Tweed Shire Council

Tweed Coast and Coastal Estuaries – Coastal Hazard Assessment

Tweed Shire CMPs Stage 2

17 January 2025

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SHIRE COUNCIL

Acknowledgement of Country

We wish to acknowledge the Ngandowal and Minyungbal speaking people of the Bundjalung Country, in particular the Goodjinburra, Tul-gi-gin and Moorung - Moobah clans, as being the traditional owners and custodians of the land and waters within the Tweed Shire boundaries. We also acknowledge and respect the Tweed Aboriginal community's right to speak for its Country and to care for its traditional Country in accordance with its lore, customs and traditions.

Acknowledgement of financial assistance

Tweed Shire Council has prepared this document with financial assistance from the NSW Government through its Coastal and Estuary Grants Program. This document does not necessarily represent the opinions of the NSW Government or the NSW Department of Climate Change, Energy, the Environment and Water.

Executive Summary

The Tweed Shire's coastline extends from the local government area's southern boundary at Wooyung Beach to its northern boundary at Point Danger. The Shire's coastline is a highly dynamic coastal environment and has experienced numerous coastal erosion events and a variety of coastal management responses.

This report presents the outcomes of a comprehensive study of the regional and local coastal processes and hazards affecting the Tweed Shire coastline and coastal estuaries. The study supports the preparation of Coastal Management Programs (CMPs) by Tweed Shire Council in accordance with the NSW Coastal Management Framework. Stage 2 of CMP preparation involves undertaking detailed studies that help Council to identify, analyse and evaluate risks, vulnerabilities and opportunities.

The study adopts a data-driven approach using a wide range of available coastal and metocean datasets. The report covers a 37km stretch of sandy beaches, three coastal creeks and their entrances, and several headlands and rocky coastlines. At its centre is an analysis of the Tweed Shire coastal sand budget, which maps historical sand volume changes in 59 sediment cells. These are used to infer the rates and directions of sand movements. The most likely drivers for the observed sand volume changes are described based on observational data, previous literature, state-of-the-art numerical modelling and/or coastal processes knowledge. Key outcomes from the contemporary assessment are:

- The beaches along the Tweed Shire coast experience change over various time scales, driven by persistent changes to sand budgets (long term) and climatic cycles (medium term) as well as storms and seasonal variations (short term).
- Average net longshore sand transport in the Tweed Shire is from south to north and ranges from 530,000m^3/year along its southern coastline to 560,000m^3/year along its northern coastline (±30%). However, longshore sand transport rates are highly variable responding to variation in the direction and energy in the offshore wave climate, which is sensitive to climate cycles of years, decades and longer timescales.
- High variability in sand supply to southern embayments at Cabarita Beach, Kingscliff Beach and Fingal Head Beach is observed due to headland bypassing processes resulting in fluctuating upper beach volumes and shoreline positions.
- A net (long-term) loss of sand was estimated at around 30,000m^3/year over a 30km stretch of sandy beaches (Wooyung to Fingal Head). The rate of sand loss varies alongshore and between beach compartments. No net sand loss was observed for the stretch of coast between Norries Headland and Cudgen Headland, possibly due to a higher rate of onshore sand supply from the lower shoreface in this area. Observed changes along the coast either side of the Tweed River entrance have been predominantly governed by Tweed Sand Bypassing (TSB) operations.

The sand budget outcomes are used to inform a Shire-wide coastal hazard assessment considering a range of specific coastal hazards, including:

- A probabilistic beach erosion and shoreline recession hazard assessment. This was informed by a statistical model comprising a volumetric coastline response model that uses detailed terrain data and a parameterised sand budget to predict the potential range of present and future coastal erosion hazards.
- A coastal inundation hazard assessment for the Tweed Shire open coast.
- Estuary specific hazard assessment at Mooball Creek, Cudgera Creek and Cudgen Creek. The type of hazards assessed vary for each estuary and include:

  - Coastal estuary entrance instability which may affect flood hazards and beach and foreshore erosion hazards as well as the estuary flushing and associated water quality.
  - Inundation of land surrounding estuaries by tidal action under average meteorological conditions.
  - Erosion and inundation of foreshores caused by tidal waters and the action of waves.

Key outcomes from the coastal hazard assessments are:

- The probabilistic coastal erosion and recession hazard assessment suggests that public and private assets are located within the immediate hazard extent at Kingscliff Beach and Fingal Head Beach at the holiday park. By 2120, the hazard extents would affect a considerably larger number of additional public and private assets and foreshore area including assets at Pottsville Beach (north), Hastings Point, Cabarita Beach, Casuarina Beach to South Kingscliff, Kingscliff Beach, Dreamtime Beach and Fingal Head Beach.
- The first pass coastal inundation assessment highlights that wave runup can result in dune overwash along most beaches. However, due to most development sites being set back from the dune along the Tweed Shire coast, developed areas identified as to be exposed to coastal inundation are limited to the following sections of beach:
  - Kingscliff Beach between the Cudgen Headland SLSC and the holiday park at the northern end of Kingscliff.
  - Fingal Head Beach at the holiday park.
- The estuary entrances to Mooball Creek, Cudgera Creek and Cudgen Creek are relatively stable. In the longer term, entrance breakthrough is possible south of the current entrance locations at Mooball Creek and Cudgen Creek which may lead to a change in the respective entrance behaviour. By 2120, a risk that long-term recession of Kingscliff Beach may undermine the creek training walls was identified.
- By 2040, high tides can expose a significant area of land surrounding Cudgen Creek to inundation. With sea level rise, land and development surrounding all three coastal estuaries may be exposed to tidal inundation by 2120
- Bank erosion within all three coastal estuaries is an ongoing issue, particularly around uncontrolled access points. Sea level rise will likely affect the frequency and duration of inundation of foreshores and increase tidal current speeds, further impacting bank stability and vegetation health where this is already occurring as well as affect additional areas.
- Sea level rise is expected to alter tidal ranges and water levels, affecting the distribution of seagrasses, mangroves, and saltmarshes. These changes could impact fish habitats, shorebirds, and overall estuarine ecology. Groundwater resources may also be affected by saline intrusion due to rising sea levels, impacting freshwater availability and increasing the inundation risk of freshwater resources in low-lying areas. However, a detailed groundwater assessment was not conducted in this study.

The approaches adopted herein are reasonable and valid for assessing the Tweed Shire's coastal hazards and underlying coastal processes. However, it is important that decision-makers recognise the assumptions underlining the assessments as well as the inherent uncertainties. The key assumptions and uncertainties for each of the hazard assessments are outlined in the relevant sections in this report.

The outcomes of this report are used to undertake a detailed risk assessment of coastal hazards affecting the Tweed Shire's coastline to identify and evaluate management options and support decision-making in Stages 3 and 4 of CMP preparation.

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1. Introduction

1.1 About this report

This report provides the outcomes of a comprehensive study of the regional and local coastal processes operating on the Tweed coastline and coastal estuaries (coastal zone). The study adopts a data-driven approach using a wide range of available coastal and metocean datasets. At its centre is an analysis of the Tweed coastal sand budget. The report presents the methodology and outcomes for the definition of coastal and estuarine hazards affecting the Tweed coastline. The study supports the preparation of Coastal Management Programs (CMPs) by Tweed Shire Council (Council).

The purpose of the report is to provide:

- an improved understanding of coastal sand movements for the entire Tweed Shire coastline
- a detailed review and update of Council's existing coastal hazard assessment study (completed in 2013) using contemporary data
- the scientific basis for understanding the nature and extent of risks to public safety, built assets, coastal land, cultural heritage/features, ecosystem health and recreational amenity from coastal hazards
- the scientific basis for understanding of the factors that contribute to vulnerability from current and future risks.

This technical study forms a major part of Stage 2 of the CMP preparation. It has been prepared in line with the *Coastal Management Act 2016* (CM Act), the NSW Coastal Management Manual (CM Manual) and associated Toolkit (i.e., the NSW Coastal Management Framework). It fulfills the requirements set out in Council's study brief (2023-020) and accords with Bluecoast's proposal document (dated 19 April 2023). In accordance with the CM Act, it takes a sediment compartment wide approach. The outcomes of this report will be used to undertake a detailed risk assessment to identify and evaluate management options and support decision-making in Stages 3 and 4 of CMP preparation.

1.2 Study context

Tweed Shire Council have commenced preparation of CMPs for the Tweed Shire coastal zone. The NSW Coastal Management Framework specifies the five stages of preparing a CMP (see Figure 1). The purpose of a CMP is to set the long-term strategy for the coordinated management of the coastal zone with a focus on achieving the objects of the CM Act. The Council has completed and adopted a Stage 1 CMP scoping study (dated 28 February 2020) which covers the entire coastal zone of the Tweed Shire local government area (LGA).

Stage 2 of CMP preparation involves undertaking detailed studies that help Council to identify, analyse and evaluate risks, vulnerabilities and opportunities. The studies conducted during Stage 2 are to provide information to support decision-making in the subsequent stages of the CMP planning process. This Stage 2 CMP study focuses on the open coast and coastal estuaries of the Tweed Shire coastal zone (not including Tweed River estuary).

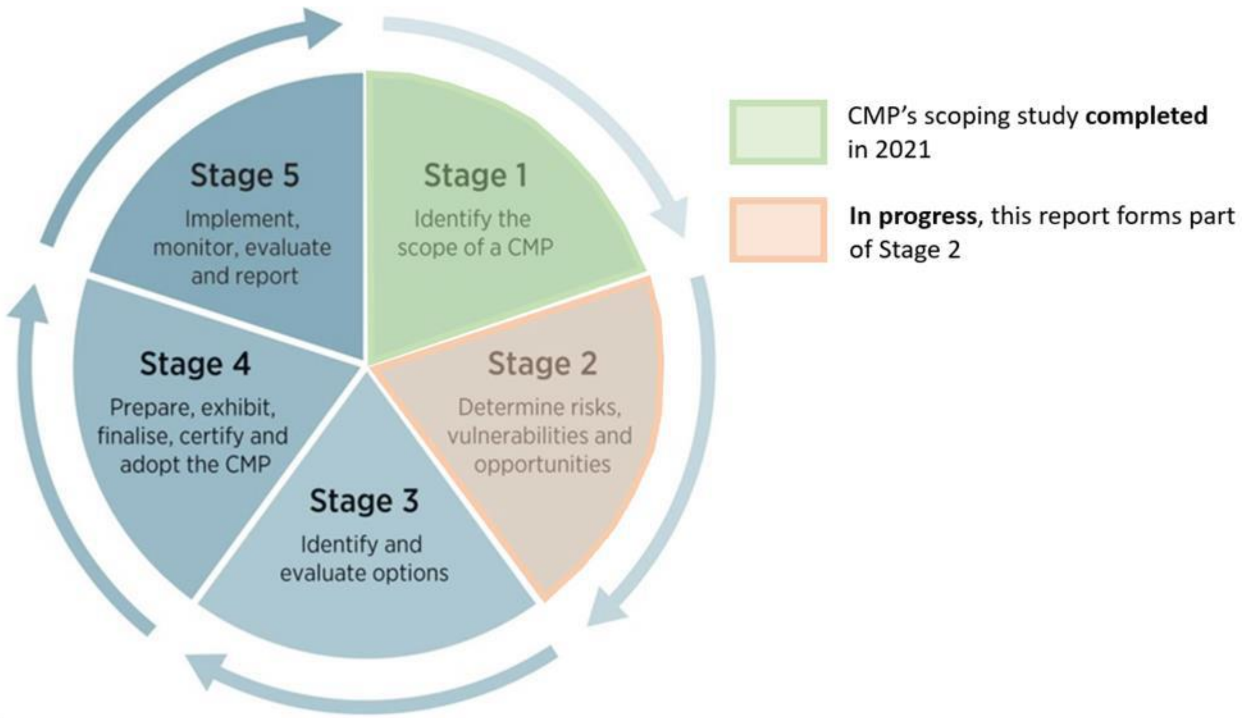


Figure 1: Stages in preparing and implementing a CMP (modified after the NSW Government).

