in Table 3-3. This deficit has been used to present an overall Sediment Budget alongside published LST rates in Figure 3-6. This indicates:

- Around 75,000 m^3/year of sand is entering the LGA
- Approximately -10,000 m^3/year of sediment is being lost from the sandy beaches between the southern LGA and breakwalls at Yamba. This is expected to be adding to the LST passing along the coastline. To balance this budget, there is 85,000 m^3/year sediment reaching the Yamba breakwalls (a slight increase in LST rates, which fits into the trends presented in Table 3-2).
- Additional losses to the LST may be offshore, which have not been considered in detail within this assessment.

Table 3-3: Annual volumetric sediment change for each beach compartment in the Clarence Valley.

Beach compartment	Annual volumetric sediment change (m^3/year)
Shark Bay	2,223
Woody Bay	-5,508
Back Beach	-31
Bluff Beach	-44
Iluka Beach	3,146
Training Walls	
Yamba	-59
Angourie	-235
Shelley Head	-1,231

Brooms Head	-1,853
Sandon	-3,106
Minnie Water	-354
Diggers Camp	-155
Wooli Beach	-1,756

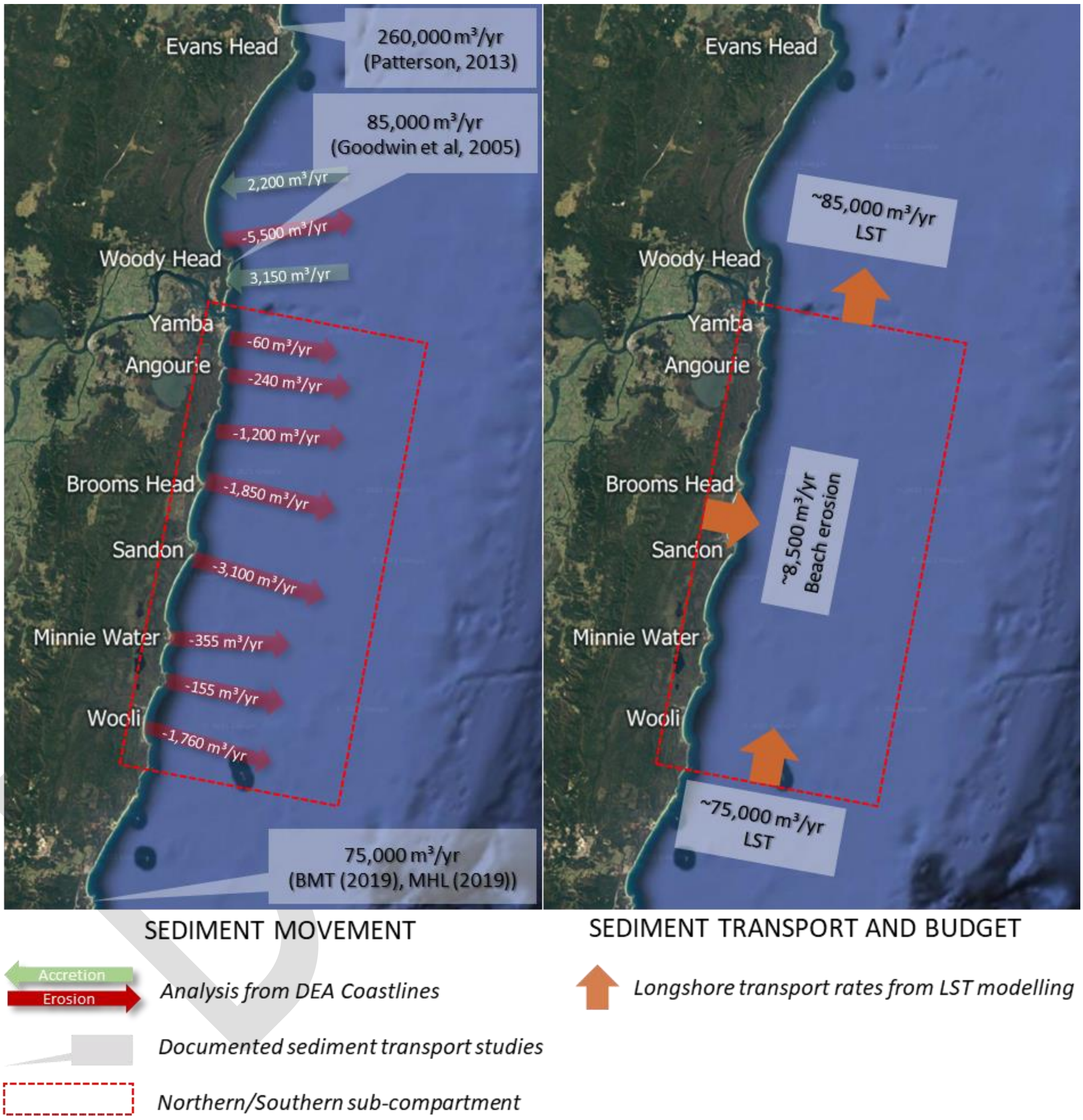


Figure 3-6: Beach recession or accretion rates (left) and overall Sediment Budget south of the Clarence River (right)

3.3.3 Longshore Sediment Transport assessment

The potential future variability in sand entering the Clarence Coastline has been analysed using new LST modelling. Available literature describes an LST rate of around 75,000m³/year able to enter the region from Coffs Harbour. This historic transport rate is fairly well understood due to sand accumulation within the Coffs Harbour breakwalls following their construction. This created a sand sink which could be quantified using bathymetric data of the harbour, with the erosion to updrift beaches also able to be observed. Recent analysis of the northern dune system shows reduced signs of erosion (Kachel 2021)[34]. This may be a signal that sand bypassing of the harbour may now be occurring, and the historic LST rate may be restored (at least partially).

A LST model was developed and calibrated to the observed historic transport rate. This uses the modified Kamphuis (2013) bulk sediment equation (Mil-Homens et al., 2013[35]). This approach builds on the commonly used CERC[36] formulae and includes the effects of particle size, slope, and wave period, and includes additional reanalysis of the original Kamphuis (1991) equation[37]. The rate of sediment transport (Q) in m^3/hr is calculated by:

$$Q_k = 7.3 \, H_{sb}^2 \; T_p^{1.5} \; m_b^{0.75} \; D_{50}^{-0.25} \; \sin(2\alpha_b)^{0.6}$$

Where, H_{sb} is the significant wave height in the breaker zone, T_p is the peak period, m_b is the slope in the breaker zone, D_{50} is the sediment particle diameter, and α_b is the angle of wave incidence at breaking. It is noted that this formula predicts the potential LST rate, with actual rate of transport generally limited by the availability of sand. This introduces a degree of uncertainty within LST modelling, which adds to the already sensitive nature of LST formulae.

The LST model was forced using the mean wave height, period and direction value for the southern LGA coastline. These mean values were calculated based on the average of the 10,000-year probabilistic nearshore wave record generated, which is described in Appendix A. A calibration factor was introduced to match the estimated LST to the 75,000m^3/year LST rates presented in literature.

The LST model was used to estimate the future changes to LST. Consideration was given to the uncertainty in the available wave, period and direction projections given within the COWCLIP2 and CAWCR ensembles. These datasets show significant uncertainty, where projections show that wave height and wave period may either increase or decrease in the future, which would subsequently increase or decrease the current LST trends. The only parameter showing a strong agreement in ensembles is wave direction, with the majority of future model ensembles showing an anti-clockwise shift. Given the greater certainty in this parameter, it was used to test the magnitude of LST changes. Future offshore wave directions were transformed into the nearshore before being input into the LST model. The 10,000 year probabilistic wave record was altered at the offshore wave model boundary to reflect the two climate scenarios in 2100, where the offshore waves for SSP2 (RCP4.5) was changed by -3.29° and SSP5 (RCP 8.5) by -6.57° (Table 2-4). The 10,000 years of wave conditions were simulated into the nearshore. At this location the wave conditions experienced a smaller anti-clockwise change than the offshore boundary, which is due to the degree of refraction simulated within the wave model. The mean nearshore results experienced an anti-clockwise shift of -0.6° (SSP2) to -1.4° (SSP5).

The input wave conditions and LST results calculated within the LST model are:

- Present day: Average wave conditions from 10,000-year dataset
    - Hs: 1.16m, Tp: 8.41, Av Dir: 99.49°
    - LST: -75,000 (northward) per year – which has been calibrated against existing literature
- 2100 SSP2 (RCP 4.5): Offshore wave direction shifted -3.29°. New average nearshore results:
    - Hs: 1.16m, Tp: 8.41, Av Dir: 98.92°
    - LST: -72,444 (northward) per year. This reflects a decrease by 3%.
- 2100 SSP5 (RCP 8.5): Offshore wave direction shifted -6.57°. New average nearshore results:
    - Hs: 1.16m, Tp: 8.41, Av Dir: 98.08°
    - LST: -68,444 (northward) per year. This reflects a decrease by 9%.

The results show a moderate decrease in northward LST rate, by 3% (SSP2) to 9% (SSP5). These support existing literature on the uncertainties in the future wave-driven longshore sediment

34 Kachel, J (2021) Investigation of Dune Profile Changes at Park Beach, Coffs Harbour. Southern Cross University Final Year Thesis

35 Mil-Homens, J., Ranasinghe, R., Van Thiel de Vries, J.S.M. and Stive, M.J.F., 2013 . Re-evaluation and improvement of three commonly used bulk longshore sediment transport formulas. Coastal Engineering 75, 29 39

36 USACE, 1984, Shore Protection Manual, CO. Eng. Res. Centre, US Army Corps of Engineers, Vicksburg, MS, USA

37 Kamphuis, J.W. 1991. Alongshore sediment transport rate. Journal of Waterway, Port, Coastal and Ocean Engineering, Vol. 117

transport given by Zarifsanayei (2022)[38] who considered changes under two climate scenarios in the Gold Coast, Queensland. The study found an overall decrease in net annual mean LST rates (less than 10% under RCP 4.5, and 10–20% under RCP 8.5), however concluded that no robust projected changes on annual and seasonal scales were found. A similar opinion is given in the present Clarence study, where detailed trends cannot be reliably predicted given the great uncertainty in future wave estimates. Ultimately a potential sediment transport variance distribution spanned from no change (0%) to 3% (SSP2) and 9% (SSP5).

3.3.4 Probabilistic inputs for future alongshore sediment flux (qy)

For sandy coasts, the gradient in LST is one of the key processes shaping the coastline shape over decadal timescales (Splinter et al. 2021)[39]. An increasing range of literature indicates future variability in LST has the potential to lead to new long-term coastal evolution (see Adams et al., 2011[40]; Anderson et al., 2018[41]; Vitousek et al., 2021[42]). This distribution of potential LST changes has used in conjunction with the observed historic erosion rate to consider how coastal evolution may change in the future. This has been applied in future years to alter the current historic recession rate (i.e. historic q_x) to a future rate (future q_x). An underlying assumption used is that the existing headland configuration (which will not change) and LST rate are the key drivers for decadal coastal change, which is driving the local Clarence beaches to evolve into their characteristic curvilinear shoreline (Silvester et al. 1980[43], Woodroffe 2003[44]). The assumption used within this analysis is that if the future LST was to slow down (e.g. half), the future beach evolution rate (future q_x) would decrease accordingly, or vice versa. The magnitude of the future recession rate is based on the estimated LST change (i.e. spanning from no change (0%) to 3% for SSP2 and 9% for SSP5).

Table 3-4: Regional-scale probabilistic inputs for alongshore sediment flux (q_y) in 2123. Negative values indicated reduction in regional sediment transport rates

Parameter	Units	Distribution	Minimum	Mean	Maximum
q_y - SSP2-4.5 (change to historic Qx)	m	Triangular	0.0%	-1.7%	-3.4%
q_y - SSP5-8.5 (change to historic Qx)	m	Triangular	0.0%	-4.4%	-8.7%

38 Zarifsanayei AR, Antolínez JAA, Etemad-Shahidi A, Cartwright N, Strauss D and Lemos G (2022) Uncertainties in the Projected Patterns of Wave-Driven Longshore Sediment Transport Along a Non-straight Coastline. Front. Mar. Sci. 9:832193. doi: 10.3389/fmars.2022.832193

39 Splinter, K. D., and Coco, G. (2021). Challenges and opportunities in coastal shoreline prediction. Front.Mar. Sci. 0:1917. doi: 10.3389/FMARS.2021.788657

40 Adams, P. N., Inman, D. L., and Lovering, J. L. (2011). Effects of climate change and wave direction on longshore sediment transport patterns in Southern California. Clim. Change 109, 211–228. doi: 10.1007/s10584-011-0 317-0

41 Anderson, D., Ruggiero, P., Antolínez, J. A. A., Méndez, F. J., and Allan, J. (2018). A climate index optimized for longshore sediment transport reveals interannual and multidecadal littoral cell rotations. J. Geophys. Res. Earth Surf. 123, 1958–1981. doi: 10.1029/2018JF004689

42 Vitousek, S., Cagigal, L., Montaño, J., Rueda, A., Mendez, F., Coco, G., et al. (2021). The application of ensemble wave forcing to quantify uncertainty of shoreline change predictions. J. Geophys. Res. Earth Surf 126:e2019JF005506. doi: 10.1029/2019JF005506

43 Silvester, R., Y. Tsuchiya, and Y. Shibano, 1980: Zeta bays, pocket beaches and headland control. Coastal Eng. Proc., American Society of Civil Engineers. pp. 1306–1319. doi: 10.9753/icce.v17.%25p

44 Woodroffe, C. D., 2003: Coasts: form, process and evolution. Cambridge University Press, 623 pp

3.4 Shoreline changes due to sea level change erosion (S)

In addition to a changing wave climate, a consequence of sea level rise is that future recession rates will not reflect past conditions. This is commonly linked to the principals described by Bruun (1962)[45], which assume that where a sea level is raised, the equilibrium beach profile will move upward and landward. At geological timescales, it is reasonable to expect that coastal processes have sufficient time to maintain relative beach and dune heights during shore-normal coastline translation. However, for the rapid rates of sea level change projected over the next century, the coastal change is considered more likely to be a loss of sand from the beach profile (i.e., erosion) and a deposition within the nearshore to balance the sediment budget.

A summary of Bruun-concept models has been described within Shand (2013)[46], shown in Figure 3-7. For the CMP framework a volumetric shoreface model has been used, similar to the concept shown in Figure 3-7 (d).

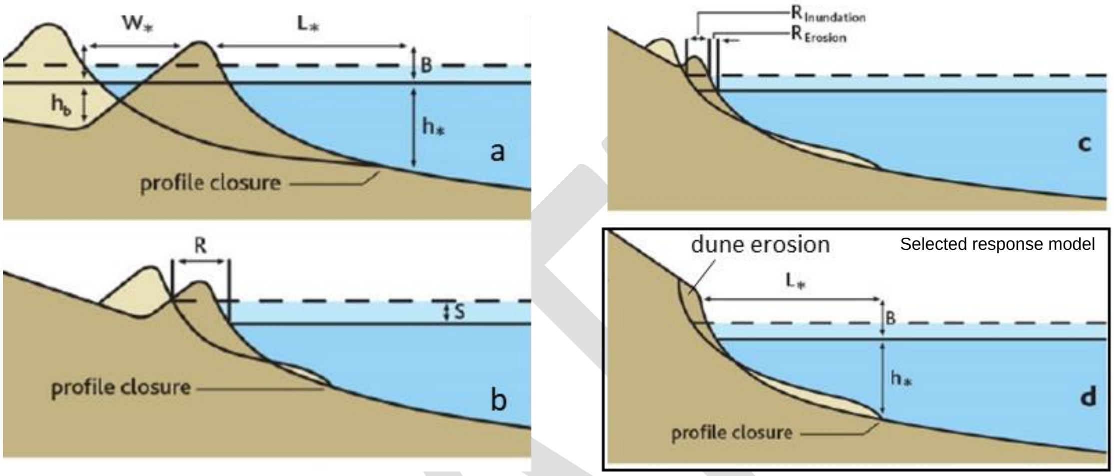


Figure 3-7: Schematic diagrams of the Bruun model modes of shoreline response after Cowell (2001)[47] with (d) adopted for the CVC CMP.

A volumetric model has been developed for each beach block. It fits an idealised shoreface profile of the form $h(x)=Ax^{2/3}$ to the available hydrographic data for each beach transect. The 'A' parameter is adjusted to fit an equilibrium profile through the existing profile data. The equilibrium profile has been fit through the existing profile data using a regression fit, as demonstrated in Figure 3-8. Offshore rocky bedforms have been identified for several beach sections from the NSW marine LiDAR-based seabed landforms dataset (DPE, 2022)[48]. From this dataset, intermittent bedforms along the cross-shore profile have been removed before applying the regression fit (as per Kinsela et al (2017)), as these areas represent potential accommodation space that is already filled by rock outcrop, and thus not available for sand deposition.

The volumetric model raises the entire profile in accordance with sea level rise estimates and translates the shoreface geometry landward to balance the required volumetric change out to the depth of closure. This approach creates a new beach equilibrium profile for future planning horizons, that retreats landward due to rising sea levels. This process is schematised in Figure 3-9. This sea level rise erosion component is combined with the components of shore-normal recession rate (qx) (Section 3.2) and predicted changes to the LST rate (qy) (Section 3.3) to account for future changes in shoreline position.