1.3 Study area

The study area (see Figure 2) includes the open beaches, foreshore, estuaries and coastal waters from the Tweed Shire's southern boundary on Wooyung Beach to the Shire's northern boundary at Point Danger. This encompasses the entire Tweed Shire open coastline (from Wooyung to Point Danger), including the three coastal estuaries at Mooball Creek, Cudgera Creek and Cudgen Creek. The Tweed River estuary is not included as part of this study. This area covers a significant portion of the Tweed coastal sediment compartment. As defined in the CM Act, the Tweed sediment compartment extents from Cape Byron to Point Danger, incorporating Byron Shire and Tweed Shire.

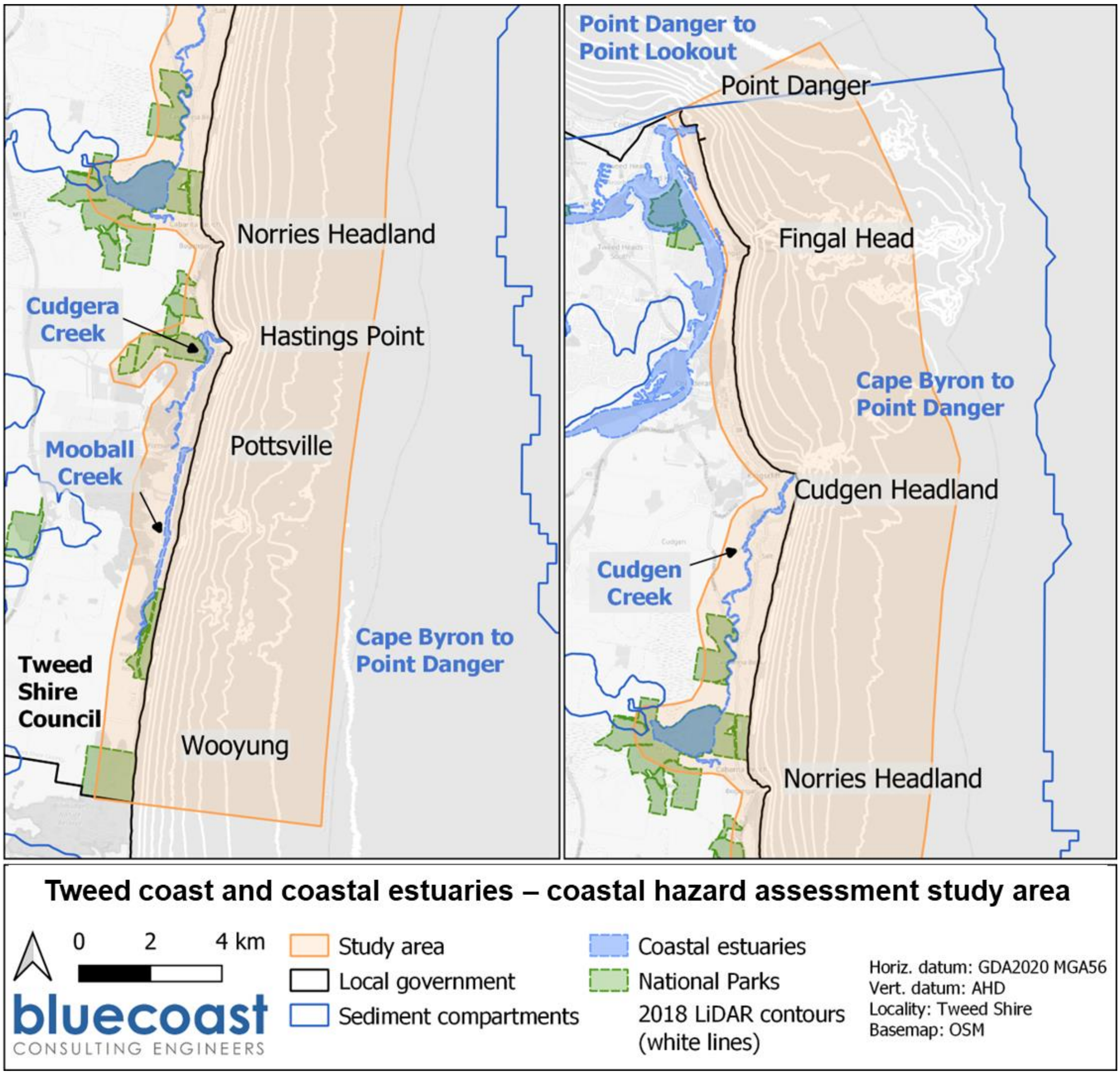


Figure 2: Study area of the Tweed coast and coastal estuaries coastal hazard assessment.

The study area includes:

- approximately 37km of sandy beaches including Wooyung Beach, Mooball Beach, Pottsville Beach, Cudgera Beach, Maggies Beach, Cabarita Beach, Bogangar Beach, Casuarina Beach, South Kingscliff Beach, Kingscliff Beach, Dreamtime Beach, Fingal Head Beach, Letitia Beach and Duranbah Beach.
- approximately 2km of headlands and rocky coastlines including Black Rocks, Potts Point, Hastings Point, Norries Headland, Cudgen Headland, Fingal Head and Point Danger
- three coastal creeks being Mooball Creek, Cudgera Creek and Cudgen Creek.

1.4 Scope and structure of this report

The scope of this study is set out in the following report structure:

- Section 1: Provides introduction to the study, context, assumptions and uncertainties.

- Section 2: Provides background information relevant for the assessment of coastal and estuarine hazards.
- Section 3: Provides a description of the coastal geomorphology, processes and hazards.
- Section 4: Describes the Tweed Shire sand budget and presents a quantified conceptual sand movement model.
- Section 5: Describes the probabilistic assessment of beach erosion and shoreline recession.
- Section 6: Provides a coastal inundation analysis including wave runup and overtopping.
- Section 7: Provides a hazard assessment specific to the study area's estuaries.
- Section 8: Introduces a detailed coastal risk assessment.

1.5 Statement of assumptions and uncertainties

The approaches adopted herein are reasonable and valid for assessing the Tweed Shire's coastal hazard and underlying coastal processes. However, it is important that decision-makers recognise the assumptions underlining the assessments as well as the inherent uncertainties. Specific assumptions, limitations and uncertainties are provided throughout this report against relevant discussions. It is further recommended that Council:

- communicate the assumptions and uncertainties to the community and stakeholders
- seek to reduce the degree of uncertainty through on-going monitoring of the full coastal profile along the Tweed Shire (where possible or in high-risk areas), nearshore coastal processes (wave, currents etc.) and sand movements.

2. Background information

2.1 Historical timeline of key coastal events and developments

A history of key events related to coastal hazards that have transpired in the Tweed Shire in the last 150 years is provided in this section. A summary of key anthropogenic influences on the coastal processes and storm events that caused extensive erosion within the study area is presented in Table 1.

Table 1: Summary of key relevant human modifications and storm events affecting the study area.

Year	Event description
1880-1910	Tweed River training walls were built along either side of the Tweed River entrance.
1926	Road to Kingscliff from Chinderah is constructed, leading to the growth of Kingscliff as a family resort town.
1933-1936	Period of severe and extensive beach erosion following a succession of tropical cyclones.
1930s	Sand mining begins on the Tweed coast with rutile and zircon minerals found on Wooyung Beach ca. 1935 and would last into the 1980s. This had a significant impact on the beach profiles, with coastal dune systems altered significantly.

Year	Event description
1950	Kingscliff bowling club was formed with construction of original bowls green in the dune area.
1954	A tropical cyclone crosses the coast near Tweeds Head with 15 metre waves reported at Dreamtime Beach. Significant erosion along the Tweed Coast.
1950s-1960s	Sand mining along Tweed Coast is at its peak with five sand mining companies holding leases and employed around 1,000 people by 1956. Coastal towns of Cabarita/Bogangar, Hastings Point and Pottsville are developed. Aerial photo below from Bogangar of sand mining operations in ca. 1945 (source: R.L. Anthony). 
1961-1964	Period of severe storms and erosion that lead to 11.7m of foreshore loss at Kingscliff Beach.
1962	Tweed River training walls are extended by 300m between Letitia and Duranbah beaches, leading to significant accretion on the upper beach at north Letitia Beach. Aerial photo below is from 1963 after completion.

Year	Event description
	
1965	Completion of construction of 'new' Cudgen Surf Life Saving Club (SLSC) house at its present location.
1967	A series of tropical cyclones and an East Coast Low in June cause severe erosion along the Tweed coast. Completion of construction of training walls at the Cudgen Creek and Mooball Creek entrances by Tweed Shire Council as part of flood mitigation (no intention of navigable access).
1970s	Sand mining became almost non-existent on Tweed beaches. However, some sand mining continued south of Cudgen headland into the 1980s.
1971	Extension of Kingscliff bowls club and construction of rock seawall on eastern side of club facilities. Previous attempts of ad-hoc rock protection works in front of the bowls club date back to 1965.
1972	Tropical Cyclone "Daisy" caused heavy damage along the northern New South Wales coastline. Kingscliff suffered significant erosion and waves were seen to wash into Kingscliff Caravan Park and Cudgen Headland SLSC.
1974	Tropical Cyclones Pam and Zoe lead to extensive erosion along Tweed Coast, with trees removed by storms along Kingscliff foreshore. In response, pine trees are planted along the Kingscliff foreshore to help stabilise it.
1978	Additional rock is added to the Kingscliff bowls club seawall is topped up with additional rock.
1995	The Kingscliff bowls club seawall is further upgraded to prevent future erosion risk.

Year	Event description
1995-1998	3.05 million m^3 of sand was dredged from Tweed River entrance as part of Stage 1 of the Tweed Sand Bypassing (TSB) project.
1996	Two East Coast Lows in February and May cause severe erosion along the Tweed coast.
1999	A series of East Coast Lows affect the northern NSW coast, causing significant erosion along the Tweed coast.
2001	Construction of the TSB pumping jetty at north Letitia Beach is completed. Initial pumping and dredging rates saw approximately 1 million m^3 of sand transported to the southern Gold Coast each year. This led to significant shoreline retreat at north Letitia Beach.
2008	TSB pumping rates are reduced to align with long-term average longshore sand transport rates at Letitia (approximately 500,000m^3 of sand per year), leading to some stabilisation of Letitia Beach.
2009	Multiple storms in early 2009, culminating with a large East Coast Low in May 2009 with 6 to 7m waves measured at Tweed and Byron buoys causing significant erosion along Tweed Coast beaches. These storms ended a period of generally accreted beaches associated with the millennial drought.
2011	Continued erosion of Kingscliff Beach due to a series of storms, period of predominantly easterly wave direction and sand bypassing process around Cudgen Creek headland.
2010-2011	Concrete seawall at Cudgen Headland SLSC, landward extension of Cudgen Creek training wall and low rock revetment between SLSC and Cudgen Creek training wall built. 14,000m^3 of sand nourishment at Kingscliff Beach from lower reaches of Cudgen Creek in response to erosive La Niña period. Construction of temporary geobag revetment immediately north of Cudgen Headland SLSC to Holiday Park and temporary rock revetment (60m long) north of the geobag revetment to protect amenities block at Holiday Park.
2013	Tropical Cyclone Oswald caused large waves, storm surge and erosion along the Tweed coast.
2016	East Coast Low causes significant erosion across much of the NSW coast, with significant wave heights exceeding 5m at the Tweed Heads wave rider buoy. 25,000m^3 of sand dredged from the Cudgen Creek entrance to improve navigation of the entrance channel and placed on Kingscliff Beach to provide sand nourishment.
2019	Tropical Cyclone Oma produced storm waves over 6 metres, causing severe erosion along the Tweed coast with an estimated 65,000m^3 of sand eroded from Dreamtime's upper beach.
2020	Severe erosion in December from a large low pressure system which produced large waves and extensive heavy rain across Tweed coast.
2022	Large waves in January from Ex-tropical Cyclone Seth cause erosion along the Tweed coast. Widespread flooding followed in March across the Tweed Coast due to extreme rainfall.

2.2 Introduction to coastal processes

Movement of water and sediments within and around the coastal profile occurs in three main areas, the shoreline and subaerial beach above the mean sea level (MSL) mark (i.e., beach), in the surf zone, and in the deeper upper shoreface waters (see Figure 3). Transportation within these areas is governed by several processes that vary on a range of spatial and temporal scales including but not limited to:

- **Regional geology** - the structure and orientation of the beach system and the sediment available.
- **Local geomorphology** - the coastal topography influences the magnitudes and directions of currents generated on the upper shoreface and the shape of the active beach face.
- **Waves** - in the coastal zone are generated predominately from two primary sources, offshore (swell), including waves associated with low pressure systems and locally generated wind-waves (sea). Within the upper shoreface, waves impact sand transport through three key processes: wave breaking, wave motion and undertow. Infragravity waves have longer periods of 25-250 seconds and are formed due to the superposition of two different short-wave trains of similar lengths and frequencies. The waves are often reflected off the coast and the presence of a sandbar may trap infragravity waves between the bar and the beach. Wave breaking, particularly in the surf zone, and infragravity waves which can dominate the wave motions at the coastline particularly during storm events, result in radiation stresses and drive cross-shore and longshore currents and are the main driver of sand transport. In addition, wave orbital motions drive mass onshore movement of sediments from differences in shear stress on the seabed leading to onshore sand transport and beach accretion, while undertow can result in transport of sediments offshore due to bottom return currents and rip currents in the surf zone leading to offshore sand transport and beach erosion. Variability in the wave climate occurs over both seasonal, interannual and decadal time scales, impacting sand movements over longer time scales. The impact of waves on a given coastline depends on its local setting, including the exposure and local bathymetry, with significantly greater sand transport occurring in the surf zone during high wave events.
- **Tides and water levels** - astronomical tide range is subject to spatial variability due to hydrodynamic, hydrographic and topographic influences. Background sea level can also be affected by other phenomenon such as seasonal fluctuations related to El Niño/La Niña cycles, relative position of ocean currents and eddies to the shoreline, coastally trapped waves and persistent monsoon winds. At many locations sea level rise due to climate change is predicted to result in recession of the shoreline as the beach profile moves landward as well as inundation of low-lying areas.
- **Wind** - wind driven (aeolian) sediment transport occurs over unconsolidated sands above the water level, with the quantity of sand transported increasing with the cube of the wind velocity. Aeolian sand transport can be significant for the overall sand budget at some locations, although is often orders of magnitude lower compared to sand transport below water.
- **Storm surges** - occur mainly due to wind set-up during strong onshore winds pushing surface waters against the coastline. This leads to temporary elevated water levels along the coast above astronomical tides during storm conditions. The rate at which the wind increases in speed also affects water level elevation, with rapid wind speed acceleration leading to larger maximum water levels at the shoreline.
- **Nearshore currents** - generated from differences in waves, tides, water levels and winds and the interactions between the processes and geomorphological landforms.

- **Coastal entrances and river outlets** - river entrances are dominated by the daily ebb and flood tides, while complex interactions between tides, waves, fluvial outflows and modifications to entrance bathymetry can generate complex secondary currents around river and harbour entrances. Many coastal lakes and lagoons alternate between being open or closed to the ocean. These are known as Intermittently Closed and Open Lakes and Lagoons (ICOLLs). When there is sufficient water flowing into the lake or lagoon from the catchment area (usually following heavy rainfall) which eventually spills over the entrance sand berm, this scours an entrance channel through the beach, or due to mechanical means, that reopens the ICOLL to the ocean. ICOLLs close when the ocean waves and tides push sand from offshore into the entrance, which gradually closes the entrance channel.

The natural coastal processes influencing the supply and movement of sand through the coastal zone is mainly from the combined action of waves, currents and winds as described above. Transportation in the nearshore zone is comprised of alongshore and nearshore transport which act concurrently and interact together:

- **Longshore sand transport** (also known as littoral drift) occurs across the surf zone due to waves approaching the beach from an oblique angle which generates radiation stresses, driving currents along the shore. The direction of sediment transport along the coast is dependent on the prevailing wave direction (i.e., transport north could occur during a south-easterly wave direction). Longshore sediment transport occurs inshore of the surf zone particularly inshore of the wave breaking zone, reducing in strength with distance shoreward and offshore due to a typical increase in depth and therefore reduction in wave breaking. In some circumstances, winds, tides and in places the East Australian Current may also contribute to longshore currents and may dominate the currents outside of the surf zone (i.e., currents outside the surf zone can run in the opposite or alternative directions to the wave driven current inside the littoral zone).
- **Cross shore sand transport** occurs across the upper shoreface beach profile. Typically, sand is transported onshore during normal swell conditions generating beach accretion and offshore during large storm/swell wave events that cause beach erosion. As waves move into shallow water the waves shoal and the wave orbital velocity becomes asymmetrical, resulting in a net sand transport onshore (the direction of wave propagation). Breaking waves induce sediment transport onshore. Undertow and rip currents within the surf zone induce mass transport of sediments offshore generated from an offshore directed return flow (from breaking waves) and a longshore variation in wave setup, respectively.
- **Net sediment transport** describes the sum of the transport rates in all positive and negative directions, whereas the gross sediment transport rate describes the total transport disregarding the direction. These processes determine and are in turn influenced by the shape of the shoreline, the alignment of the shoreline and the bathymetry. As wave energy is a function of the square of wave height the amount of sand transported increases exponentially with increasing wave height.

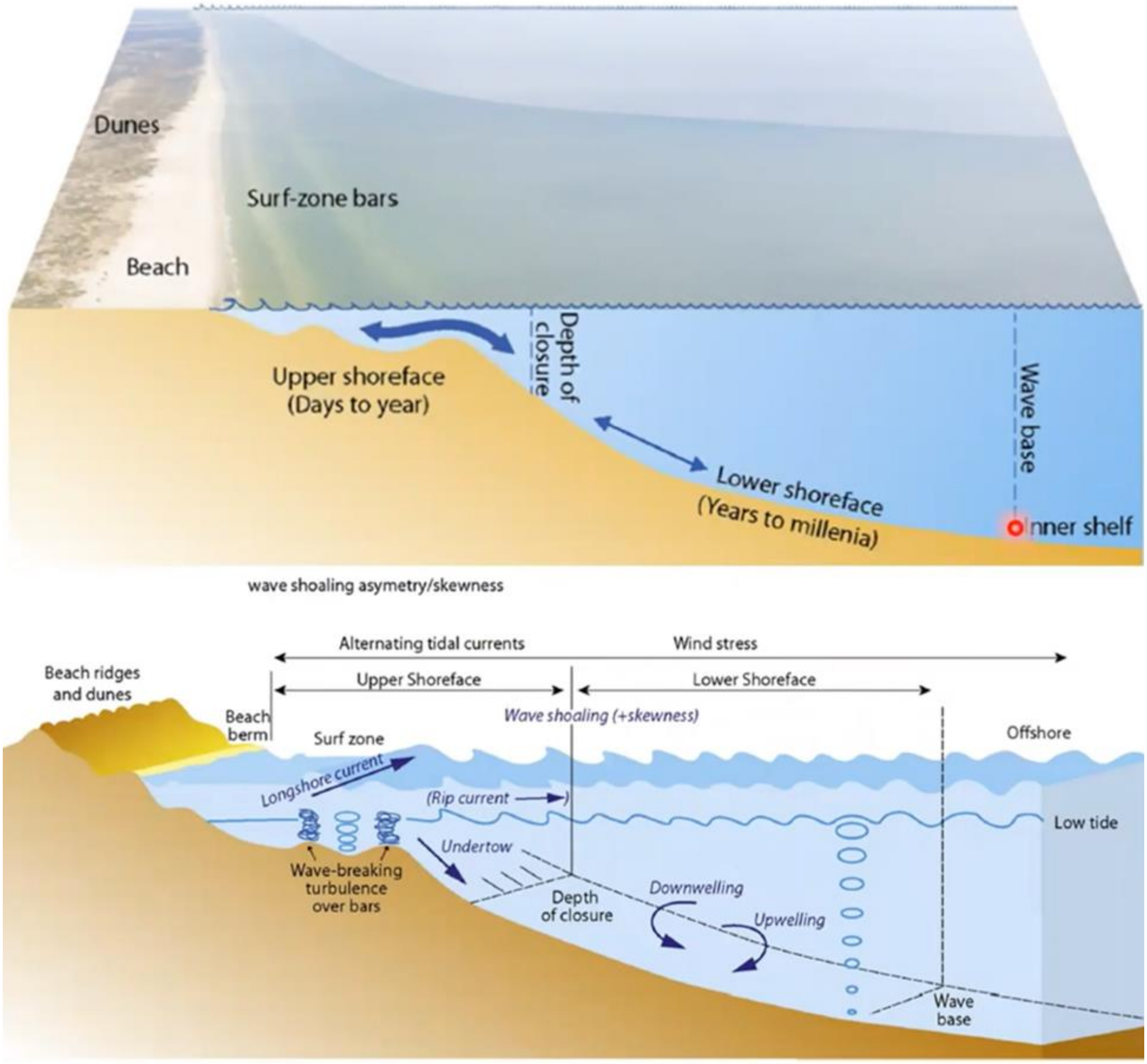


Figure 3: Definition of terms across the coastal profile (source: Cowell et al., 1999; Anthony and Aagaard, 2020).