45 Bruun, P. (1962) Sea level rise as a cause of shore erosion. J. Waterw. Harb. Div. ASCE, 88, 117–130.

46 Shand, T, Shand R, Reinen-hamill, R, Carley, J, Cox, R. (2013). A Review of Shoreline Response Models to Changes in Sea Level.

47 Cowell P.J. and Kench, P.S. (2001) The Morphological Response of Atoll Islands to Sea-Level Rise. Part 1: Modifications to the Shoreface Translation Model. JCR, SI 34 ICS(2000) 633-644

48 Linklater, M., Morris, B., Kinsela, M., Ingleton, T. and Hanslow, D. (2022), Exploring patterns of reef distribution along the southeast Australian coast using marine lidar data. Manuscript in preparation.

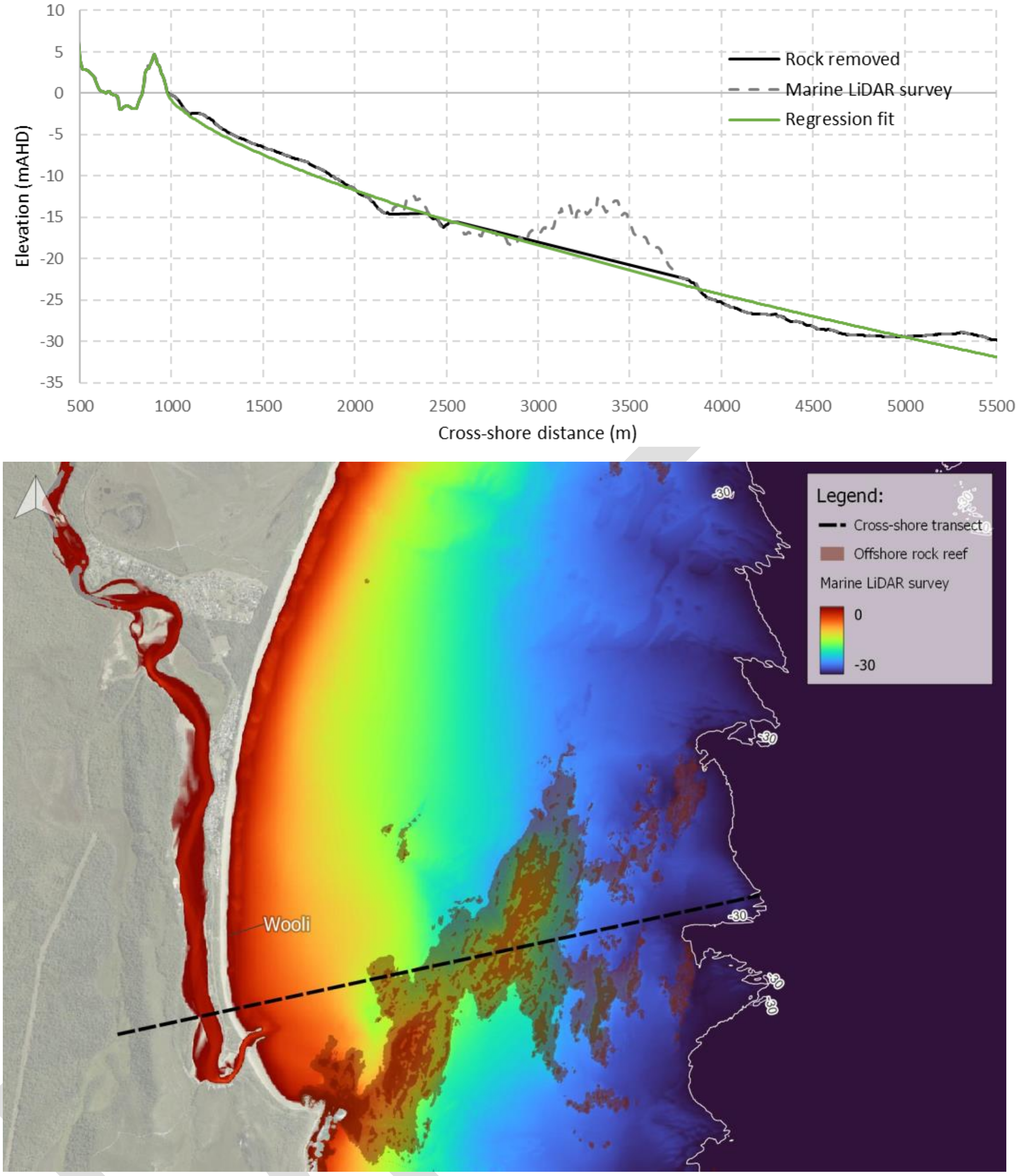


Figure 3-8: Example cross-shore erosion model profile. An equilibrium profile has been fit to the surveyed bathymetry, with seabed rock features removed, using regression fit.

3.4.1 Depth of closure

The depth of closure (DoC) is the seaward limit of effective profile fluctuation over long-term (seasonal or multi-year) time scales and has been estimated using the Coffs Harbour wave buoy data, based on the Birkemeier and Hallermeier formulae. From these formulae, the inner depth of closure was estimated at around -10m AHD for open coast beaches within CVC[49,50]. It was initially proposed to model the DoC as a triangular distribution between the inner and outer Hallermeier limits for future planning horizons. Testing of this method in SLR erosion response modelling produced a significant bias towards large SLR volume loss associated with large DoC.

Following further consideration, it was determined that the modal value of triangular distributions of DoC would be used for each planning period to account for cross-shore profile fluctuation over longer timescales. As the alternative approach of including a distribution of DoC in the erosion width is overly conservative, use of the model value may overlook the influence of a deeper DoC which

49 Birkemeier, W. A. 1985. “Field Data on Seaward Limit of Profile Change,” Journal of the Waterways, Port Coastal and Ocean Engineering, American Society of Civil Engineers, Vol 111, No. 3, pp 598-602.

50 Hallermeier, R. J. 1981. “A Profile Zonation for Seasonal Sand Beaches from Wave Climate,” Coastal Engineering, Vol 4.

may influence profile response in the future. This should be considered in future review and update of this coastal hazard assessment. The DoC has been truncated to account for unerodable offshore rock bedforms as well as sheltering and planform orientation for several beaches. DoC has also been limited for estuarine beaches as noted in Table 3-5. Table 3-5 summarises the depth of closure used for each coastal locations across all planning horizons.

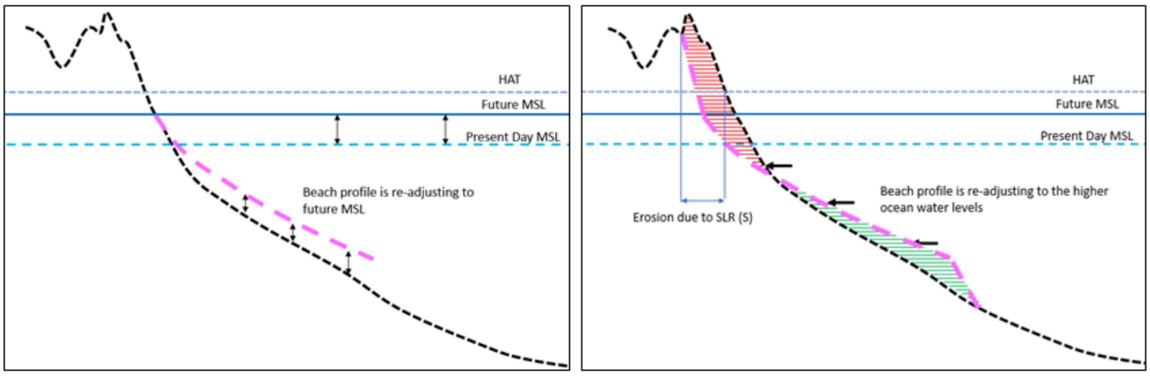


Figure 3-9: Schematisation of erosion-deposition volume balance due to sea level rise

Table 3-5: Depth of closure used in SLR erosion modelling for each coast section.

	2023	2043	2073	2123	Notes
Wooli					
All sections	10	12	14	19	Open coast
Diggers camp					
All sections	7	8	10	13	Scaled to reflect planform orientation and embayment
Minnie Water					
All sections	10	12	14	19	Open coast
Sandon					
Campground	7	8	10	13	Scaled to reflect planform orientation and embayment
North of campground	10	12	14	19	Open coast
Sandon village	2.5	2.5	2.5	2.5	Location within estuary, set to maximum existing channel depth
Brooms Head					
Village	7	8	10	10	Scaled to reflect planform orientation and embayment, max value limited to depth of rock layer
North of Lake Cakora	10	12	14	19	Open coast
Angourie					
All sections	7	8	10	13	Scaled to reflect planform orientation and embayment
Yamba					
Pippi Beach	10	12	14	19	Open coast
Whiting Beach	4	4	4	4	Location within estuary, set to maximum existing channel depth
Woody Head					
All sections	7	8	10	10	Scaled to reflect planform orientation and embayment, max value limited to depth of rock layer
Shark Bay					
All sections	7	8	10	10	Scaled to reflect planform orientation and embayment, max value limited to depth of rock layer

3.4.2 Probabilistic inputs for sea level rise erosion (S)

The modelling uses probabilistic inputs for sea level rise and depth of closure:

- Sea level rise estimates will be based on estimates from IPCC AR6 projections at Yamba (PSMSL310) based on SSP2 (RCP4.5) and SSP5 (RCP8.5) scenarios - see Section 2.3.7 for more details.
- The shape of the distribution of sea level rise is unknown, therefore a triangular distribution is assumed. The triangular distribution is a good approximation of a normal (Gaussian) distribution when the Gaussian parameters are not known, however it does under-predict the number of samples within one standard deviation and over-predicts above 2 standard deviations.
- Linear extrapolation has been used to extend the triangular distribution of sea level rise to the 0th and 100th percentile limits.
- Modelling considers variability in the Depth of Closure. This is based on the potential for increases to the seaward limit of transport over longer time periods, using the Hallermeier (1981) formulae applied to the offshore Coffs Harbour Wave Buoy dataset.

Table 3-6: Probabilistic inputs for (S) sea level rise erosion

Year	SSP2 (RCP 4.5) (m)			SSP5 (RCP 8.5) (m)		
	0th percentile SLR (m)	50th percentile SLR (m)	100th percentile SLR (m)	0th percentile SLR (m)	50th percentile SLR (m)	100th percentile SLR (m)
2043	0.10	0.17	0.27	0.12	0.19	0.30
2073	0.23	0.37	0.62	0.30	0.46	0.76
2123	0.43	0.76	1.34	0.63	1.09	1.89

3.5 Event-based erosion due to storms (V)

This component considers the extent of present day short-term erosion. A summary of the erosion methodology is provided below, with further detail and results presented in Appendix A. Long-term coincident wave, tide and surge data has been analysed from the Coffs Harbour waverider buoy and water level gauge. The data is de-clustered to identify independent storms, a dependence model developed between each variable, and a 10,000-event offshore dataset created using copula-based sampling.

Offshore wave conditions are transformed to the nearshore of each beach block using an LGA-wide spectral wave model. This was undertaken using the Simulating Waves Nearshore (SWAN) model. The offshore model boundary was set to align with the depth of the Coffs Harbour wave rider buoy (approximately -70m).

3.5.1 Exposure factor

Nearshore wave results have been extracted from the model at each coastal location. These results have been used to quantify the level of exposure for the varying types of coastal locations along the CVC coast. As tabulated below, the exposure factor includes the effects of planform sheltering (e.g. Woody Bay), pocket beaches (e.g. Minnie Water), and estuaries (e.g. Whiting Beach). The range of exposure factor for each beach type allows for exposure variation along a given beach, for example due to alignment to prevailing wave conditions.

Table 3-7: Exposure factors for types of CVC beaches, derived from nearshore wave modelling.

	Example location	Exposure factor
Open coast	Wooli Beach	0.85 - 1.0
Pocket embayment	Minnie Water	0.7 - 0.85
Planform sheltering	Woody Bay	0.4 - 0.7
Within estuary	Whiting Beach	0.1 - 0.4

3.5.2 Short-term erosion volume estimation

A volumetric approach has been applied to assess present day short-term erosion. For each beach block, a gamma distribution has been established to describe the potential volume loss from present day short-term erosion, in line with extreme beach erosion volumes presented in Gordon (1987) and augmented with long term beach measurements at Collaroy-Narrabeen Beach (Kinsela et al, 2017). These studies suggest an extreme 1% AEP (100-year ARI) short-term erosion volume of 250m^3/m for open coast locations, as shown in Figure 3-10. The exposure factor at each beach block has been used to scale the respective gamma distribution. The gamma shape parameter has been set to 2.5 for all locations. Figure 3-11 compares storm-bite erosion distributions for open coast and sheltered locations.

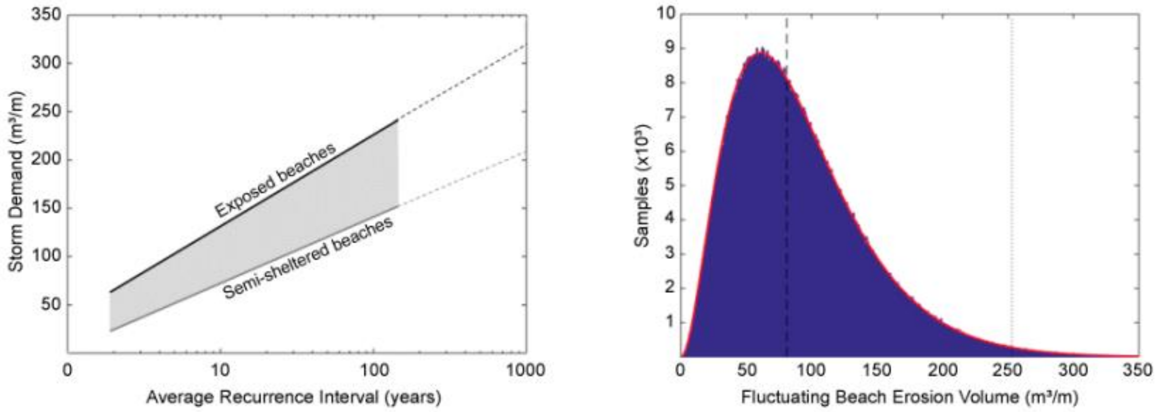


Figure 3-10: Estimation of extreme short-term erosion (storm demand) volume (left), gamma distribution of potential short-term erosion showing 50th (dashed line) and 99th (dotted line) percentiles (right), from Kinsela et al, 2017.

Table 3-8: Example probabilistic input table for V - event-based erosion

Parameter	Units	Distribution	shape	scale
V - event-based erosion[1]	m^3	Gamma	2.5	29.7
[1]Example for one beach, Wooli Beach Block 7				

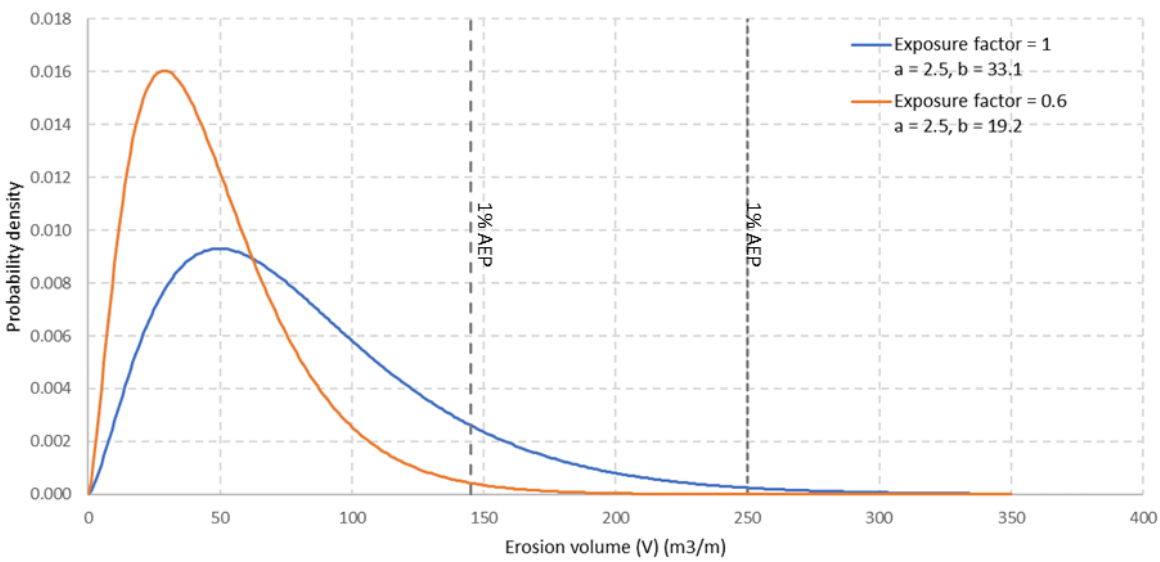


Figure 3-11: Comparison of event-based erosion distributions and 1% AEP storm bite for sheltered (factor = 0.6), and open coast (factor = 1.0) beach locations. Dashed line is 1% AEP for sheltered location (0.6), dotted line is 1% AEP for open coast (1.0).

3.5.3 Zone of reduced foundational capacity (ZRFC)

An additional Zone of Reduced Foundation Capacity (ZRFC) has been incorporated into the event-based erosion calculations. This is an additional Factor of Safety approach applied to estimate the extent of dune instability behind the slumped profile, as shown in Figure 3-12. The extent of this zone has been calculated following the schema of Nelson (1992)[10] which uses the following parameters:

- Scour level of -1m AHD
- Nominal swash zone up to 2m AHD.
- Angle of repose for dune sand (i): 34˚
- Safe angle of repose of dune sand (α): 24˚

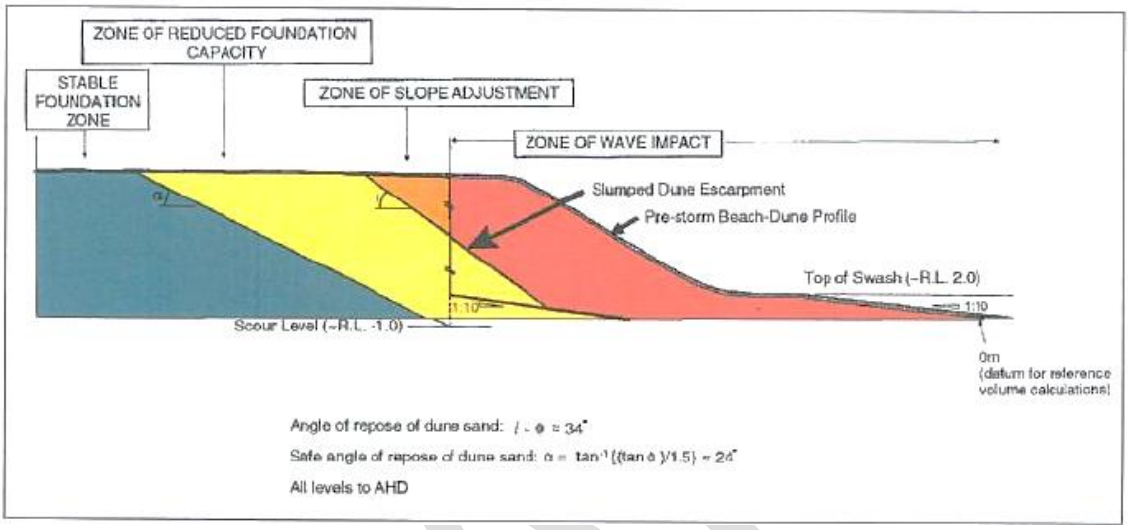


Figure 3-12: Zone of Reduced Foundation Capacity (ZRFC) schematisation (Nielson 1992)

3.6 Total erosion and recession hazard

Each of the components of erosion and recession hazard described above have been represented as a probability distribution:

- Shore-normal recession rate (q_x): normal distribution.
- Recession changes due to future alongshore sediment flux (q_y): triangular distribution.
- Shoreline changes due to sea level change (S): triangular distribution.
- Event-based erosion due to storm (V): gamma distribution.

For each planning period (2023, 2043, 2073, and 2123) a random sample is taken from each distribution and combined using:

$$E_T = q_x N(1 + q_y) + S + V$$

Where E_T is a random total erosion and recession hazard volume. This is repeated a large number of times to produce a distribution of E_T. From this distribution, the 50%, 10%, 2%, and 1% exceedances are extracted, as indicated in Figure 3-10. This process has been conducted for each beach block, planning horizon, and SSP.

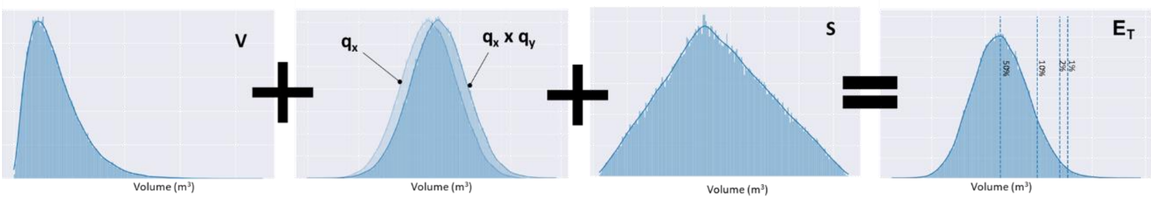


Figure 3-13: Derivation of total erosion and recession hazard (E_T) exceedances

3.6.1 Convergence testing

Random sampling must be conducted a large number of times to ensure a full distribution of E_T, from which exceedance volumes are being derived. Theoretically, an infinitely large sample population will consistently produce the same exceedance value, however this requires a trade off with computational time. Therefore, convergence testing was conducted to determine the number of sample iterations necessary to reliably reproduce the 1% exceedance value, within an acceptable tolerance. The acceptable number of sampling iterations was determined to be 100,000, which is demonstrated in Figure 3-14.

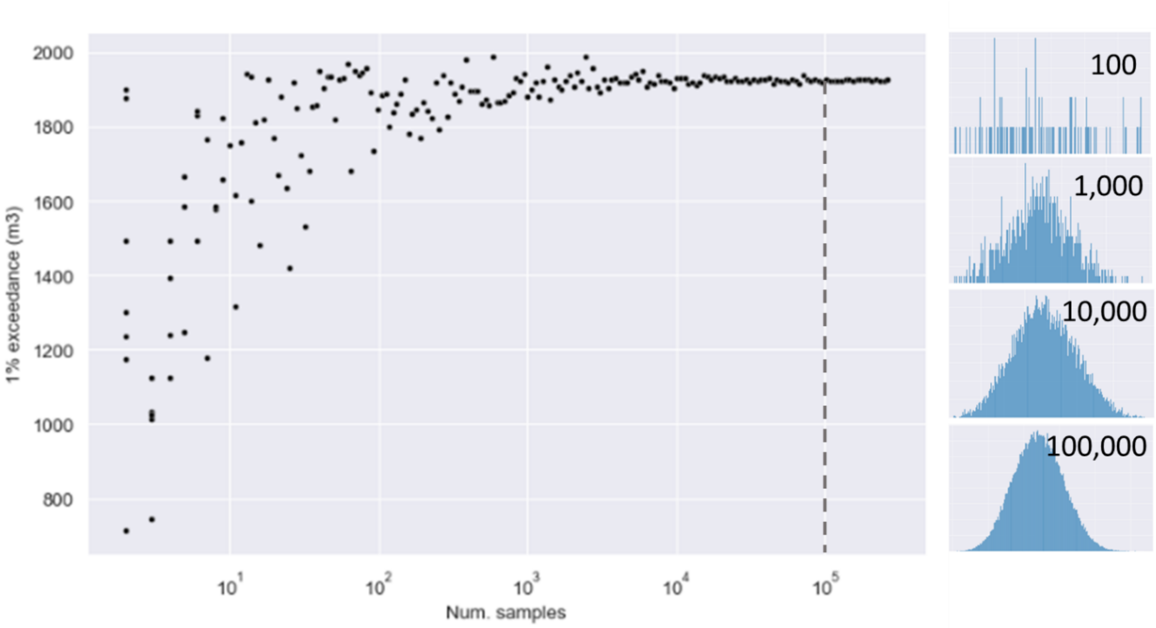


Figure 3-14: Convergence testing of total erosion and recession hazard 1% exceedance

4 Mapping

The erosion and recession assessment considered five factors. The first is the hazard scenario in terms of its planning horizon, return period and climate pathway. The remaining four relate to the historic recession rate, future variability in wave climate, potential sea level rise impacts, and storm (event-based) erosion at a beach block. Each parameter has been applied within a probabilistic framework, which uses a statistical distribution within the analysis. Results can then be extracted and mapped for any statistical likelihood or exceedance probability.

All erosion and recession hazard zones have been mapped from the 2mAHD contour derived from the NSW Marine LiDAR Topo-Bathy (2018) dataset. Hazard mapping has been conducted for the following scenarios:

- Present day, 2043, 2073 and 2123 planning horizons
    - 50% exceedance probability
    - 10% exceedance probability
    - 2% exceedance probability
    - 1% exceedance probability
- Each future scenario includes SSP2 (RCP4.5) and SSP5 (RCP8.5) climate change conditions.

4.1 Volume to width mapping

All erosion and recession hazard components have been determined volumetrically, representing a loss (or gain) of the cross-shore profile volume from 0mAHD. To convert the cross-shore volume to a hazard width, the following process has been used for each exceedance, planning horizon, and SSP:

- Total erosion and recession (E_T) exceedance volumes (50%, 10%, 2%, and 1%) are derived from the distribution.
- The exceedance volume is applied to the cross-shore profile above the 0mAHD contour, with a 1 in 2.25 landward slope. This slope is based on the natural repose angle of dry sand.
- The hazard width is measured as the distance from the present day 2mAHD contour to the intersection of modelled eroded slope and profile.

It should be noted that increases in hazard between exceedances (e.g. from 2% to 1%) within a given planning horizon is relatively minor. As event probabilities of hazard volumes become more severe (and less likely) they approach an asymptote where the contributing factors for each hazard volume (e.g. storm severity, sea level rise, recession rate, etc.) reach a natural maximum. This results in the differences between each exceedance width being relatively minor. This trend is also present in previous state-wide planning studies.

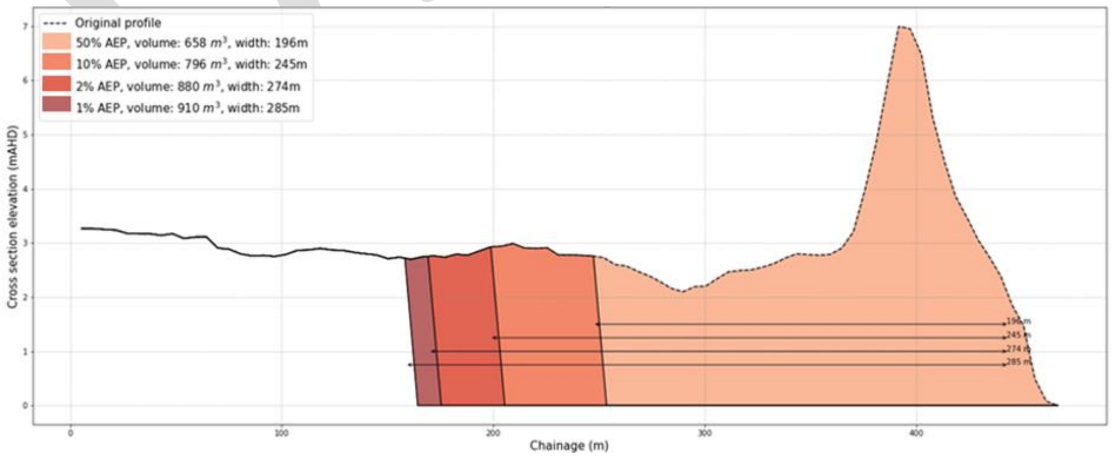


Figure 4-1: Example volumetric calculation of erosion and recession hazard at Wooli Beach 7 under 2123, SSP5

4.2 Post processing

Several assumptions and GIS smoothing approaches were used to develop the final erosion and recession mapping.

1. All erosion and recession hazard zones have been mapped landwards from the 2m AHD contour. This contour has been derived from a 5m gridded DEM from Geoscience Australia[51].
2. All beach blocks are merged together. If the estimated erosion width differs, a fillet has been applied to smooth between each block. This is a triangular shape, which extends 200m from the wider erosion hazard width to the narrower erosion hazard width.
3. At Woody Bay the future erosion extent has been subject to additional modelling and a crenulate (parabolic) shaped bay assessment (described in Section 7.3.2).
4. The hazard zones have not been trimmed around areas of exposed bedrock, however these layers are shown in mapping based on NSW Geological maps which are made available by the Department of Regional NSW[52]. The potential for substrata of bedrock below the erodible surface has not been considered, except for seabed compartment space and scaling factors applied as described above. There was no independently verifiable method to determine layer thicknesses for all beaches.
5. For some beach sections and planning horizons, the hazard zone has been limited by the alignment by the presence of coastal rivers and estuaries. In these instances, only the potential width is shown in mapping.

4.2.1 Considerations of coastal protection works

The presence of coastal protection works (e.g., seawalls) has not been considered when mapping erosion and recession hazard widths. The presence and condition of existing protection structures cannot be guaranteed across all planning horizons without appropriate engineering assessments. While fit-for-purpose structures may reduce the erosion/recession hazard, they may not limit the risk for rare or very rare events. This is because they would be expected to fail depending on their design, or over the longer term where structures are not maintained/upgraded to account for sea level rise. Consequently, the maps should be considered as 'undefended' erosion and recession zones. Furthermore, the mapping of potential hazard widths where coastal structures currently exist allows for the area of benefit provided by these structures to be quantified.

Where a properly designed seawall exists, i.e. a structure designed with engineering certification as an erosion protection structure, the erosion risk may be reduced. In these areas the 'undefended' maps can be used to quantify the area (and value) of protection offered by the structure.

51 Geoscience Australia, 2015. Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid. Geoscience Australia, Canberra. Accessed from: http://pid.geoscience.gov.au/dataset/ga/89644

52 Colquhoun G.P., Hughes K.S., Deyssing L., Ballard J.C., Folkes C.B, Phillips G., Troedson A.L. & Fitzherbert J.A. 2022. New South Wales Seamless Geology dataset, version 2.2 [Digital Dataset]. Geological Survey of New South Wales, Department of Regional NSW, Maitland.

5 Modelling limitations

Uncertainty exists within all datasets, numerical modelling outputs and the mapping approach used within this study. This can be due to the approach used to capture data, filtering or extrapolation techniques, modelling techniques, inputs used, the source of bathymetry, the selection of the mapping contour (i.e. 2m AHD), and the classification of return period and planning horizons. These have been discussed throughout this report, and are summarised in this section, which aims to address questions and comments received by stakeholders or the public when using the mapping results. This work presents the outcomes of the first detailed probabilistic assessment for the Clarence coastline. The assessment should be revisited and refined in future with a shoreline response model that ideally addresses some of these limitations.

5.1 Long term recession

The historic shore-normal recession rate has been calculated using the long-term trends within annual shoreline positions estimated through the Geoscience Australia Digital Earth Australia (DEA) dataset. In reality there is no single 'annual' shoreline position, which changes constantly in response to coastal processes. This is an estimated location only and is created using long-term data analysed through the DEA dataset. The use of the DEA dataset has both advantages and disadvantages over other methods. The primarily advantage of using the DEA data is the greater frequency and length of the available timeseries data which allows an in-depth analysis of the long-term shoreline position. The significant quantity of data is considered beneficial as a broad analysis of annual and seasonal variation and can allow a correlation to climate drivers. However, uncertainty exists due to:

- The approach to identify the 'annual' shoreline positions uses an assumed beach slope and a tidal harmonic model (not recorded tides). It is an estimated level only.
- The shoreline is processed using an estimated sea level position, which is situated within a dynamic part of the beach. It is typically more practical to consider the movement of the dune crest, not the mean sea level.
- The approach to extrapolate the present-day 'annual' shoreline position to a future planning horizon uses a linear projection. This assumes erosion trends will continue linearly and un-restricted and does not consider the shape the beach is evolving into. This has been considered in more depth at Woody Bay only.

5.2 Variability in wave climate

This assessment considered the role in future wave climate in changing the rate of longshore sediment transport. This is a very complex physical process that was simplified to a level that could be feasibly represented in a probabilistic framework. Uncertainty exists throughout this assessment due to:

- LST modelling has a high degree of complexity, with models very sensitive to small changes in model inputs. For a present-day scenario, the modelling approach was to calibrate outputs to match the estimated LST rate entering the Clarence LGA Coastline. No detailed sediment transport rates exist at this location, and instead the incoming rate has been based on rates observed at the Coffs Harbour breakwalls after their construction. This rate represents sediment volumes that have been trapped at the Coffs Harbour breakwalls, which may not exactly represent the amount of sand currently bypassing the harbour and being transported into the Clarence LGA.
- Future conditions are based on mean changes of the present day wave climate, using the global wave modelling outputs from the Centre for Australian Weather and Climate Research (CAWCR). The raw data includes a range of potential iterations ('ensembles'), which have a significant variability around the mean. When run under the same SSP pathway, different ensembles present the potential for completely different future wave conditions; for example some predicting increases in wave height and some predicting decreases. Whilst greater consistency is found in the future estimates of wave period (all models predicting a decrease) and wave direction (an anticlockwise shift), they all vary in magnitude.
- The changes in future sediment transport have been incorporated through a simple concept. This considers if future LST was to slow down (e.g. halve), the future beach evolution rate (future q_x) would subsequently halve, and if future LST was to increase (e.g.

double), the future beach evolution rate would double. This relationship, and the entire LST analysis is acknowledged to be uncertain, and recommendations are made for further work in this area.