2.3 Introduction to coastal hazards

The Tweed Shire contains a diverse natural waterway environment which includes rivers, creeks, wetlands, lakes, estuaries, lagoons and beaches. Coastal processes have shaped the coastline over many thousands of years and will continue to do so. The coast is subject to hazards from waves and rising sea levels that affect recreational use and development along the coastline and surrounding the estuaries. The CM Act defines a coastal hazard as meaning the following:

Beach erosion: Beach erosion is the loss of beach and dune material because of changing wave and water conditions. Beach erosion is commonly caused by increased wave height and energy, higher than usual tides, a storm surge (or elevated water levels as a result of barometric pressure and wind), or a combination of all three. Sometimes these factors do not need to be particularly intense to cause beach erosion which can occur over a period of days, weeks, or months.

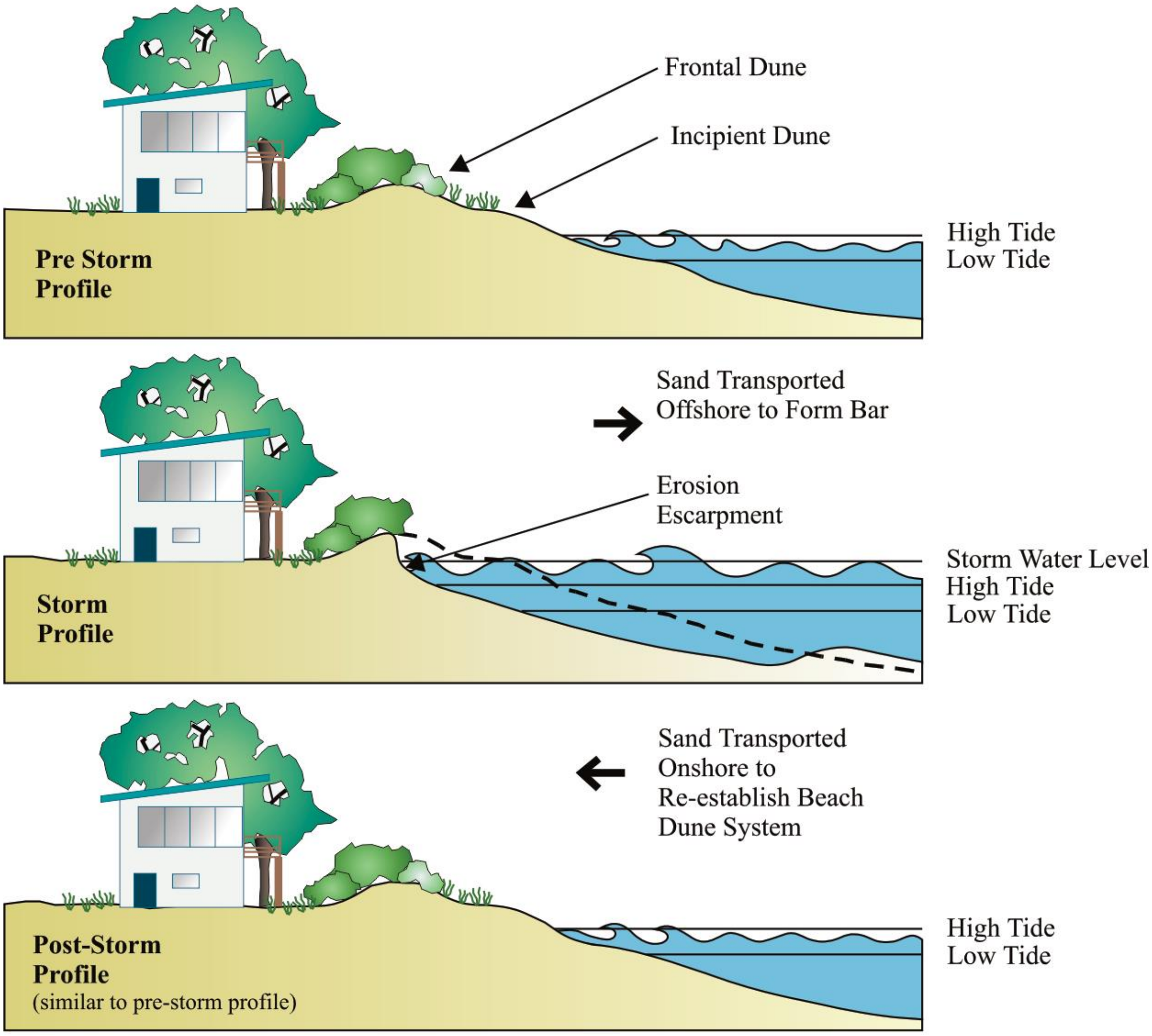


Figure 4: Diagram showing beach erosion and recovery phases (Office of Environment and Heritage, 2018).

Shoreline recession: Shoreline recession refers to a net landward movement of the shoreline over a specified time. Recession is a natural process which occurs whenever the transport of material away from the shoreline is not balanced by new material being deposited onto the shoreline. Shoreline recession can be in response to or increase due to rising sea levels.

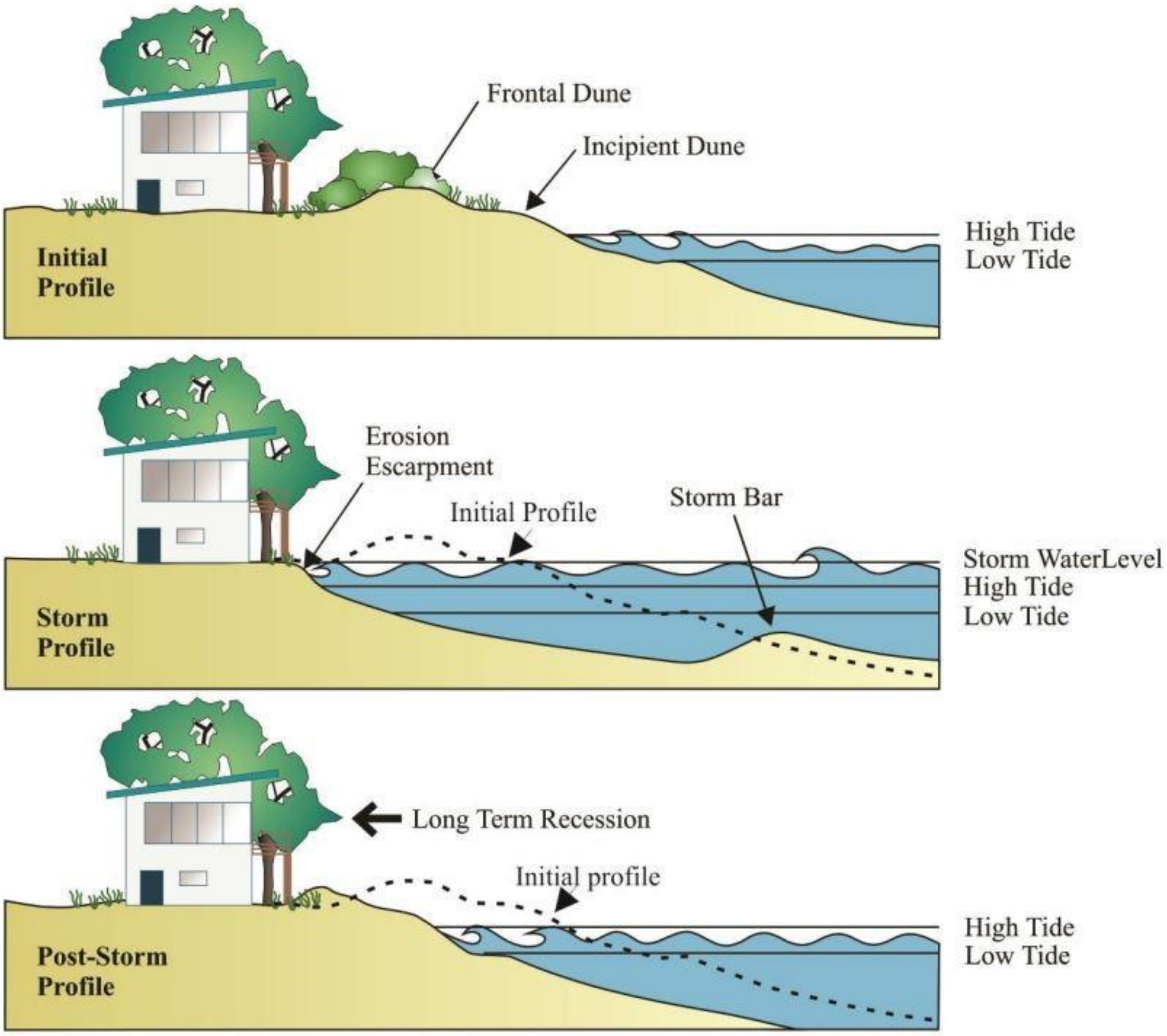


Figure 5: Diagram showing long-term shoreline recession (Office of Environment and Heritage, 2018).

Coastal entrance instability: Both natural and trained entrances of estuaries and coastal lakes present a variety of risks. The entrance dynamics and the condition of the entrance may affect flood hazards, water quality and ecological health in the estuary or coastal lake. The dynamics of estuary entrance along NSW coastline can generally be divided into two main categories:

Large estuaries which entrances are partially infilled with sand forming highly mobile flood tide deltas. If not trained, their entrance shape constantly changes in response to alongshore sediment transport, tidal flows, storms, and catchment flooding. If trained, sediment transport patterns are generally modified, which exacerbates potential impacts on beach erosion, current velocity patterns and channel stability.

Intermittently Closed and Open Lakes and Lagoons (ICOLLs) are separated from the ocean by a sand beach barrier or berm which forms and breaks down depending on the movement and redistribution of sand and sediments by waves, tides, flood flows and winds. Entrance conditions of ICOLLs affect a range of factors such as berm height, water levels, flushing, water quality, salinity and sediment dynamics in coastal lakes and lagoons. The ecological processes (i.e., prawn and fish spawning) are highly sensitive to catchment runoff and the frequency of entrance opening and closure.

Coastal inundation: Coastal inundation occurs when a combination of marine and atmospheric processes raises ocean water levels above normal elevations and inundate low-lying areas or overtop dunes, structures, and barriers. It is often associated with coastal storms resulting in elevated water levels (storm surge) and waves.

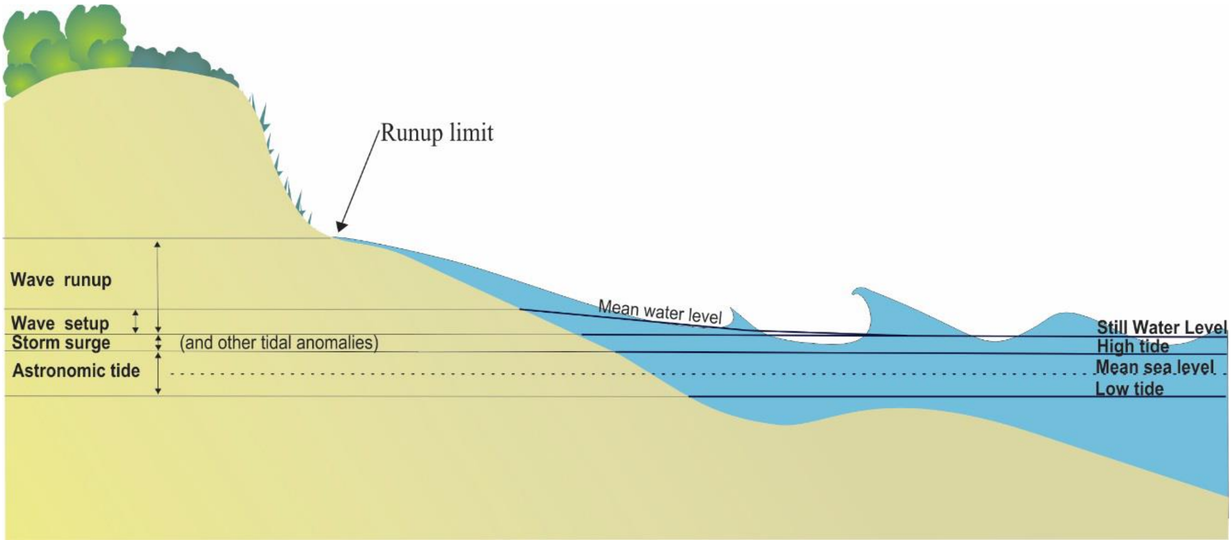


Figure 6: Diagram showing components of elevated water levels on an open coast (Office of Environment and Heritage, 2018).

Coastal cliff or slope instability: Cliff instability refers to a variety of geotechnical processes on coastal cliffs and bluffs, including rock fall, slumps and landslides. It may be driven by coastal processes such as wave undercutting and overtopping, or by differential weathering of rock layers in cliffs and bluffs or by surface and groundwater flows. Instability may occur during or following a coastal storm event but may also occur at other times. There may be very little warning that a cliff instability incident is imminent.

Tidal inundation: Tidal inundation or nuisance flooding is the inundation of land by tidal action under average meteorological conditions. Tidal inundation may include shorter-term incursion of seawater onto low-lying land during an elevated water level event such as a king tide or more permanent inundation due to land subsidence, changes in tidal range or sea level rise. In some scenarios, the risk associated with tidal inundation may be exacerbated when a king tide coincides with coastal inundation or catchment flooding.

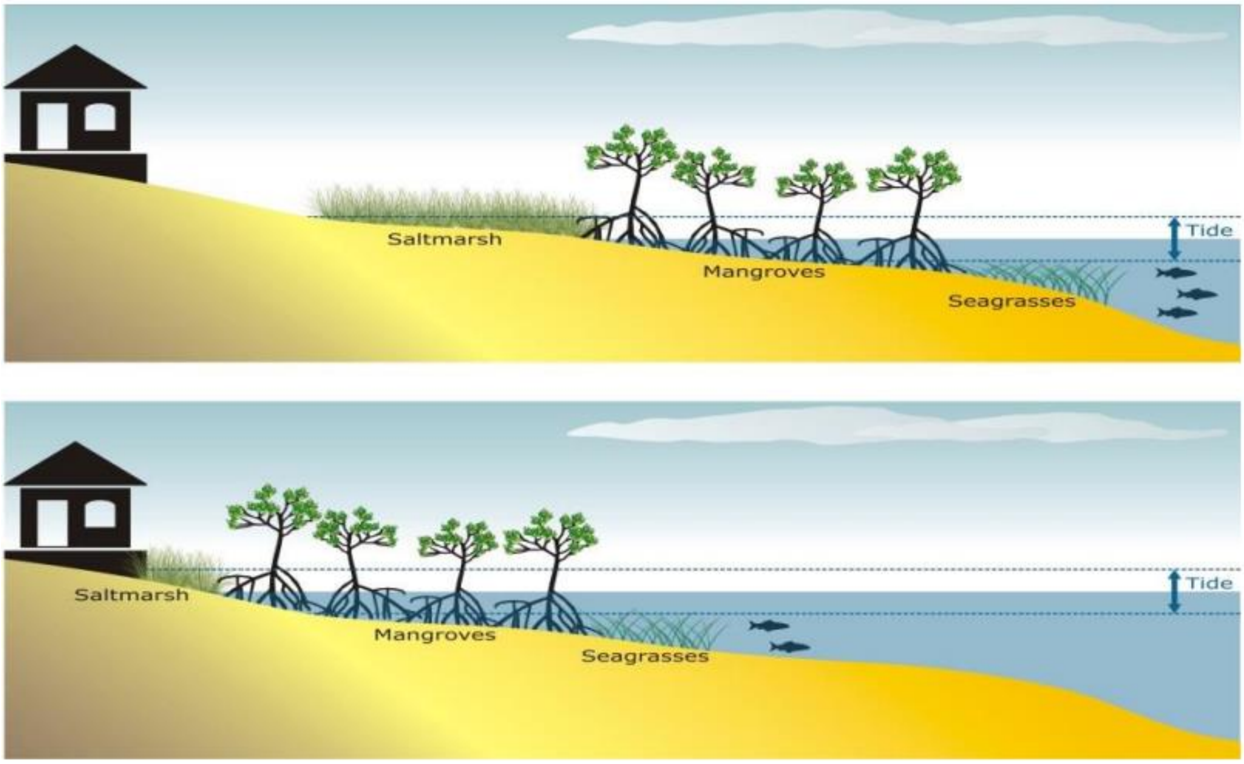


Figure 7: Diagram showing tidal inundation (Water Research Laboratory, 2016).

Erosion and inundation of foreshores: hazards related to estuary bank erosion and foreshore inundation due to the combination of coastal and estuarine processes with erosion or inundation a result of tidal waters and the action of waves (including the interaction of those waters with catchment floodwaters). Erosion and inundation of estuary foreshores can also be influenced by entrance training works, dredging and entrance management practices that may change tidal ranges, allow the incursion of oceanic waves, and change current velocities and sediment dynamics. Inundation around estuaries may occur due to coastal or catchment flooding, operating independently or due to a combination of both, derived from the same meteorological event (a coincident event).

2.4 Previous studies

There have been numerous studies examining the coastal processes and management across the Tweed Shire Coast. Key studies from which this study has drawn include:

- 1978 *Byron Bay – Hastings Point Erosion Study* (NSW Department of Public Works (PWD), 1978)
- 1980 *Dreamtime Beach Coastal Engineering Advice* (PWD, 1980)
- 2001 *Tweed Coastline Hazard Definition Study* (WBM Oceanics, 2001)
- 2005 *Tweed Shire Coastline Management Study: Stage 1 and 2* (Umwelt, 2005)
- 2011 *Coastal erosion at Kingscliff* (NSW Coastal Panel, 2011)
- 2013 *Tweed Shire Coastal Hazards Assessment* (BMT WBM, 2013)
- 2013 *Coastal Zone Management Plan (CZMP) for the Tweed Coast Estuaries* (Hydrosphere, 2013)
- 2017 *Kingscliff - Dreamtime Beach CZMP* (BMT WBM, 2017)

- 2022 *Letitia Beach Behaviour Report* (Bluecoast, 2022)
- In addition, the literature is referred to throughout the report wherever relevant to do so.

2.5 Data used in this study

This study follows a data-driven or evidence-based approach using data made available for use. A summary of these extensive datasets is presented in Table 2.

Table 2: Overview of existing observational data used in this study.

ID	Description	Source	Dates
Water levels*	Water levels every 15 minutes from: • Bogangar • Brunswick Heads ocean tide gauge • Kingscliff • Kingscliff Upstream • Mooball Creek at Tweed Coast Road • Tweed Entrance South ocean tide gauge	MHL	B: Dec 1985 – Dec 2015 BH: Feb 1986 – Jan 2016 K: May 1985 – Apr 2014 KU: May 2014 – June 2023 MC: Feb 2021 – June 2023 TES: May 2014 – Jun 2023
	Tweed offshore tide gauge	MHL	1982 – 2019
Waves	Measured wave heights, directions and periods at Tweed WRB	TSB	Jan 1995 – Nov 2022
	Nearshore wave data using NSW Nearshore Wave Tool at 1 hour sampling period	DCCEEW	Nov 1999 – Jun 2023
Winds	Murwillumbah (Bray Park) at 9 am and 3 pm daily	BOM	Oct 1972 – June 2023
	Coolangatta Airport at 10-minute sampling period	BOM	Sep 2003 – June 2023
Rainfall	Tweed Heads Bowls Club at 9 am daily	BOM	Nov 1886 – Nov 2022
	Coolangatta Airport	BOM	Dec 1982 – June 2023
Topography and bathymetry	Beach profile data (photogrammetry)	DCCEEW	1947 – 2022
	Historical charts	PWD	1982
	Digital Earth Australia (DEA) shorelines	Geoscience Australia	1988 – 2021

ID	Description	Source	Dates
	Coastal LiDAR data at 5m resolution	OEH	2011
	Coastal LiDAR data at 5m resolution	OEH	2018
Aerial imagery	Historical imagery	NSW Government	1930 – 2011
	High resolution, rectified aerial imagery	Nearmap	2012 – 2023

Note: * No water level data was made available for Cudgera Creek.