5.3 Shoreline changes due to sea level change erosion

The future shoreline response to sea level is unknown, which will depend on a range of factors such as the speed of sea level rise. Various conceptual models have been proposed in literature, with this assessment selecting a volumetric shoreface model that will erode the beach during a landward translation. Uncertainty exists throughout this assessment due to:

- As a future-looking model there is uncertainty of how accurately this will reflect the future physical changes. Calculations involving shoreline translation, obtained via the theories presented by Bruun, should be considered as indicative estimates only.
- This model assumes a uniformly sandy cross-shore profile. It does not account for consolidated or cohesive soils, as well as rock layers, that may be present behind the foredune. This model does not consider the presence of coastal protection works.
- To maintain continuity across all profiles, an equilibrium profile following $h(x) = Ax^{2/3}$ has been fit to each of the modelled profiles to align with the depth of closure. The 'A' parameter is adjusted to fit an equilibrium profile through the data, using a "least-squared-error" method.

5.4 Event-based erosion

This erosion modelling considers the open coast only. Modelling has not considered inland storms, rainfall or flood conditions that may also be a driver for erosion in lower estuaries and adjacent coastline. Uncertainty exists throughout this assessment due to:

- A level of exposure has been determined for each beach section from the results of nearshore wave modelling. This exposure factor was further refined for some beach sections based on planform orientation and sheltering (e.g. location with an estuary)
- Event-based erosion volumes have been based on the publications of Gordon (1987) and furthered by Kinsela et al (2017) which estimated a 1% AEP storm erosion in the order of $250m^3/m$ for open coast beaches in NSW. The probability of event-based erosion has been represented as a gamma distribution with scale factors adjusted to satisfy this 1% AEP condition.
- The exposure factor for each beach section has been used to scale the respective probability distribution. The shape of the gamma distribution remains a constant value of 2.5 for all beaches.
- The volume of event-based erosion is assumed to be lost above the 0mAHD contour.
- An additional zone of reduced foundational capacity (ZRFC) has been included in the assessment of event-based erosion, in line with State guidance. ZRFC is most suitable for idealised unconsolidated dunal systems with a natural repose angle of 34 degrees. As this was regional assessment that did not include site-specific geotechnical information, a uniform methodology has been used for calculating ZRFC for each beach section along the coast. Without geotechnical information (i.e. soil bearing capacity, shear stress, core samples) at each coastal section, it is difficult to quantify an appropriate substitute for ZRFC for each location. In some areas with large dunes, the resulting ZRFC is wide which is typically due to the high elevations in these areas.

5.5 Mapping

The probabilistic erosion and recession assessment calculates a hazard width. Mapping requires this to be measured from a specific location, with the present day 2mAHD contour selected as the start of the erosion zone. Several GIS smoothing approaches were then used to develop the final hazard map. Uncertainty exists throughout this assessment due to:

- The location of the 2mAHD contour, which is dependent on the time of survey and local conditions experienced at that time. Within the published erosion maps the shoreline position shown as an aerial image is noted to differ from the mapped 2mAHD contour in several locations. For Brooms Head and Woody Bay, the most recent aerial image has been used in mapping to resolve rapid shoreline change in these areas.

- The resolution of the assessment. This has been based on beach blocks, which range from 100m to several kilometres. Small local features will not be considered at this scale.
- A representative cross-shore profile has been selected for each coastal beach block. The erosion hazard width for the length of each beach block has been estimated based on this one profile and applied along the entirety of the block.
- All mapping has first been mapped as an erodible sandy beach.
- Areas of bedrock have been based on NSW-wide geological maps. No other local-scale ground-truthed geological maps are available for the coastline. Consequently additional geotechnical information, such as boreholes and local studies, could be used to confirm the protection provided by any bedrock features,
- No adjustments have been made for seawalls or dune nourishment. Consequently, the maps should be considered as 'undefended' erosion and recession zones.
- The approach used to limit the future erosion extent at Shark Bay and Woody Bay have been based on an equilibrium planform concept, which considers the loss of the tombolo. The future evolution of the tombolo has a high degree of uncertainty.
- Hazard mapping has been conducted using a volumetric loss approach which assumes a uniform soil composition along the cross-shore profile. As such, the width of hazard extents for longer time periods (e.g., 2123) is due to the total landward volume loss extending behind the frontal dune system.
- Any consideration of dune/barrier roll-over or a slowing or recession after the frontal dune is lost has not been included as no suitable methodology has been identified
- Hazard zones have been limited by the alignment of the 0mAHD elevation contour within coastal rivers and estuaries, with the assumption being that it is unrealistic to map these features as at risk of erosion or recession.

6 Shark Bay, Iluka

The erosion/recession hazard assessment results for Shark Bay are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

6.1 Background

Shark Bay is the northernmost beach within the Clarence Valley LGA. It is situated at the southernmost section of Ten Mile Beach, positioned within the Bundjalung National Park. It is a sandy beach which extends south to a small rocky island and tombolo which forms the barrier to Woody Bay. Adjacent to Shark Bay is Iluka Road; the only entry point to Shark Bay, Woody Head, and Iluka.

6.2 Coastal segments

Shark Bay beach has been defined by four beach blocks following the NSW Beach Profile Database. These are mapped in Figure 6-1, which shows the average annual rates of change between 1988 and 2020 from the GA DEA.

6.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for all beach blocks is shown in Table 6-1 and Table 6-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

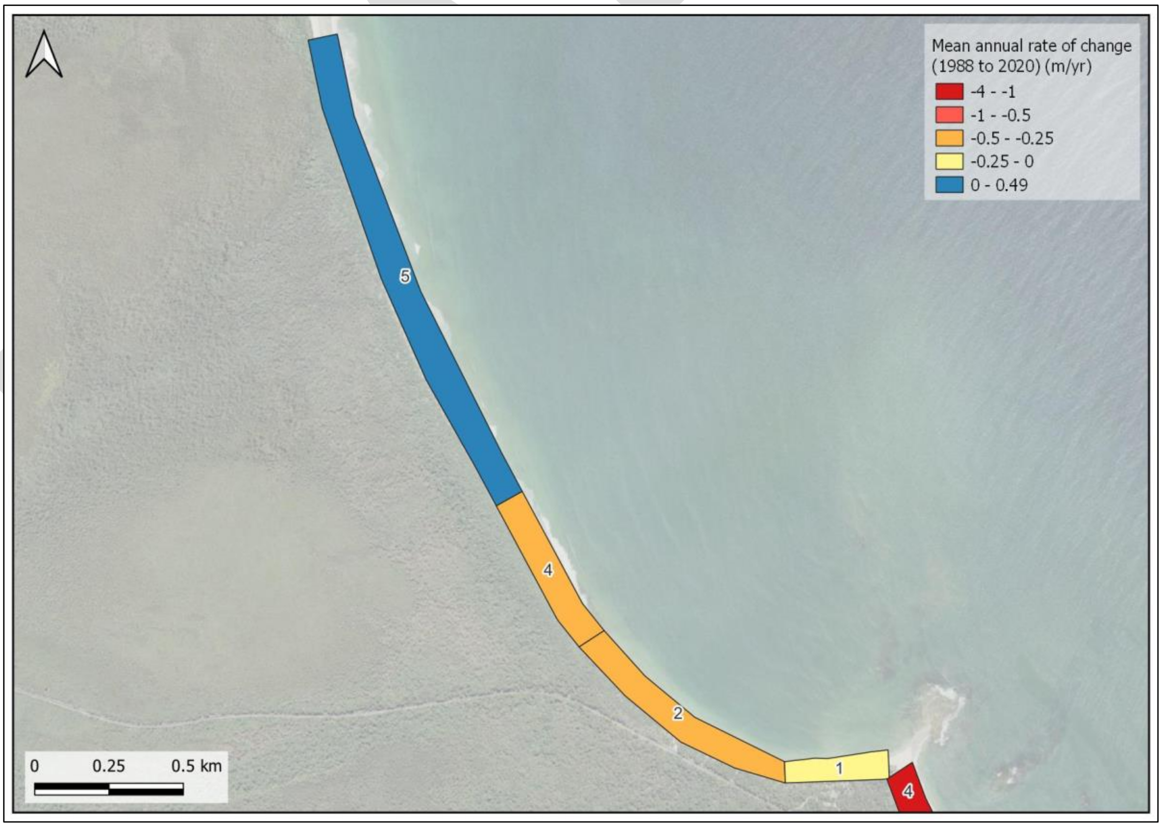


Figure 6-1: Shark Bay beach block mean annual rates of change (from 1988 and 2020)

Table 6-1: Shark Bay total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	16.4	31.6	45.1	50.3
	2043	33.2	49.4	62.7	68.6
	2073	71.0	92.3	107.3	113.4
	2123	118.7	154.7	174.4	180.6
2	2023	21.5	39.9	55.2	61.7
	2043	42.4	60.9	76.6	82.9
	2073	84.5	103.8	119.0	126.1
	2123	140.2	162.2	174.5	179.3
4	2023	13.1	41.5	57.8	63.4
	2043	40.1	59.9	74.1	79.2
	2073	74.6	93.1	108.9	113.2
	2123	116.6	147.9	**148***	**148***
5	2023	9.1	38.8	49.8	56.8
	2043	14.9	40.9	53.4	61.3
	2073	32.6	50.8	73.0	83.9
	2123	43.0	92.3	135.8	**152***
*limited by parabolic shoreline model - refer to maps					

Table 6-2: Shark Bay total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	16.4	31.6	45.1	50.3
	2043	35.1	51.3	64.1	70.2
	2073	82.4	103.9	120.1	125.8
	2123	154.3	195.6	220.7	228.5
2	2023	21.5	39.9	55.2	61.7
	2043	44.0	62.8	78.3	84.8
	2073	93.5	113.3	131.2	139.4
	2123	162.2	191.8	209.8	215.2
4	2023	13.1	41.5	57.8	63.4
	2043	42.3	61.0	74.6	80.0
	2073	81.9	102.7	116.1	121.2
	2123	139.9	**148***	**148***	**148***
5	2023	9.1	38.8	49.8	56.8
	2043	16.7	41.2	53.7	61.3
	2073	37.3	57.3	83.9	94.6
	2123	58.7	122.8	**152***	**152***
*limited by parabolic shoreline model - refer to maps					

7 Woody Bay

The erosion/recession hazard assessment results for Woody Bay are dicsussed in this section with detailed outputs provided in Appendix B and Appendix C.

7.1 Background

Woody Bay is located south of Shark Bay, separated by the small rocky island and tombolo. It is located on the northern side of Woody Head, a rock shelf and headland. The beach is experiencing some of the fastest rates of shoreline recession in New South Wales. It has been the subject of several investigations since 1942, when coastal photogrammetric data collection was first commenced. Two mechanisms for the long-term coastal recession have been proposed:

1. Within the Coastal Processes and Hazard Definition Study (MHL 2000)[53], recession is considered due to the bedrock reef extending offshore to the north of Woody Head, which acts as a barrier to a sand being transported into the bay.
2. Alternatively, Goodwin et al (2006)[54] proposes that sand bypassing does occur at Woody Head (albeit at a small rate). However, a shift in the dominant wave direction along the NSW coast is primarily responsible for the recession trends experienced in Woody Bay

Woody Bay was identified in the CMP Stage 1 Scoping Study as a site for further detailed investigation, in particular around the Woody Head campground which has been subject to recent reconfigurations and management actions. This has included dune rehabilitation and new rock revetment protection works to mitigate erosion along the campground. This was constructed in the south-eastern section of Woody Bay by National Parks and Wildlife Service (NPWS) which was extended by another 20m in 2006. A further small extension was added to the seawall in late 2009 following a storm event mid-2009 which eroded into the dune[55], and a more recent extension was built in 2018. Current observations (circa 2022) show erosion continuing adjacent to the western seawall extent.

7.2 Coastal segments

Woody Bay has been defined by three beach blocks. These are mapped in Figure 7-1, which shows the average annual rates of change between 1988 and 2020 from the GA DEA Coastlines.

53 MHL. 2000. Woody Head Erosion Mitigation Coastal Processes Hazard Definition Management Study and Management Plan.

54 Goodwin, I. D., Stables, M. A. and Olley, J. M. 2006. Wave climate, sand budget and shoreline alignment evolution of the Iluka-Woody Bay sand barrier, northern New South Wales, Australia, since 3000 yr BP. Marine Geology, 226, 127-144

55 NSW Department of Climate Change and Water (DECCW) (2012). Woody Head Coastal Hazard Review

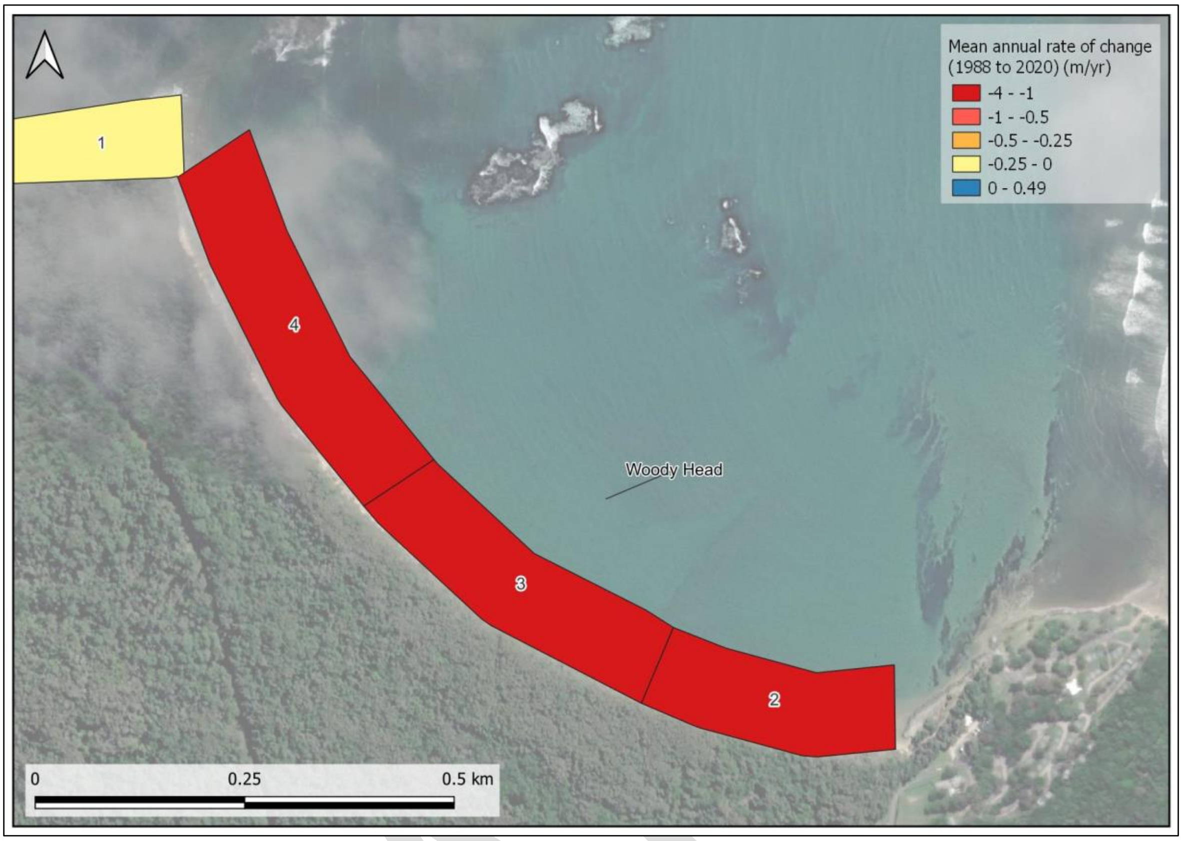


Figure 7-1: Woody Bay beach block mean annual rates of change (from 1988 and 2020)

7.3 Additional erosion analysis

Detailed assessment of historic recession rate, future variability in wave climate, sea level rise impacts and storm erosion were undertaken following the probabilistic framework. In addition, new analysis was undertaken to consider the stability of the tombolo and the shoreline response if it was to lose its connection with the nearshore island.

7.3.1 Effect of tombolo

Consideration has been given to the Woody and Shark Bay tombolo and its effect on stabilising the beach. This is an important morphological feature that separates both beaches and is responsible for the crenulated shape of the shoreline. However, due to the potential long term shoreline recession and climate change impacts, it is possible the tombolo may be breeched and cause a realignment of the current shoreline planform (further reviewed in Section 7.3.2). Research undertaken within the Woody Head Coastal Hazard Review (DECCW 2012) considered the stability of the tombolo based on research presented by Sunamura and Misuzo (1987)[56]. Here, the shape of a tombolo is considered in relation to the offshore distance to the structure (J) and the length of the offshore structure (l), where:

- J/l < 1.5 - formation of tombolo
- 1.5 < J/l < 3.5 – development of a salient
- J/l > 3.5 – the offshore feature has no influence.

Based on aerial photography during 2011, the study presented a 370m offshore distance (J) and 270 tombolo length (l), giving a J/l value of 1.4 which supported the stability of the tombolo. However, when repeating the measurements within this current study, small changes to input width and length are found to shift the results form a tombolo formation towards a salient formation (i.e. suggesting the island will become disconnected). For example, a change in the measured island

56 Sunamura, T and Misuzo, O. (1987) A study on depositional shoreline forms behind an island, Ann. Rep. Inst. Geoscience, University Tsukuba, 13, 71-73.

length from 270m to 250m recalculates J/l as 1.5, which is the threshold for salient/tombolo development. This shows the potential uncertainty around the current formation.

Further assessment was undertaken using a hydrodynamic model to consider if sea level rise could also influence the tombolo formation. The progressive retreat and thinning of the tombolo over recent years has allowed increased tidal flow through the passage. With sea level rise, additional flow may occur. At geological timescales coastal processes are believed to have sufficient time to maintain relative beach heights to match sea level rise. However, for the rapid rates of sea level change projected over the next century, the tombolo is not anticipated to grow to keep pace (similar to the concepts presented in Section 3.4). The hydrodynamic model was used to understand the change in flow-through conditions under a future sea level rise scenario, without a subsequent increase in sand levels.

Modelling was undertaken using Delft3D-FLOW, an open-source hydrodynamic model[57] capable of estimating tides, extreme water levels, currents, salinity, and sediment transport conditions. As schematised in Figure 7-2, several modules of Delft3D can be used to support coastal studies. For this assessment, the Delft3D-FLOW model was used to simulate hydrodynamics, operating over constant bed level.

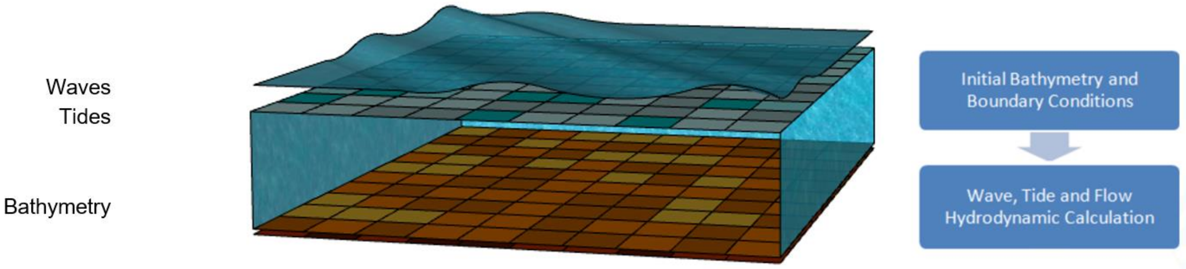


Figure 7-2 Available Delft3D hydrodynamic, wave and sediment transport calculations

The modelling domain has been constructed as a curvilinear grid to resolve the form and meandering of the coastline. The model extends from the offshore region through to the coastline. The model has used a curvilinear grid with a spatially-varying grid resolution, which allows higher-detail around the tombolo, whilst optimising computational runtimes. The grid resolution ranges from approximately 20m in the offshore area to 5m at the tombolo. Model elevation has been based on the bathymetric 5m NSW Marine LiDAR Topo-Bathy (2018).

The model was run for three scenarios:

- A present day spring-neap cycle
- A 2123 SSP2-4.5 spring-neap cycle, where tidal inputs were increased by the 50th percentile sea level rise value of 0.76m
- A 2123 SSP5-8.5 spring-neap cycle, where tidal inputs were increased by the 50th percentile sea level rise value of 1.09m

The change in current velocity was extracted adjacent to the tombolo and is shown in Figure 7-3. The peak tidal flow patterns mapped during a mean high water spring are shown in Figure 7-4. The results show the tides currently split around the rocky island. Under future sea level rise scenarios the currents will increasingly submerge the island, with the nearshore tide velocity adjacent to the shore potentially doubling (or more) in speed. Whilst they remain relatively low under tide-only conditions, this is expected to be another factor that will drive a change in beach conditions and destabilise the tombolo.

57 Website: http://oss.deltares.nl/web/delft3d/download

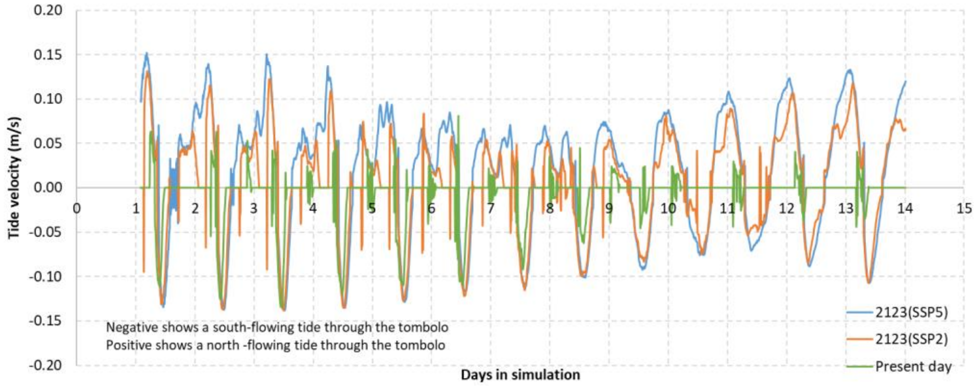


Figure 7-3: Tidal flow velocity under common conditions between the shoreline and the Shark Bay-Woody Bay tombolo.

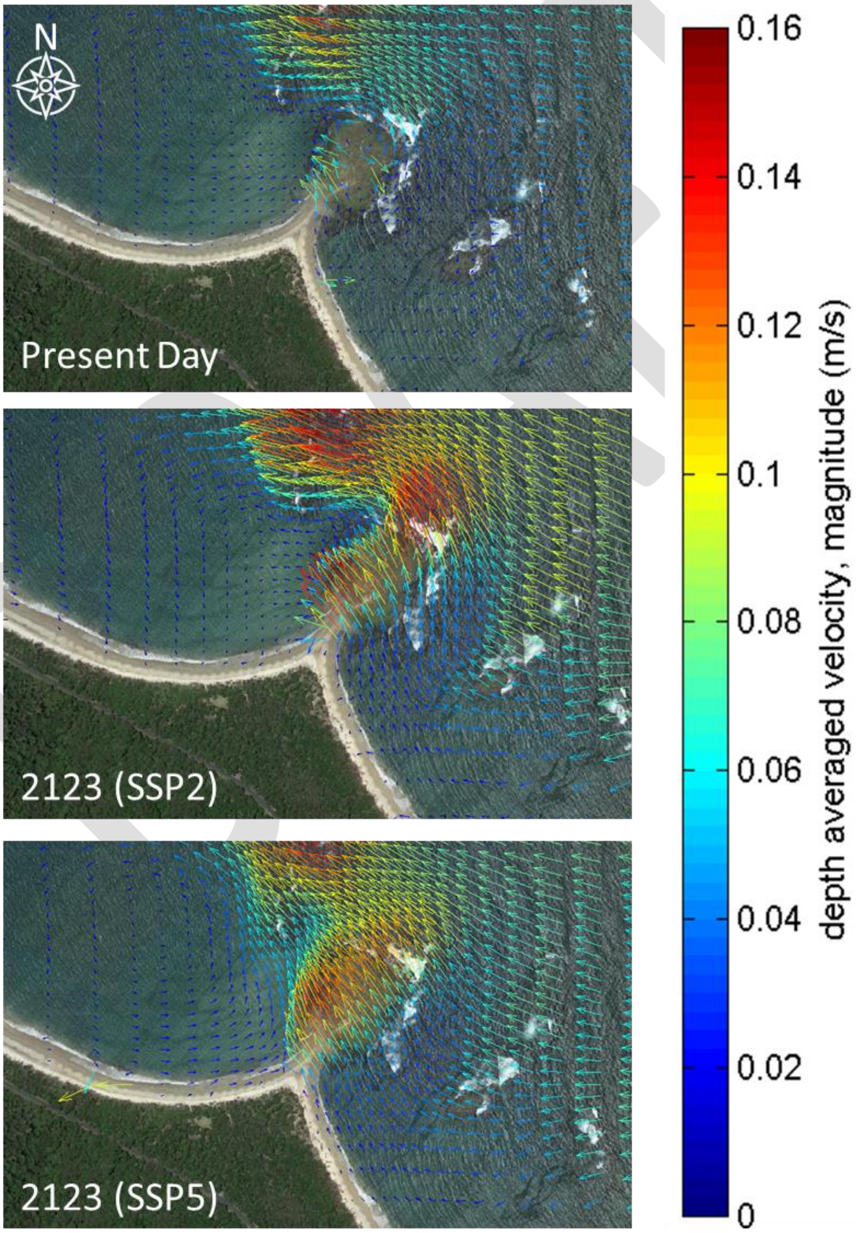


Figure 7-4: Tidal flow patterns around the Shark Bay-Woody Bay tombolo under different planning horizons.

7.3.2 Equilibrium planform layout

The planform shape of an embayment is influenced by local geology (including reefs, headlands etc) and wave climate, the latter driving LST. This longshore transport of sandy material along a coastline will shape a beach and will allow an embayment to form in the presence of a headland. Once a beach becomes 'anchored' to a headland, the wider shoreline can evolve to face the incident wave climate, which is diffracted and refracted along the shoreline. It is possible that the entire Woody Head coastline would have a shape representing a single embayment if not for the nearshore rocky island that is creating the Woody/Shark Bay tombolo. If this was to disconnect, the coastline could reasonably be expected to then shift towards a single embayment, as suggested in DECCW (2012). This lateral shift assumes that realignment of the planform beach shape is not constrained by potential non-erodible rock layers in the substrata.

Various planform shape models exist (logarithmic, hyperbolic, parabolic) which can be used to map embayment shapes. These are referred as a planform equilibrium shape. Research into the applicability of the empirical equations delivered by Benedet et al. (2004)[58] gives greater merit to the parabolic equation, as developed by Hsu and Evans (1989)[59]. This shape is common along the northern NSW beaches, which can be identified by its long straight coastline connected to downdrift (in our case northern) headland, and a parabolic curve section beside the southern headland, as shown in Figure 7-5.

A Parabolic Shape Model has been applied to the Woody Bay and Shark Bay coastline, using the JBP-Embayment (JBAY) tool. This applies the parabolic shape based on the position of a wave refraction point adjacent to Woody Head, a downcoast point representing the end of the parabolic embayment, and the incoming wave conditions. These inputs were varied to align the model with the general coastline shape away from the Woody/Shark Bay tombolo, with the model outputs then mapped through the southern corner to consider the shoreline without the influence of the tombolo. The model was rerun in a future profile position, with the shoreline shifted landward to represent the potential 2123 recession rates. The resulting coastlines are shown in Figure 7-6, which have been used as the limit of future landward recession calculated through the full probabilistic framework. This has been applied due to the problem when large recession rates are projected into the future, which does not consider the final shape that the coastline may be evolving into.

7.4 Erosion and recession hazard summary

The width of the total erosion and recession zone for all beach blocks is shown in Table 7-1 and Table 7-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

58 Benedet, L., Klein, A.H.F., Hsu, J.R.C. (2004). Practical insights and applicability of empirical bay shape equations. Proceedings of the 29th International Conference on Coastal Engineering: ASCE, vol. 2, pp. 2181–2193.

59 Hsu, J and Evans, C. 1989. Parabolic bay shapes and applications. Proc., Institution of Civil Engineers, London, England, 87(2), 556 - 570.

Figure 7-5: Examples of parabolic beaches in the study area, and the Definition sketch for the parabolic equations

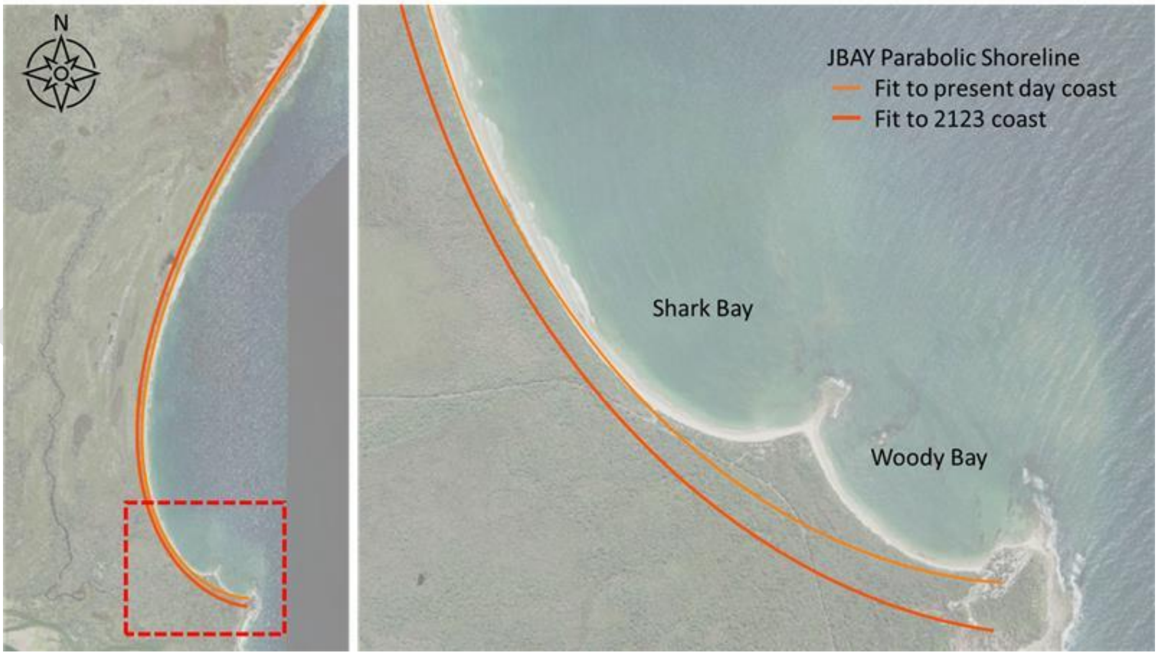


Figure 7-6: Results of the JBAY parabolic shoreline model

Table 7-1: Woody Bay total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	15.0	29.4	41.7	46.8
	2043	94.1	108.3	119.6	124.0
	2073	**211***	**211***	**211***	**211***
	2123	**211***	**211***	**211***	**211***
3	2023	11.7	24.9	35.5	39.8
	2043	96.1	108.1	117.5	122.2
	2073	223.3	244.9	**246.8***	**246.8***
	2123	**246.8***	**246.8***	**246.8***	**246.8***
4	2023	16.5	29.4	40.0	44.5
	2043	106.8	118.9	128.1	131.5
	2073	230.5	249.2	262.9	268.2
	2123	**436.8***	**436.8***	**436.8***	**436.8***
*limited by parabolic shoreline model					

Table 7-2: Woody Bay total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	15.0	29.4	41.7	46.8
	2043	96.6	110.8	122.6	127.5
	2073	**211***	**211***	**211***	**211***
	2123	**211***	**211***	**211***	**211***
3	2023	11.7	24.9	35.5	39.8
	2043	98.1	110.2	119.8	124.2
	2073	232.3	**247***	**247***	**247***
	2123	**247***	**247***	**247***	**247***
4	2023	16.5	29.4	40.0	44.5
	2043	109.1	120.5	129.5	133.1
	2073	238.3	261.2	276.1	281.1
	2123	**437***	**437***	**437***	**437***
*limited by parabolic shoreline model					

8 Whiting Beach

The erosion/recession hazard assessment results for Whiting Beach are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

8.1 Background

Whiting Beach is the north-eastern facing beach on Hickey Island, positioned near the Clarence River entrance in the lee of the Yamba Breakwall and Turners Beach. Hickey Island was originally a sand-spit that accreted and formed an attachment to Yamba mainland over a number of decades following dredging activities and the construction of 'Middle Wall' between 1893 and 1903.

Erosion was observed along the northern face of Hickey Island and Whiting Beach following extensions of the Iluka and Yamba Breakwalls between 1952 and 1971[60]. More recent erosion led to the construction of a Geotextile Sand Container (GSC) revetment in 2013, positioned on the south-eastern end of Whiting Beach. In 2008, approximately 9,400m^3 of sediment was dredged from the Clarence River channel and used to nourish the beach, followed by a further 10,000m^3 nourishment in 2016.

8.2 Coastal segments

Whiting Beach has been split into two sections, an eastern block (Yamba 7) and a western block (Yamba 8). The eastern block at Whiting is exposed to wave action from offshore swell entering the estuary (described below). The western section is exposed to tidal processes only, due to its orientation and sheltered location within the estuary (Royal HaskoningDHV, 2015) and therefore only long-term recession and erosion from sea level rise components have been applied to this section. Figure 8-1 shows the average annual rate of change between 1988 and 2020.

Figure 8-1: Whiting Beach mean annual rate of change (from 1988 to 2020)

60 Royal Haskoning (2015). Options to manage recession of Whiting Beach, Yamba

8.3 Additional erosion analysis

Detailed assessment of historic recession rate, future variability in wave climate, sea level rise impacts and storm erosion were undertaken following the probabilistic framework. In addition, new analysis was undertaken to consider the potential for swell waves to penetrate through the harbour breakwalls and cause erosion.

8.3.1 XBeach modelling of swell wave propagation

An XBeach wave model has been developed to estimate both the beach erosion and the effects of nearshore bathymetry on incoming waves to the sheltered Whiting Beach area. XBeach is an open-source numerical model originally developed to simulate hydrodynamic and morpho dynamic processes on sandy coasts and has been validated with a series of analytical, laboratory and field test cases using a standard set of parameter settings.