3. Coastal morphology and local setting

3.1 Regional geology and sediments

The northern NSW coast is characterised by drift-aligned, long sandy barriers which were shaped as the present-day sea level was attained approximately 6,500 years ago. During this period of post-glacial sea level rise sand migrated onshore from the continental shelf and the high influx of sand led to the formation of extensive dune barriers comprised of predominantly marine sand.

The geology of the Tweed Shire coast comprises of a series of bedrock embayments between bedrock headlands and low submarine rock reefs at Black Rocks, Potts Point, Hastings Point, Norries Headland, Cudgen Headland, Fingal Head, and Point Danger (Roy, 1975). These embayments have been filled with late Quaternary age sediments of marine, estuarine and fluvial origin.

The following sections provide detailed information on the regional distribution of sediment deposits, bedrock highs and other key geological features.

3.1.1 Sediment deposits

A description of sediment deposits is based on information from the following sources:

- Coastal geology of the Cudgen area, North Coast of NSW (Roy, 1975)
- Seamless Geology dataset (Colquhuon et al., 2022) which is a digital compilation of the state's best available geological mapping data predominantly obtained from field observations from Geological Survey of NSW
- NSW seabed landforms mapping derived from marine LiDAR data captured in 2018 (Linklater et al., 2022)
- Recent regional geotechnical assessment presented in Morrison Geotechnic (2021).

The coverage of Pleistocene and Holocene (Quaternary) sediments that form the modern geological setting of the study area is shown in Figure 8.

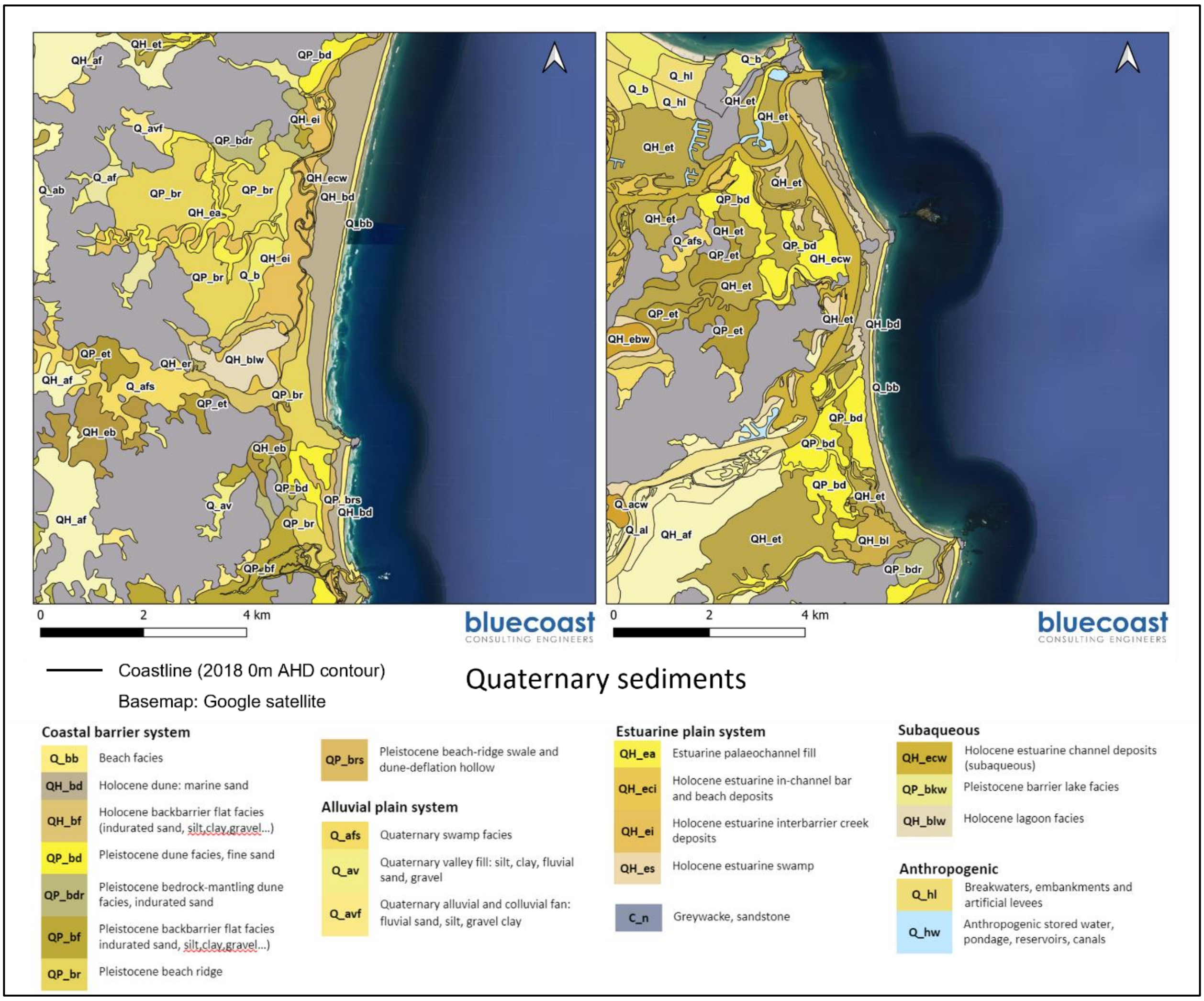


Figure 8: Quaternary coastal sediment deposits (derived from NSW Seamless Geology data).

Pleistocene age sediments make up much of the coastal deposits in the study area. Postglacial transgression at the beginning of the Holocene age led to the accretion of marine quartzose sand on the pre-exiting Pleistocene shoreline (Roy, 1975). In the contemporary setting, the younger Holocene sediments are found in the coastal margin, restricted to a narrow foredune and beach as well as estuarine sand and muds. The Holocene sediment deposits are typically underlain by Pleistocene sediments.

3.1.2 Bedrock highs and coffee rock regions

Rocky headlands exist along the Tweed Coast at Hastings Point, Norries Headland and Cabarita Beach rockface, Fingal Head and rockface, and Tweed Headland (Point Danger). The bedrock of the region is mostly comprised from Devonian to Carboniferous Age, Neranleigh-Fernvale Beds overlain by Holocene aged sedimentary bedrock (Morrison Geotechnic, 2021). The bedrock headlands are the eastern end of irregular spurs that protrude northeast from the hilly country (Roy, 1975). Fingal Head and Point Danger in the north are basaltic outcrops associated with the Tweed shield volcano, whereas the headlands to the south are mostly constituted mafic meta-volcanics (Morrison Geotechnic, 2021).

Based on the review of the historical and recent observations, the key bedrock and indurated sand features of the Tweed Shire coast can be summarised as follow:

Onshore:

- Bedrock surface outcrops were identified on the beach at Black Rocks (between Mooball and Pottsville Beaches), Potts Point (Pottsville Beach), Hastings Point, Cabarita Beach and South Kingscliff Beach (Cudgen Headland).
- Coffee rock (indurated sands) outcrops along the banks of Mooball Creek and Cudgera Creek which have prevented any extensive meandering of these coastal creeks (Roy, 1975).

Offshore:

- Shallow bedrock reef was identified at:
  - Black Rocks
  - Hastings Point
  - Norries Headland
  - Cudgen Headland (Kingscliff Reef)
  - Kingscliff Beach (between Faulks Park and SLSC, see Figure 9)
  - Fingal Head & Cook Island
  - Fingal Head Beach (see Figure 9).

Figure 9: Evidence of shallow bed rock exposed at Kingscliff Beach and Fingal Head Beach captured in aerial imagery (source: Nearmap).

3.1.3 Sediment characteristics

Consideration has been given to the particle size distribution (PSD) and distribution of sediment sizes along the open coast and within the various entrances and ICOLLs. The beach system is composed of well sorted fine to medium quartz sand with grain size typically around 0.25mm (PWD, 1982; Mariani et al., 2013). PWD (1978, 1982) described the distribution of two key sand types representative of their respective sediment transport processes according to grain size, sorting, colour and shell and rock particle content:

- Inner nearshore sand – Fine to medium grained active beach sand with low shell content. The distribution of this active sand deposit is associated with the effects of surfzone processes. The seaward extent of this sand type was to depths of -5 to -8m.
- Outer nearshore sand – Fine grained olive grey sand with low shell content. The seaward extent of this sand deposit was to depths of approximately -23m between Wooyung and Hastings Point. Offshore from Norries Headland to Cudgen Headland, this sand deposit was also evident beyond

the convex part of the profile (i.e., shelf sand body) to around -50m depth, approximately 7km offshore of Norries Headland to Cudgen Headland beach compartment.

A third sand type seaward of the outer nearshore sand (below -23m depth) was classified by PWD (1978), i.e., shelf plain relic sand, which is considered outside of the active coastal profile with insignificant exchange of sand with the neighbouring sand unit.

3.2 Modern geomorphic structure and morphology

Key features of the modern geomorphic setting of the Tweed Shire are shown in Figure 10.

The Tweed Shire coast is characterised by a series of crenulate shaped embayments that are reflective of the modal south-east wave climate and associated net northward sand movements (i.e., drift-aligned beaches). Controlled by the major headlands of Hastings Point, Norries Headland, Cudgen Headland and Fingal Head, the sandy embayments of the Tweed Coast are more hooked at their southern ends and aligned with the dominant swell direction at the northern ends (BMT WBM, 2013).

The topography of Tweed Coast is characterised by a low backshore and dune barrier profile, with dune heights less than 15m in height (Roy, 1975). Typical dune elevations are approximately 6m AHD between Wooyung Beach and Pottsville Beach, 8 to 10m AHD between Pottsville Beach and Cabarita Beach, and 6 to 8m AHD between Cabarita Beach and Duranbah Beach. Low-level flood plains extend westwards from the coast, with elevations of 1 to 2m AHD near the coast and over 4m AHD at the heads of the valleys (Roy, 1975). Widespread flooding occurs throughout these coastal flood plains, with periodic floodwaters slowly released through coastal creeks in the sea (Roy, 1975).

The embayed beaches are interrupted by the entrances to three coastal creeks; Mooball at Pottsville, Cudgera at Hastings Point and Cudgen at Kingscliff.