The XBeach model was simulated in a “Surfbeat” configuration. This model uses a unique approach in which long wave motions are resolved while short-waves are phase averaged. This offers an advantage in limiting computational demand as this process was originally developed to predict local extreme beach response to storm conditions. Model bathymetry has been developed from a 2018 LiDAR survey of the NSW coastal region with a 5m resolution. This has been used for the offshore, nearshore, and topographical locations within the model extent. The offshore extent includes the -10m contour and extends inland approximately 2km to the most western extent of the LiDAR dataset. Figure 3-1 shows the grid extent and bathymetry of the local wave model representing Whiting Beach and the wider bay region. It includes model outputs showing waves penetrating the inner harbour area.

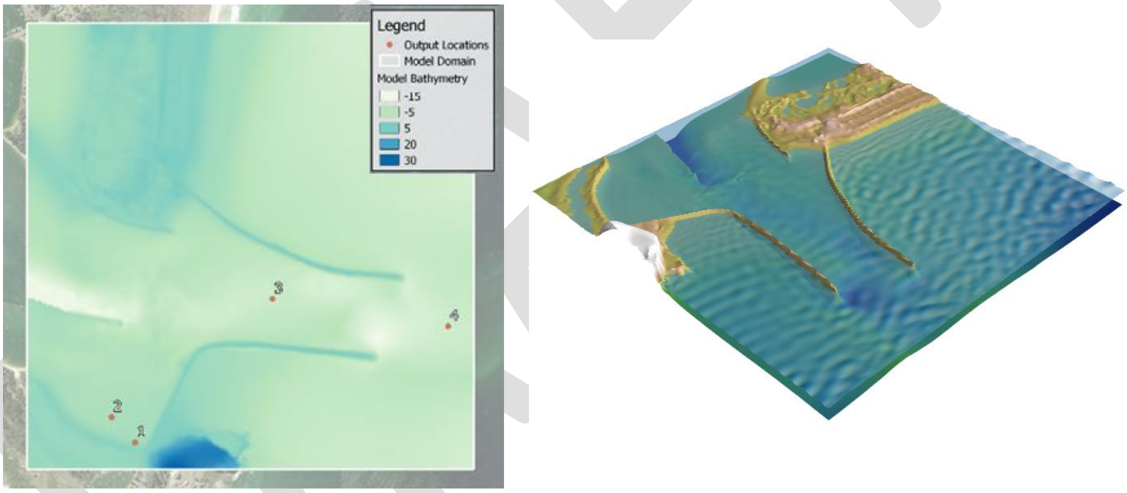


Figure 8-2: Left: XBeach model domain and bathymetry. Right: Simulated wave conditions

The nearshore waves were extracted at the -2m AHD depth contour at the beach. When expressed in terms of their incident (open coast) wave height, a typical 90% reduction factor is observed. i.e. nearshore conditions are around 10% of the offshore conditions. The resulting beach erosion was simulated within the model, and used to interpolate different erosion widths, as shown in Table 8-1.

Table 8-1: Extreme erosion at Whiting Beach (based on residual swell waves)

Event, AEP (ARI)	Storm based erosion (m)
10% (10-year)	0.7
2% (50-year)	0.9
1% (100-year)	1.2

8.4 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 8-2 and Table 8-3 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

Table 8-2: Whiting Beach total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
7	2023	4.9	7.2	9.3	11.4
	2043	28.4	31.8	35.9	37.7
	2073	110.9	386.4	400.9	404.8
	2123	440*	440*	440*	440*
8	2023	7.1	7.1	7.1	7.1
	2043	23.4	28.5	32.3	34.1
	2073	91.2	124.0	143.1	149.6
	2123	251.7	320.4	343.9	361.0
*limited by estuary - refer to maps					

Table 8-3: Whiting Beach total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
7	2023	4.9	7.2	9.3	11.4
	2043	27.9	31.3	34.6	36.4
	2073	118.9	396.8	408.1	411.7
	2123	440*	440*	440*	440*
8	2023	7.1	7.1	7.1	7.1
	2043	21.8	26.9	30.5	32.1
	2073	107.5	143.0	162.6	169.6
	2123	289.5	342.2	402.5	500*
*limited by estuary - refer to maps					

9 Yamba Beaches (Pippi Beach)

The erosion/recession hazard results for Pippi beach are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

9.1 Background

The headland at Yamba includes small pocket beaches of Convent Beach, Main Beach, and Turners Beach, as well as the south-east facing Pippi Beach between Barri Point and Yamba Point. The east-facing pocket beaches in this section are controlled by rocky headlands, with Turners Beach controlled by Clarence Head and the southern Clarence River breakwall and as a result has not been included in this assessment. Convent Beach and Main Beach have also not been included in this assessment as it was determined through consultation with Council that slope stability of high-crested cliffs will be the primary hazard at these locations, which will be considered in a separate assessment.

9.2 Coastal segments

Pippi Beach has been defined by four beach segments. Figure 9-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

Figure 9-1: Pippi Beach mean annual rate of change (from 1988 to 2020)

9.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 9-1 and Table 9-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

Table 9-1: Pippi Beach total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	27.3	52.6	65.8	71.1
	2043	35.6	56.8	70.2	76.2
	2073	50.4	70.2	84.8	89.2
	2123	88.7	109.9	120.8	124.5
2	2023	20.2	47.9	59.5	63.1
	2043	35.4	55.3	65.0	68.9
	2073	52.9	71.2	84.1	89.1
	2123	86.7	121.5	137.3	142.3
3	2023	24.9	48.8	62.8	68.8
	2043	37.4	64.3	87.7	96.3
	2073	54.0	107.7	119.7	124.3
	2123	105.4	177.1	202.5	209.4
4	2023	20.8	40.3	51.7	56.4
	2043	29.2	47.3	59.1	63.4
	2073	41.6	66.6	78.7	82.2
	2123	75.5	104.2	133.4	133.4

Table 9-2: Pippi Beach total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	27.3	52.6	65.8	71.1
	2043	36.1	57.2	70.6	76.5
	2073	54.1	73.8	87.9	92.1
	2123	104.7	126.4	138.1	142.3
2	2023	20.2	47.9	59.5	63.1
	2043	36.1	55.8	65.5	69.4
	2073	55.5	73.9	86.4	91.4
	2123	105.6	138.3	153.3	159.1
3	2023	24.9	48.8	62.8	68.8
	2043	38.0	64.6	88.0	97.1
	2073	57.1	109.1	120.5	125.1
	2123	116.8	191.4	211.4	217.4
4	2023	20.8	40.3	51.7	56.4
	2043	29.7	47.8	59.9	63.8
	2073	45.0	68.8	80.4	83.9
	2123	91.1	133.4	133.4	133.4

10 Angourie (Spooky Beach)

The erosion/recession hazard assessment results for Spooky Beach are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

10.1 Background

Spooky Beach is located at the township of Angourie. The beach is an approximately 400m long pocket embayment enclosed by headlands and backed by a steep, well-vegetated 10m high dune. The township of Angourie is set around 100m back from the beach into sloping hills. The beach at Angourie is composed of beach sand and fringing rock platforms, with weathered cobble rock along the backshore zone.

10.2 Coastal segments

Spooky Beach has been represented as one beach segment (Angourie 3). Figure 10-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

10.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 10-1 and Table 10-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

Figure 10-1: Angourie (Spooky Beach) block mean annual rates of change (from 1988 to 2020)

Table 10-1: Angourie total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
3	2023	31.5	39.8	43.1	44.2
	2043	38.1	43.1	45.3	46.4
	2073	43.4	48.9	55.5	58.0
	2123	76.2	101.9	111.6	114.9

Table 10-2: Angourie total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
3	2023	31.5	39.8	43.1	44.2
	2043	38.1	43.1	45.3	46.4
	2073	44.5	51.9	59.1	66.6
	2123	98.6	117.7	127.6	130.7

11 Brooms Head Beach

The erosion/recession hazard assessment results for Brooms Head are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

11.1 Background

Brooms Head Beach is a 4km long sandy beach adjacent to the Yuraygir National Park, which includes the coastal township of Brooms Head. Brooms Head Beach is located between the Red Cliff headland to its north and the Cakora Point headland to its south. A rocky reef is present offshore of Cakora Point which surrounds Buchanans Rock, both of which attenuate wave energy at the southern end of the beach. Existing protection works along Brooms Head Beach includes a rock revetment spanning north from Cakora Point in front of the Brooms head Caravan Park. The revetment ranges from 3 to 4.5m AHD in height and was improved in 2010 and extended north by 50m in 2012. A further extension of existing revetment has been proposed in 2017[61] that would extend to the Lake Cakora entrance. The entrance to Lake Cakora is untrained and has a dynamic estuary mouth that is subject to sand accumulation, blockages, erosion and scour. The lake is an Intermittent Closed and Open Lake or Lagoon (ICOLL), with its entrance state changing periodically. Informal coastal protection has been built along the northern side of the lagoon entrance in front of private properties. The extent of the wall varies in crest level, design, materials, and construction quality and performance.

11.2 Coastal segments

Brooms Head Beach has been defined by three segments. The row of private residences along Ocean Road at the entrance to Lake Cakora have been mapped as part of segment 2. Figure 11-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

11.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 11-1 and Table 11-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

61 SMEC (2017). Brooms Head Beach and Lake Cakora Coastal Zone Management Plan.

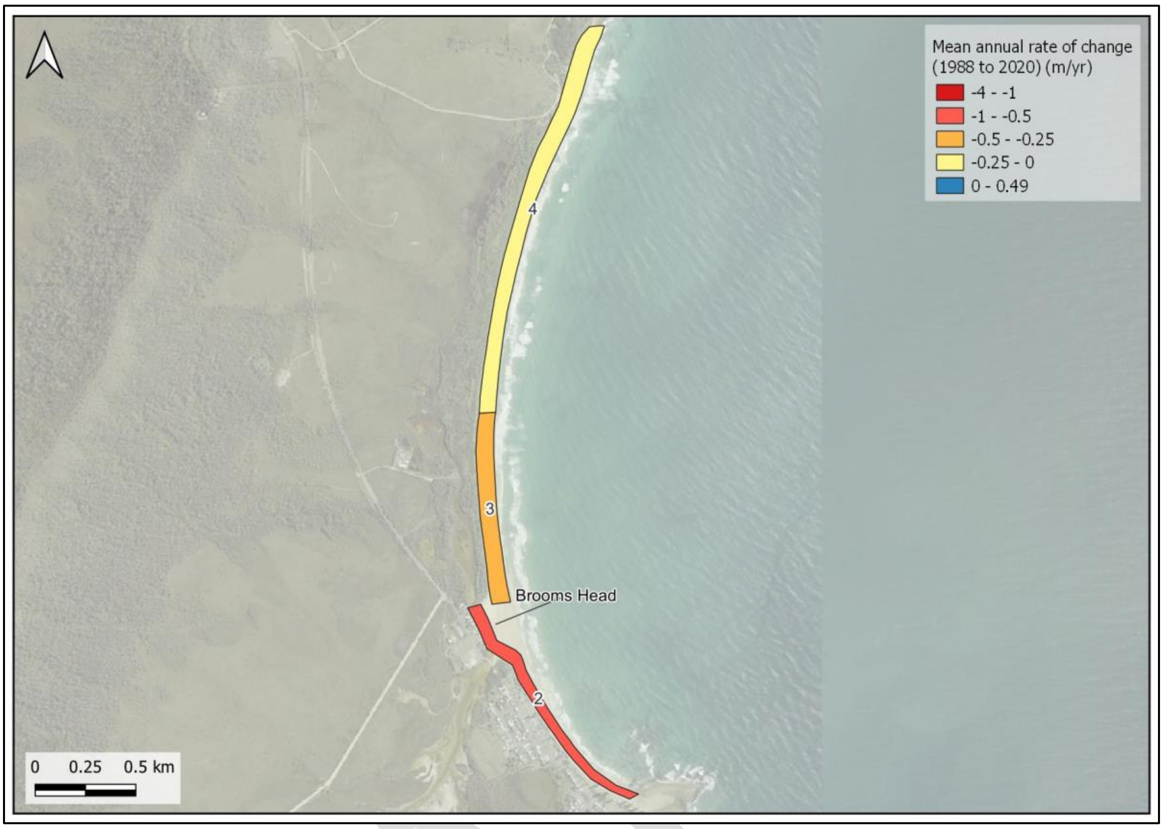


Figure 11-1: Brooms Head beach blocks mean annual rates of change (from 1988 to 2020)

Table 11-1: Brooms Head total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	18.7	38.7	55.4	62.2
	2043	36.2	56.3	73.2	79.7
	2073	62.8	84.5	107.2	118.3
	2123	123.7	176.0	224.9	241.3
3	2023	24.6	36.3	54.2	71.4
	2043	38.5	69.0	138.1	160.1
	2073	127.1	188.5	214.0	224.3
	2123	241.0	317.8	351.6	362.9
4	2023	27.7	41.9	54.6	59.7
	2043	33.2	47.9	60.6	66.7
	2073	42.1	57.8	71.7	77.5
	2123	64.0	88.1	109.7	118.6

Table 11-2: Brooms Head total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	18.7	38.7	55.4	62.2
	2043	36.8	56.8	74.1	81.1
	2073	65.9	88.2	111.7	122.5
	2123	166.3	258.1	369.8	399.7
3	2023	24.6	36.3	54.2	71.4
	2043	38.7	70.5	140.0	161.3
	2073	135.5	192.5	217.4	227.7
	2123	259.7	342.7	374.9	386.4
4	2023	27.7	41.6	54.6	59.7
	2043	33.7	48.1	60.9	66.4
	2073	44.5	60.6	75.3	81.6
	2123	76.0	105.6	129.0	141.3

12 Sandon

The erosion/recession hazard assessment results for Sandon are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

12.1 Background

Sandon Beach is located to the north of the Sandon River and stretches northwards to Cakora Point in Brooms Head. The beach is enclosed by the Cakora Point headland to its north, and Plover Island and tombolo to the south. The southern section of Sandon Beach is a narrow spit of land that runs adjacent to Sandon River and the Sandon River Road, with the Sandon River Campground located at the southern tip before the river entrance. The village of Sandon has also been included in this assessment. Sandon village is located at the mouth of the Sandon River estuary and is made up of approximately 30 private land parcels. The village is low-lying (around 3m above MSL) with a beach crest of approximately 4mAHD. This location is semi-sheltered from offshore conditions by headland to the east, however some swell is observed to propagate in to the estuary mouth.

12.2 Coastal segments

Sandon Beach has been defined by two beach segments with a third (Sandon X) for the village. Figure 12-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

12.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 12-1 and Table 12-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C. Sandon beach blocks 3 and 4 were not included in the erosion assessment as these locations were identified as rocky, non-erodible headland from the NSW Geological maps.

Figure 12-1: Sandon beach blocks mean annual rates of change (from 1988 to 2020)

Table 12-1: Sandon total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
5	2023	19.5	36.0	45.3	48.9
	2043	32.4	44.1	52.8	57.0
	2073	53.1	71.3	88.4	96.0
	2123	146.4	**315***	**315***	**315***
7	2023	25.9	50.7	68.7	72.1
	2043	36.0	62.9	73.3	76.2
	2073	64.4	76.6	82.4	84.6
	2123	95.2	136.3	153.9	170.7
X (Village)	2023	19.3	27.6	33.8	36.7
	2043	25.2	32.8	39.5	42.1
	2073	33.3	41.4	47.8	50.7
	2123	48.8	58.8	65.9	69.0
*limited by estuary - refer to maps					

Table 12-2: Sandon total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
5	2023	19.5	36.0	45.3	48.9
	2043	33.5	44.7	53.7	57.9
	2073	60.7	82.8	101.6	110.0
	2123	**315***	**315***	**315***	**315***
7	2023	25.9	50.7	68.7	72.1
	2043	36.8	63.4	73.8	76.6
	2073	69.4	79.3	85.0	87.2
	2123	131.7	182.6	239.0	259.5
X (Village)	2023	19.3	27.6	33.8	36.7
	2043	25.2	32.8	39.0	42.4
	2073	33.8	41.9	48.6	51.2
	2123	50.7	60.7	67.8	70.7
*limited by estuary - refer to maps					

13 Minnie Water

The erosion/recession hazard assessment results for Minnie Water are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

13.1 Background

Minnie Water Beach is immediately north of the Minnie Water headland (Tree Point) and extends northward to Rocky Point, south of Sandon. The beach extends past the Minnie Water village and the Minnie Water-Wooli Surf Life Saving Club (MWWSLSC). Localised beach erosion has been observed particularly around the beach access points and adjacent to the Nip Welsh Memorial Park.