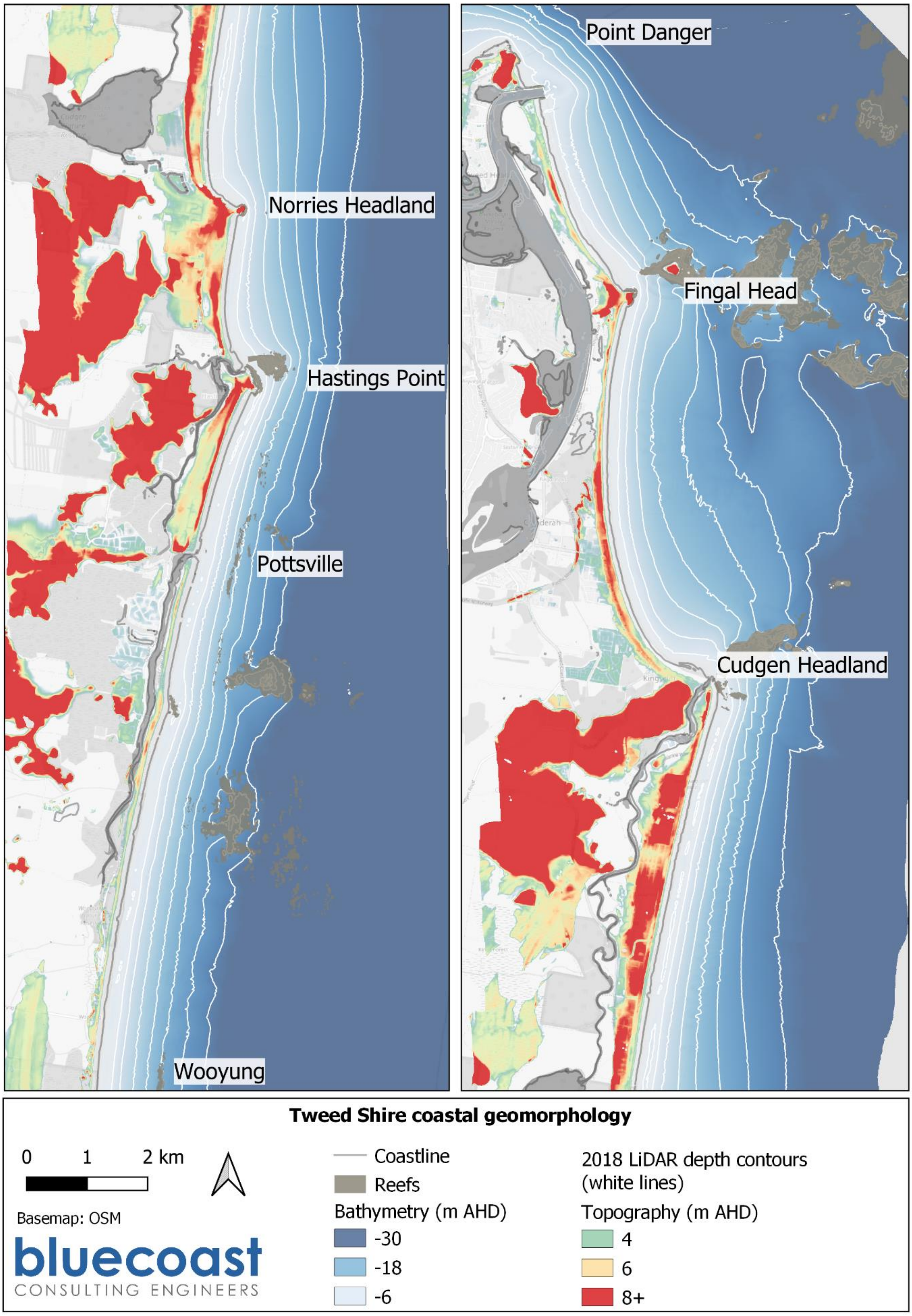


Figure 10: Geomorphic setting for the Tweed Shire coast.

3.3 Wave climate

3.3.1 Offshore wave climate

A review of observed wave data from the Tweed Heads waverider buoy (WRB) from 1995 to 2023 was undertaken. The buoy is in 22m of water depth off Letitia Beach. The average as well as seasonal wave climate statistics for the Tweed Heads WRB are provided in Table 3. Wave roses for total (combined swell and sea waves), swell (swell waves, peak period >8s) and sea (local sea, peak period <8s) are provided in Figure 11. Monthly average significant wave heights and peak wave periods are presented in Figure 12.

The wave climate at the WRB site is described as consisting of low to moderate swell events from the east and east-south-east with peak wave periods generally between 9 and 13s. Locally generated sea waves come predominantly from the east to north-east with low peak periods (~7s). The mean significant wave height is 1.24m, with a 75th percentile wave height of 1.47m annually, predominately from the east.

Table 3: Wave measurement statistics derived from Tweed Heads WRB.

Parameters	Statistics	Long term averages (1995 to 2023)				
		All seasons	Winter	Autumn	Summer	Spring
Significant wave height (H_s) [m]	Mean	1.24	1.15	1.37	1.32	1.12
	20%ile	0.84	0.76	0.93	0.91	0.81
	50%ile	1.14	1.05	1.27	1.22	1.06
	75%ile	1.47	1.35	1.63	1.55	1.31
	90%ile	1.87	1.78	1.07	1.96	1.60
	99%ile	2.98	2.86	3.38	3.08	2.42
	99.5%ile	3.40	3.17	3.99	3.47	2.72
	Max	7.52	5.56	7.52	6.70	4.66
Peak wave period (T_p) [s]	Mean	9.4	10.1	9.7	9.0	8.5
	20%ile	7.4	8.1	8.0	7.1	6.4
	50%ile	9.4	10.2	9.6	8.9	8.9
	75%ile	10.9	11.5	10.9	10.3	10.6
	90%ile	12.1	12.9	12.1	11.7	12.0
	99%ile	15.0	15.7	14.9	14.2	14.8
	% of time sea (Tp < 8s)	27	18	20	32	38
	% of time swell (Tp > 8s)	73	82	80	78	62
Peak wave direction (D_p) [°N]	Weighted average	90	95	86	88	94
	Mean	95	101	95	91	92
	Standard deviation	23	22	18	21	29

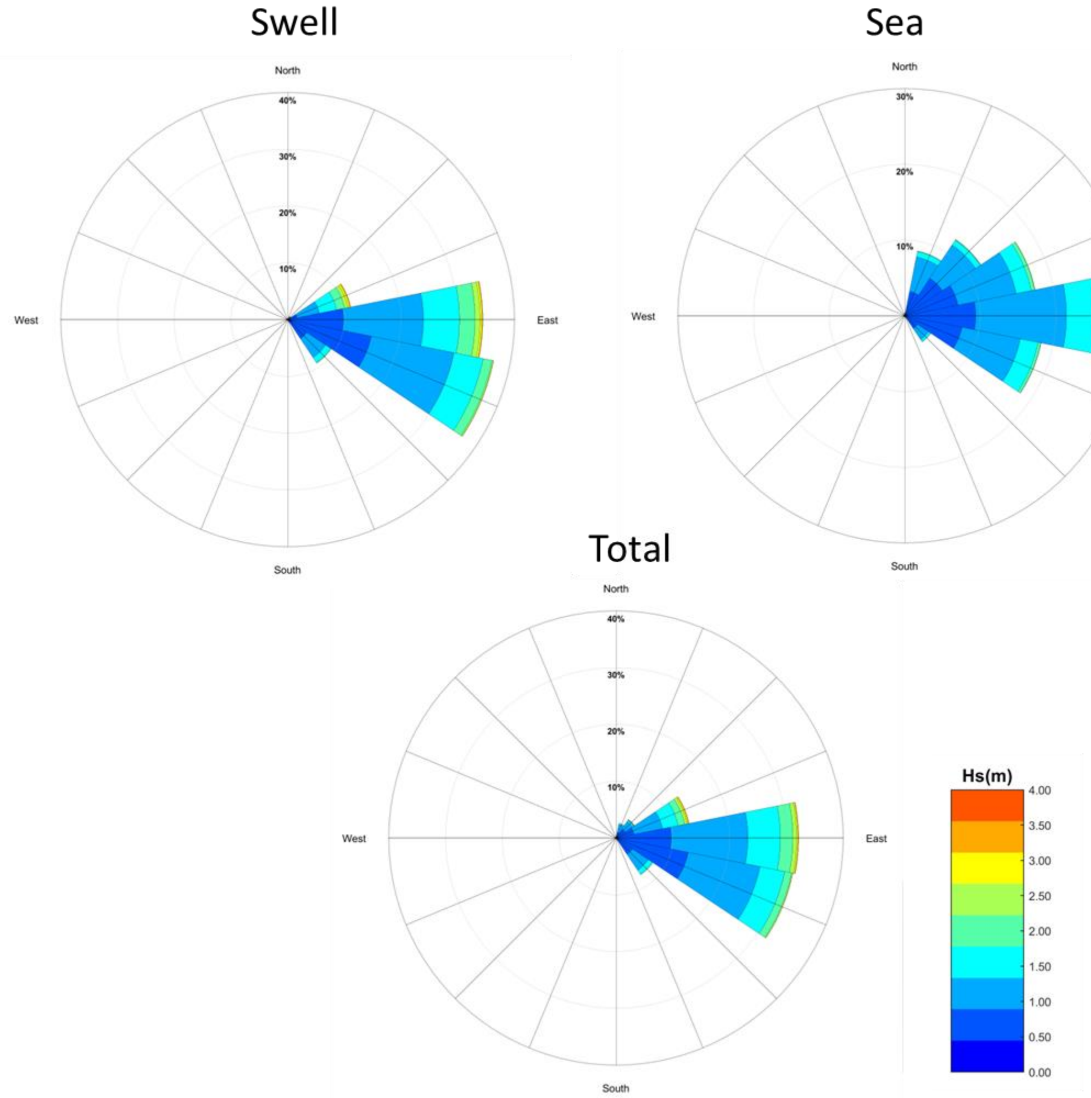


Figure 11: Wave roses at Tweed Heads WRB for sea conditions (Tp < 8s), swell conditions (Tp > 8s) and total.