13.2 Coastal segments

Minnie Water Beach has been represented as one beach segment (Minnie Water 2). Figure 13-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

13.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 13-1 and Table 13-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

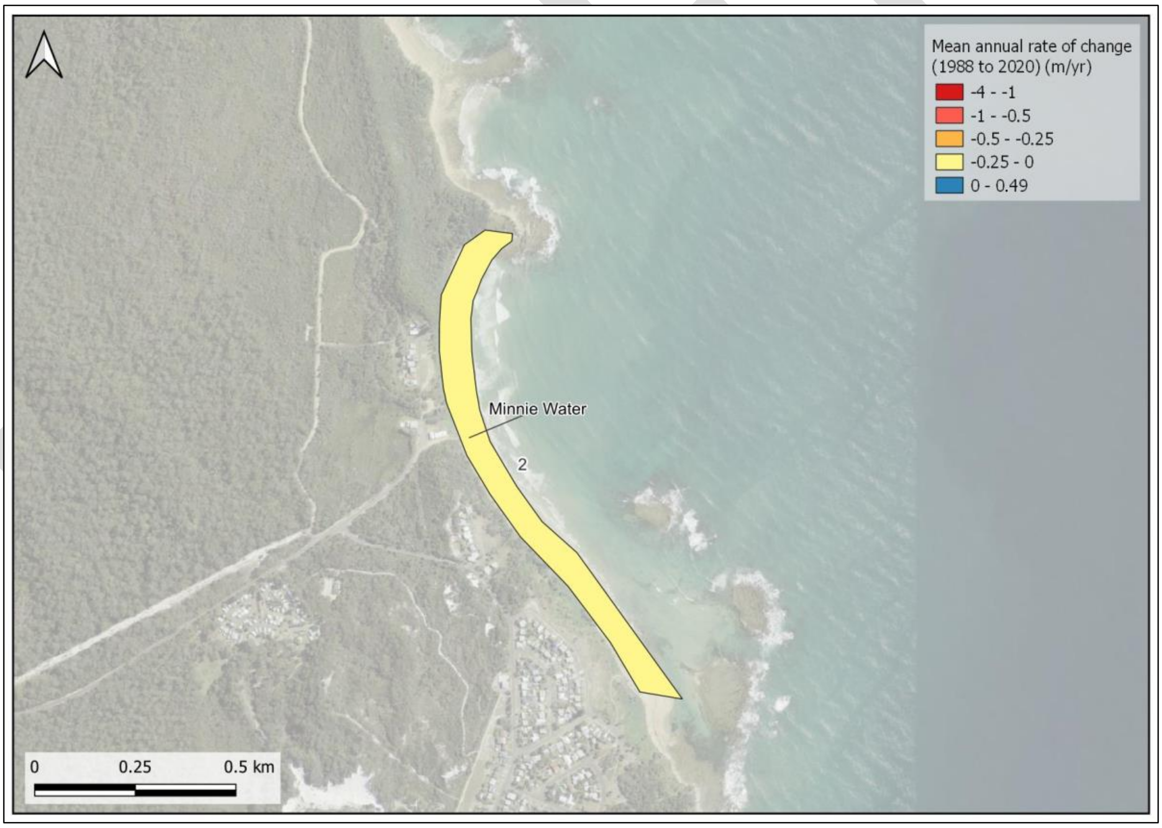


Figure 13-1: Minnie Water beach blocks mean annual rates of change (from 1988 to 2020)

Table 13-1: Minnie Water total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	28.1	44.5	55.0	58.8
	2043	39.5	52.8	62.3	65.9
	2073	55.4	67.8	75.4	78.8
	2123	96.1	112.1	119.5	121.6

Table 13-2: Minnie Water total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
2	2023	28.1	44.5	55.0	58.8
	2043	39.7	53.1	62.3	65.9
	2073	59.7	71.9	80.0	82.8
	2123	112.1	129.5	142.8	147.3

14 Diggers Camp

The erosion/recession hazard assessment results for Diggers Camp are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

14.1 Background

The beach at Diggers Camp is an approximately 500m long pocket embayment backed by a steep 20m high escarpment. The township of Diggers Camp is accessible from Wooli Rd via around 5km of gravel track and established around 80m back from the beach into sloping hills. The beach at Diggers Camp is composed primarily of beach sand and is controlled to the south by wide fringing rock platform as well as rock headland to the north.

14.2 Coastal segments

Diggers Camp has been represented as one beach segment (Diggers Camp 1). Figure 14-1 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

14.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 14-1 and Table 14-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

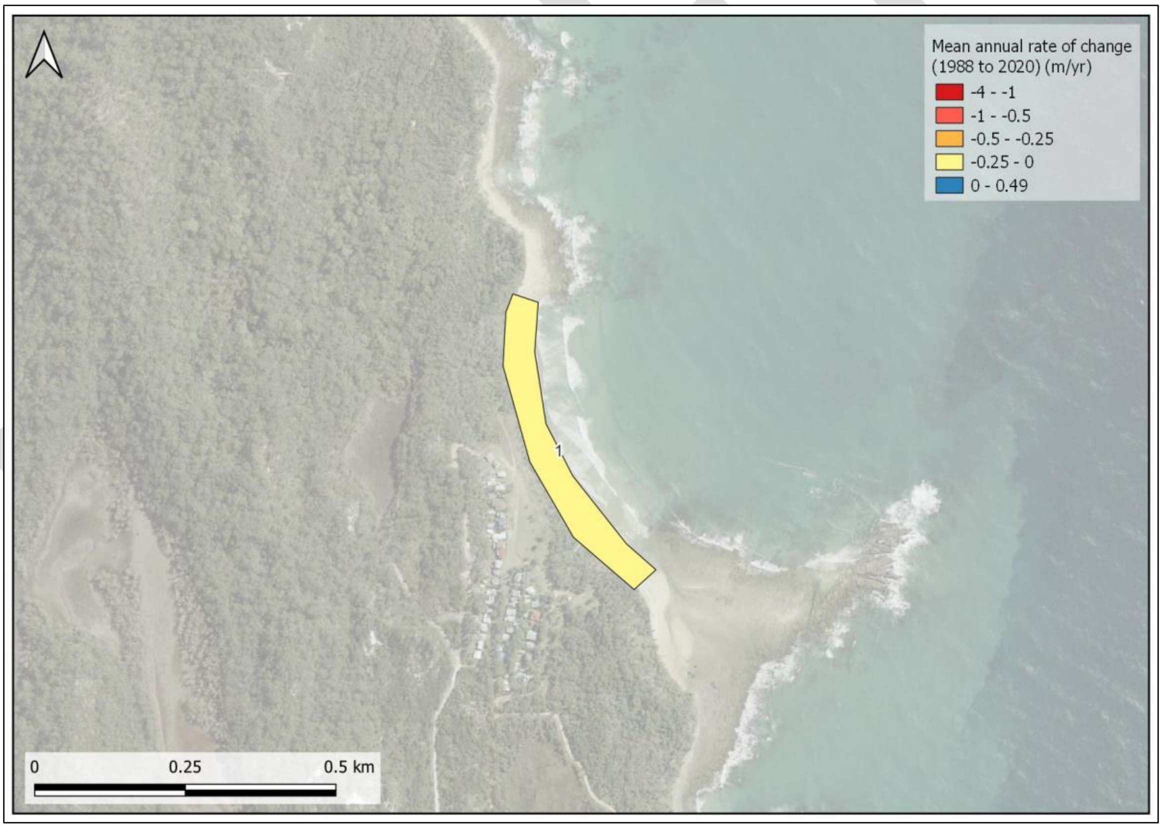


Figure 14-1: Diggers Camp beach blocks mean annual rates of change (from 1988 to 2020)

Table 14-1: Diggers Camp total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	62.8	73.1	77.9	79.7
	2043	65.8	74.9	79.2	81.2
	2073	78.2	85.0	88.7	89.7
	2123	127.5	135.5	139.1	140.3

Table 14-2: Diggers Camp total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
1	2023	62.8	73.1	77.9	79.7
	2043	66.6	74.9	79.2	81.2
	2073	84.0	89.5	92.8	94.8
	2123	136.5	146.1	150.4	151.4

15 Wooli Beach

The erosion/recession hazard assessment results for Wooli are discussed in this section with detailed outputs provided in Appendix B and mapping provided in Appendix C.

15.1 Background

Wooli is the southernmost coastal village within the Clarence Valley LGA. Wooli Beach begins to the south of Diggers Camp headland (Bare Point) and continues to the Wooli Wooli River entrance at the end of South Terrace Road. The northern end of the beach is adjacent to the Yuraygir National Park, and the southern end is adjacent to the town of Wooli and the Wooli Wooli River. The Wooli Wooli River is separated from the Pacific Ocean by a narrow neck of land (Wooli Spit) where the village is located. Jones Beach is situated to the south of the Wooli Wooli River, with Jones Point as its northernmost tip and a rocky headland to its south.

15.2 Coastal segments

The section of Wooli beach being assessed includes the main township of Wooli and has been defined by four beach blocks. Figure 15-2 shows the average annual rate of change between 1988 and 2020 from the GA DEA Coastlines dataset.

Blocks 4 to 7 front the main township which show a trend of minor recession, however Block 5 shows long-term stability. This means the mean sea level contour is in approximately the same location as it was at the start of the long-term analysis in 1988. Over this period the beach would have seen periods of erosion and accretion, however it has returned to a consistent position.

This trend has also been identified in previous assessments. A summary of sediment loss from the Wooli Beach Recession Analysis (RHDHV 2020)[62] is shown in Figure 15-1, and shows the variation (black lines) and average (blue) volume loss from each beach profile over a long-term analysis. This graph shows variability in recession rates, with both Block 4 and 5 showing the potential for erosion and recession (shown as positive and negative values), whilst blocks 6 and 7 only show recession trends.

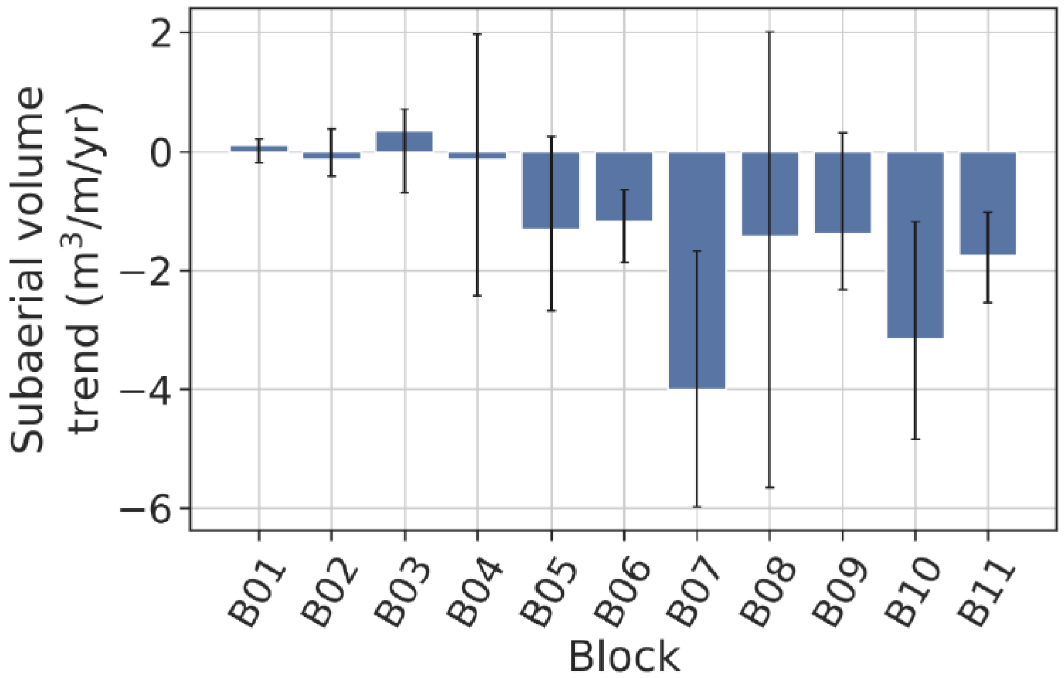


Figure 15-1: Subaerial volume change trend 1966-2019 (recession (losses) are negative). Bar Graph – Average, Line Graph – Range (Source: RHDHV 2020 Figure 8)

62 RHDHV (2020) Wooli Beach - Recession Analysis. Memo to Peter Wilson from Rick Plain. 17 September 2020

15.3 Erosion and recession hazard summary

The width of the total erosion and recession zone for the beach is shown in Table 15-1 and Table 15-2 for climate change scenarios SSP2 and SSP5, respectively. Full erosion and recession results are within Appendix B and full maps are shown in Appendix C.

Figure 15-2: Wooli coastline beach blocks mean annual rates of change (from 1988 to 2020)

Table 15-1: Wooli total erosion and recession hazard width - SSP2

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
3	2023	26.9	50.0	61.9	66.6
	2043	45.5	60.3	72.9	79.0
	2073	70.5	92.1	124.3	**125***
	2123	**125***	**125***	**125***	**125***
4	2023	25.9	45.2	55.0	58.8
	2043	41.1	53.9	63.2	67.0
	2073	62.9	78.6	91.7	98.6
	2123	**150***	**150***	**150***	**150***
5	2023	31.1	47.3	54.0	56.4
	2043	40.8	51.6	57.9	60.5
	2073	55.2	69.5	87.8	96.0
	2123	100.6	171.0	192.5	**200***
7	2023	30.2	52.9	59.8	62.1
	2043	52.4	60.6	67.0	70.8
	2073	66.5	82.6	105.3	114.2
	2123	159.5	213.2	241.8	251.5
* limited due to estuary.					

Table 15-2: Wooli total erosion and recession hazard width - SSP5

Beach block	Planning horizon (year)	50% exceedance probability (m)	10% exceedance probability (m)	2% exceedance probability (m)	1% exceedance probability (m)
3	2023	26.9	50.0	61.9	66.6
	2043	46.9	61.6	74.0	81.1
	2073	79.0	102.4	**125***	**125***
	2123	**125***	**125***	**125***	**125***
4	2023	25.9	45.2	55.0	58.8
	2043	42.1	55.0	64.5	68.1
	2073	68.8	86.4	102.5	111.7
	2123	**150***	**150***	**150***	**150***
5	2023	31.1	47.3	54.0	56.4
	2043	42.2	52.3	58.6	61.3
	2073	59.6	78.4	101.5	111.4
	2123	150.0	171.0	192.5	**200***
7	2023	30.2	52.9	59.8	62.1
	2043	53.2	61.1	67.7	71.3
	2073	71.3	96.1	119.6	129.6
	2123	202.7	251.0	280.0	291.6
* limited due to estuary.					

Appendices

A Additional detail on the probabilistic erosion analysis

A.1 Wave conditions analysis

Event-based erosion along the Clarence Valley coast has been estimated based on wave data recorded at the Coffs Harbour wave buoy. This data was used to assess exposure to coastal processes at key study sites in the area. Historic wave records at Coffs Harbour buoy span from the early 1976 to present day, representing approximately 50 years of real data. However, in order to adequately represent the full range of potential wave and water level conditions within the area, a much longer record is required. Therefore, a probabilistic approach has been used to establish a 10,000-year simulated dataset. This dataset represents the full range of potential wave and water level conditions at the Coffs Harbour buoy. The following methodology has been used:

1. **Metocean data collation:** Historical wave and water level data was collated
2. **Data declustering:** The historical data series was declustered into discrete events
3. **Data simulation:** The declustered data was used to produce a 10,000-year simulated dataset
4. **Data sampling:** A subset of 200 discrete events was sampled from the 10,000-year dataset
5. **Wave modelling:** The 200 representative events were applied to a numerical wave model
6. **Nearshore conditions:** Nearshore conditions were extracted at key locations in the model
7. **Nearshore wave emulation:** A machine-learning algorithm was used to translate the remaining 10,000-years of simulated wave data to the nearshore

The offshore and nearshore simulated wave conditions have been used in this study to assess various coastal processes as schematised in Figure 15-3.

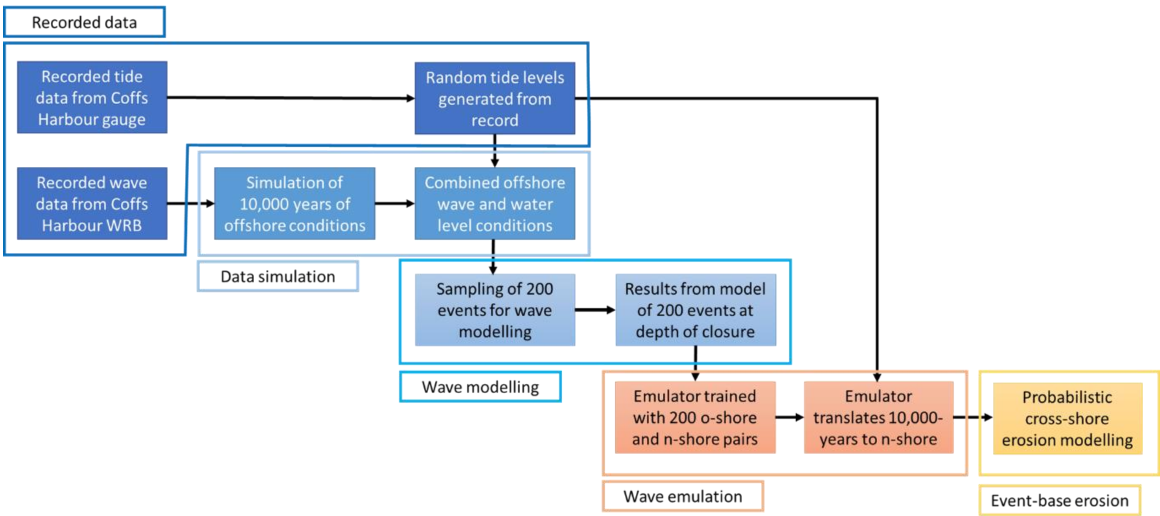


Figure 15-3: Schematisation of event-based erosion assessment methodology

A.1.1 Data declustering

The historical dataset has been processed using peak analysis to isolate discrete weather events in the record. For the purposes of this study, a discrete weather event is defined as a peak in the wave height (Hs) record. The minimum duration for a weather event has been set to 2 days, with a minimum prominence of 0.2m (i.e. wave heights above 0.2m to their nearest neighbour in the time series). From the 50-year recorded data series, approximately 2200 weather events have been discretised. Figure 15-4 shows an example of declustered events of peak wave height and corresponding surge levels.

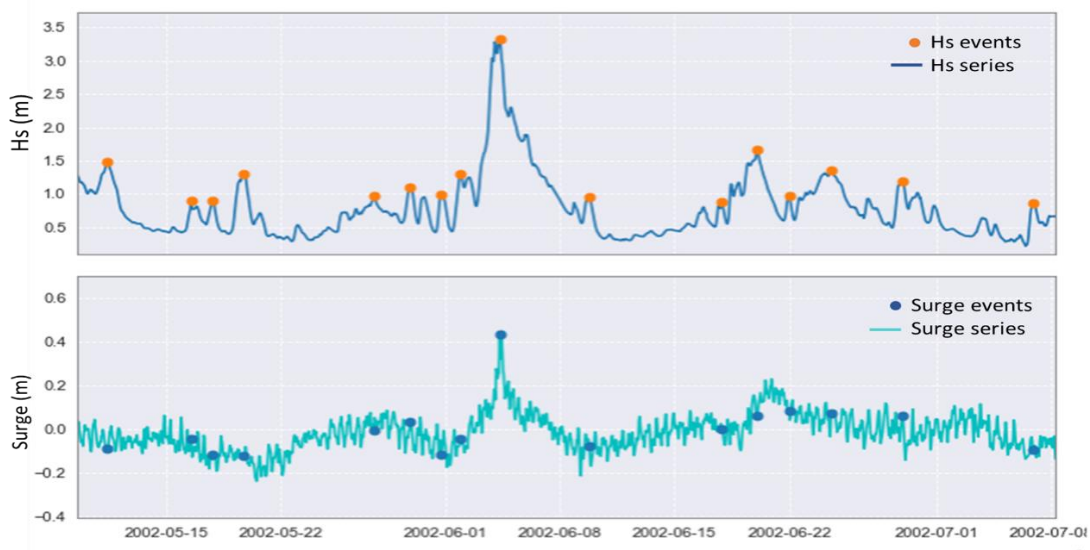


Figure 15-4: Declustering of discrete weather events in wave record (top), and corresponding surge record (bottom)

A.2 Data simulation

To fully represent the metocean conditions at Coffs Harbour, a full range of potential wave and water level events is required. Conventionally, this would be accomplished by creating a set of conditions where all possible combinations for wave height, period, direction, and surge level are favoured equally. However, a more robust method has been used which relies on multivariate analysis to simulate the set of possible conditions. This method favours a more realistic distribution of wave and water levels conditions, as the characteristics of the historical data are used directly to simulate a much larger set of conditions.

First, the distribution of each of the declustered event parameters (Hs, Tp, Dir, and surge) is determined, as well as the correlation of each parameter to every other, as shown in Figure 15-5. This figure shows good correlation between Hs and residual surge, as well as Hs and Tp. Figure 15-5 also shows the largest wave conditions arriving from the east.

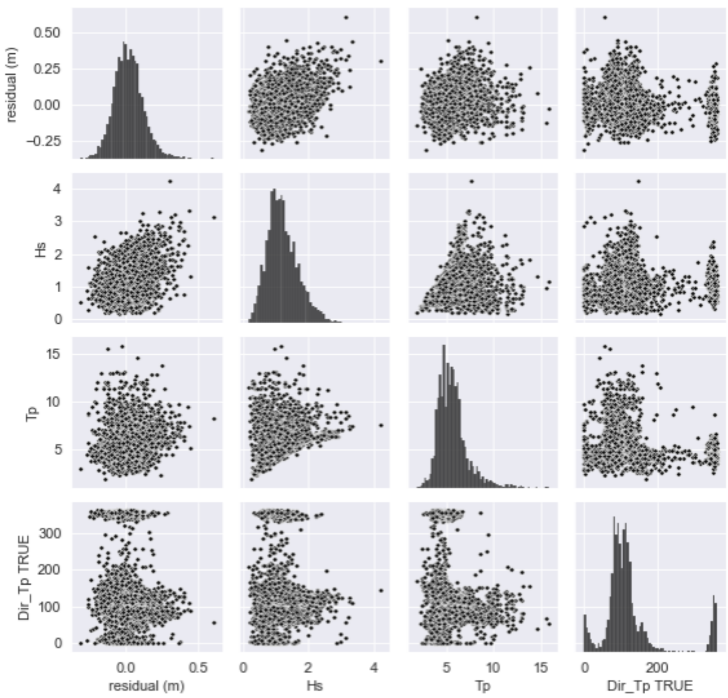


Figure 15-5: Pair plot of historical wave Hs, Tp, Dir, and residual surge events.

Next, a Gaussian copula method is applied to the data. This method fits a univariate distribution to each parameter and creates a set of 10,000 years' worth of simulated conditions. Figure 15-6 shows a comparison of historical events to the larger simulated set.

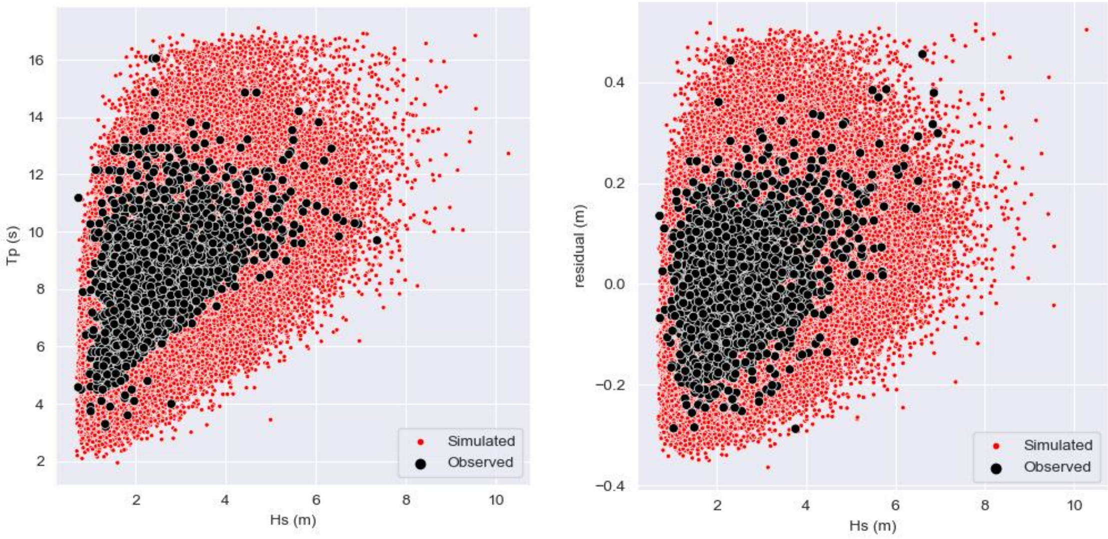


Figure 15-6: Historical and simulated offshore data showing Hs and Tp (left), and Hs and residual surge (right).

A.2.2 Data sampling

The large set of 10,000-year offshore data is required to be translated to the nearshore to assess sediment transport processes at key coastal locations. Numerical modelling will be used to simulate conditions in the nearshore, however it is not computationally efficient to model each event. Therefore, a subset of 200 events have been sampled from the large set to be used in numerical modelling. A Maximum Dissimilarity Algorithm (MDA) has been used for sampling. This method ensures that the full distribution and extremes of the larger dataset are retained in numerical modelling. The larger simulated dataset has been directionally limited to wave conditions from 10 to 180°N, as conditions outside of this range are not relevant to the study area. The MDA has been performed on this limited set. Figure 15-7 shows the sampled events and the larger dataset.

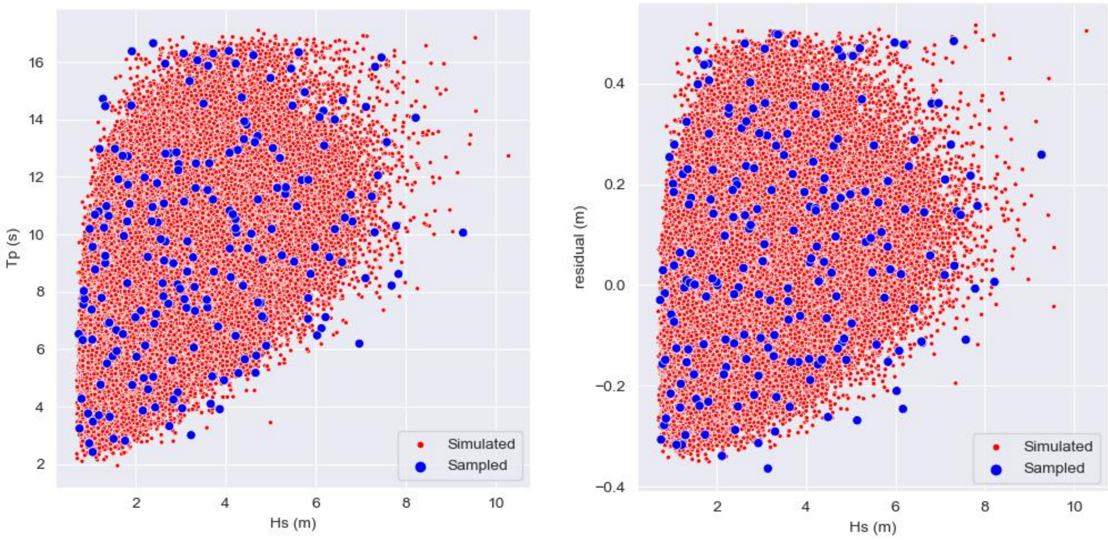


Figure 15-7: Simulated and MDA-sampled offshore data for Hs and Tp (left), and Hs and residual surge (right).

A.2.3 Tide and surge levels

Each of the 200 sampled events require an associated water level for numerical modelling. It is assumed that the duration of each event is greater than 6 hours, therefore a high tide level has been applied to each event. High tide levels have been randomly sampled from the astronomical tide record at Coffs Harbour. The modelled water level for each event is the combination of the residual and the random astronomical tide (i.e., tide + surge).

A.2.4 Wave Modelling

The 200 sampled events have been simulated in a numerical wave model to understand general nearshore wave conditions along the CVC coastline. Wave modelling has been undertaken using the SWAN spectral wave model in Delft3D. SWAN is a third-generation wave model that simulates wave propagation in coastal and inland areas. It accounts for the following physics:

- Wind-wave interactions, which is the transfer of wind energy into wave energy, leading to the growth of waves.
- Shoaling, which is the build-up of energy as a wave enters shallow water, causing an increase in wave height.
- Refraction, which is the change in wave speed as waves propagate through areas of changing depth, causing a change in wave direction.
- Wave breaking, which is the destabilisation of a wave as it enters shallow water, causing broken waves with the characteristic whitewash or foam on the crest.
- Wave dissipation, which limits the size of waves through white-capping, bottom friction and depth-induced breaking.

A.2.5 Modelling domain

The extent of the wave modelling grid has been designed to align with the offshore 70m depth contour, matching the depth of the Coffs Harbour wave buoy. The model has a varying spatial grid resolution and a bathymetry based on the merged 5m NSW Topography and Bathymetry dataset. Figure 15-8 shows the wave model domain.

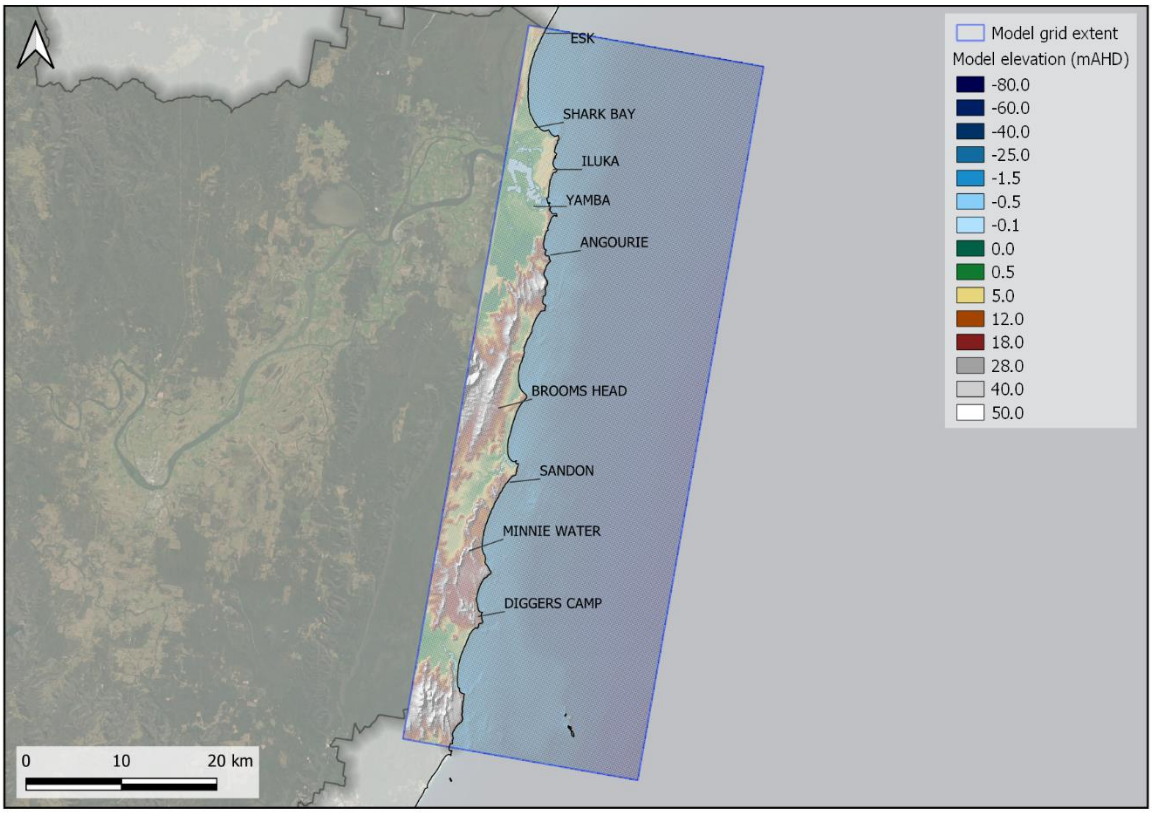


Figure 15-8: Wave model grid and bathymetry

A.3 Nearshore wave emulation

The wave model has been used to simulate the set of 200 sampled wave events. Nearshore results have been extracted at the depth of closure for points along the CVC coastline from Wooli to Shark Bay. For each location, nearshore results for the 200 modelled runs are paired with their respective offshore input conditions to be used to train a Random Forest Regression (RFR) machine learning model.

The RFR model uses the set of 200 offshore and nearshore pairs to generate a large number of cascading decision "trees" based on wave height, period, direction and water level. When new offshore data is applied to the RFR model, each tree makes a prediction of the nearshore conditions, the final prediction is the averaged values of all trees. The trained RFR model has been used to emulate the full set of 10,000 years of offshore conditions to the nearshore, with a prediction threshold of 90%.

A.3.6 Results of nearshore wave emulation

Table 15-3 shows statistics for wave height, period, and direction for each location at the present-day closure depth. At Woody Head, these results show a trend towards smaller waves due to the sheltering provided by the adjacent headland to east- and south-easterly waves. At more exposed locations such as Yamba and Sandon wave conditions are correspondingly larger and more easterly.

Table 15-3: Nearshore wave condition statistics

	Av. Hs (m)	Max Hs (m)	Av. Tp (s)	Max Tp (s)	Av. Dir (°N)
Shark Bay	1.5	3.3	8.5	16.5	77.4
Woody Head	1.0	1.9	8.5	15.4	58.3
Yamba	1.9	4.9	8.3	16.5	117.5
Brooms Head	1.8	4.8	8.4	16.6	103.1
Sandon	1.9	4.8	8.4	16.7	103.8
Minnie Water	1.6	3.9	8.3	16.8	97.7
Wooli	1.3	4.7	8.2	15.6	103.1

A.4 Cross-shore beach profiles

Initial beach profiles have been developed for locations along the CVC coastline, based on the beach blocks delineated in the NSW Coastal Profile Database. Each profile has been derived from a combination of 1m topographic LiDAR and 5m topo-bathymetric survey. To maintain continuity across all profiles, an equilibrium profile following $h(x) = Ax^{2/3}$ has been fit to each of modelled profiles. Offshore rocky seabed bedforms have been identified for several beach sections from the NSW marine LiDAR-based seabed landforms dataset (DPE, 2022)[63]. The equilibrium profile has been fit through the existing profile data with rock bedforms removed using a least-squared errors regression fit. Each cross-shore profile is assumed to be representative of its respective beach block.

63 Linklater, M., Morris, B., Kinsela, M., Ingleton, T. and Hanslow, D. (2022), Exploring patterns of reef distribution along the southeast Australian coast using marine lidar data. Manuscript in preparation.

B Additional detail on erosion and recession data

Supplied separately.

C Erosion and recession hazard maps

Supplied separately

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