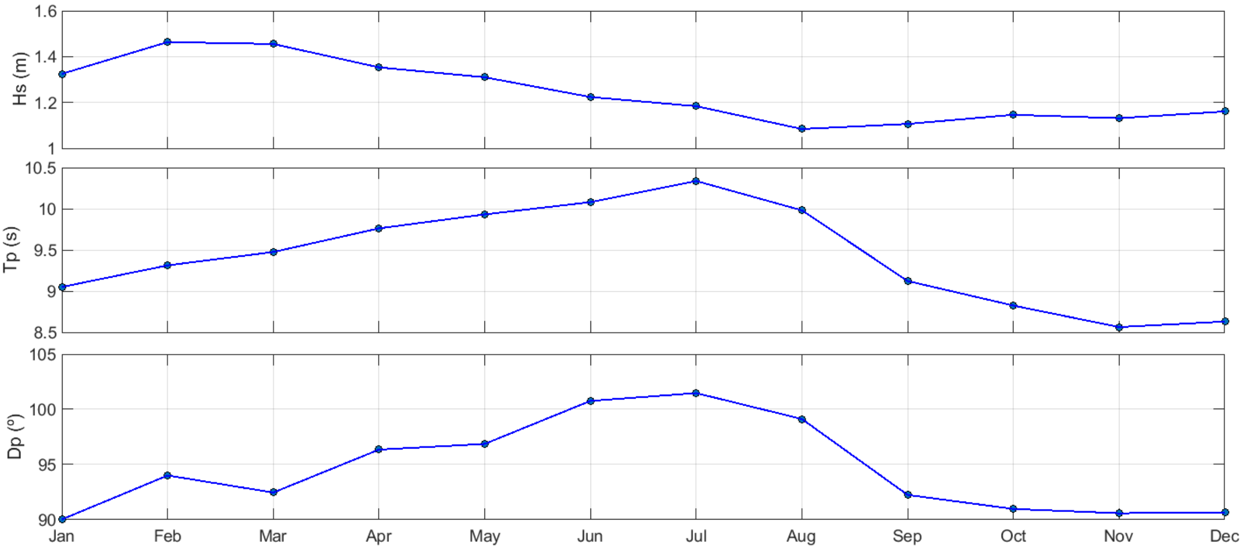


Figure 12: Annual significant wave heights, peak periods and peak directions at Tweed Heads WRB.

An Extreme Value Analysis (EVA) of the Tweed Heads WRB spanning the 28 years of available data was undertaken. A peak over threshold analysis of the measured wave heights identified the extreme events and a Weibull distribution was fitted to the extreme wave heights to provide the average recurrence interval (ARI) wave heights. The resulting design ARI wave conditions are presented in Table 4. Figure 13 shows the extreme value distribution of significant wave heights and associated wave direction. The 50-year and 100-year ARI significant wave heights are 7.51m and 8.10m, respectively for a 1-hour duration. As shown in Figure 12, extreme wave events at the Tweed Heads WRB typically arrive from east to north-east directions.

Table 4: Average recurrence interval (ARI) wave heights for Tweed Heads WRB.

ARI (year)	H_s (m)	98% confidence limit (m)
1	4.14	4.00 – 4.28
5	5.55	5.03 – 6.08
10	6.15	5.50 – 6.79
20	6.74	5.94 – 7.53
50	7.51	6.47 – 8.56
100	8.10	6.83 – 9.36

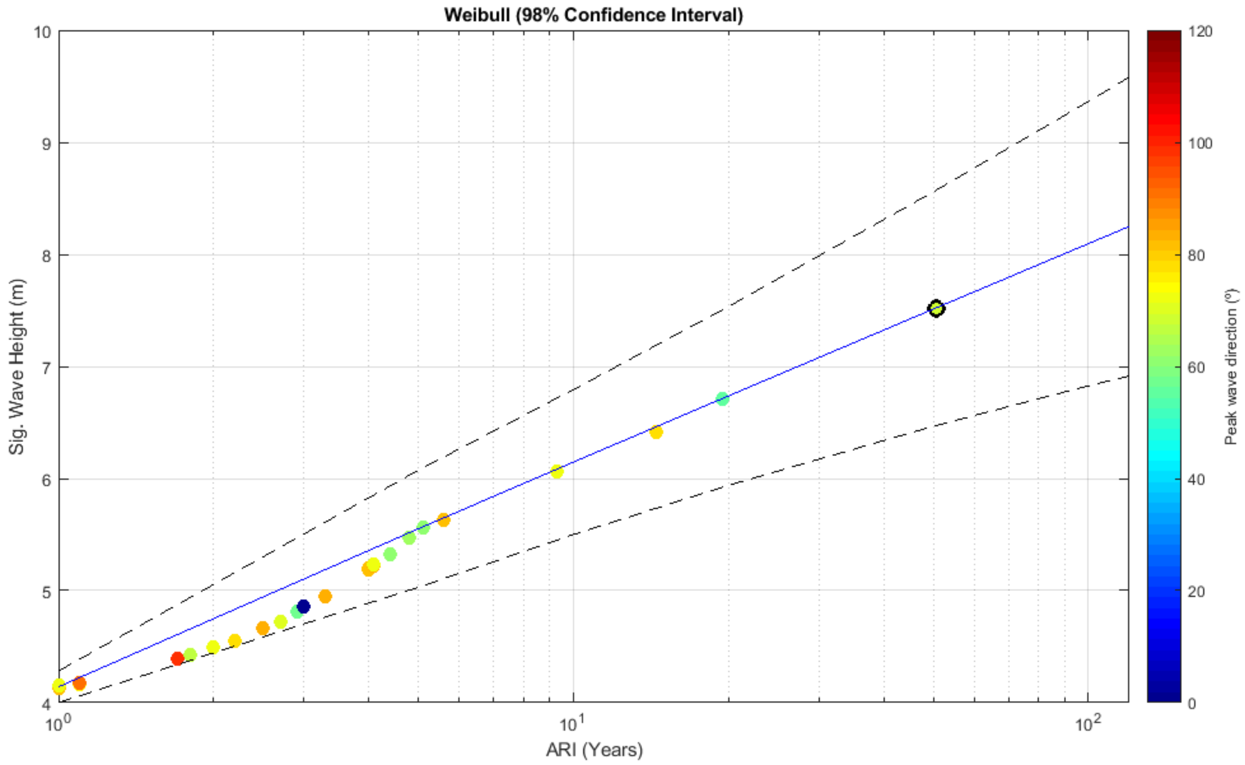


Figure 13: Results of extreme value analysis at Tweed Heads WRB.

3.3.2 Nearshore wave climate

Nearshore wave information was provided by Manly Hydraulics Laboratory (MHL). The nearshore wave information was derived from the NSW Nearshore Wave Tool (OEH, 2017a), details of which are reported in Baird (2017). In short, the Tweed Heads WRB offshore wave data was transformed to nearshore, at the -10m depth contour, covering the period from 1 November 1999 to 1 July 2023.

The directional nearshore wave climates (-10m depth contour) along Tweed Shire are provided in Figure 14. The average wave climate statistics are provided in Table 5.

Overall, the mean significant wave height along the coast is 1.14m, with a minimum of 0.95m observed at Kingscliff. A maximum wave height of 7.90m was observed off Dreamtime Beach. Nearshore wave direction is east-south-east.

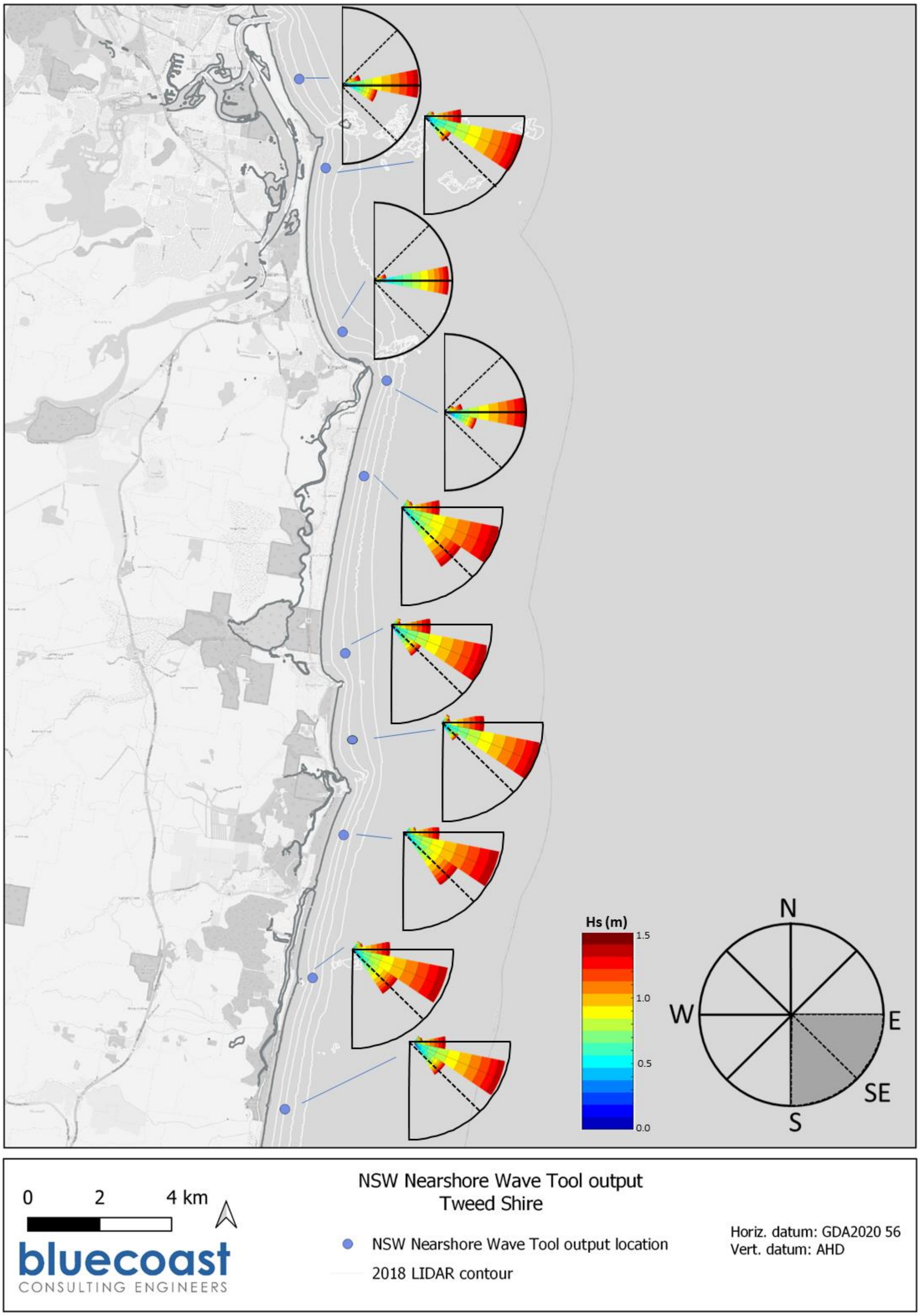


Figure 14: Nearshore wave roses along Tweed Shire.

Table 5: Nearshore wave statistics based on NSW Nearshore Wave Tool.

Beach	Significant wave height (Hs) [m]		Peak wave period [T_P] (s)	Wave direction [Dp] (ºdeg)
	Mean	Max	Mean	Weighted average
Wooyung to Pottsville	1.14	7.47	9.6	107
Pottsville	1.20	7.59	9.6	108
Cudgera Beach	1.21	7.58	9.6	111
Hastings Point to Norries Headland	1.16	7.23	9.6	102
Cabarita Beach	1.15	7.27	9.6	104
Casuarina Beach	1.18	7.52	9.6	110
South Kingscliff Beach	1.22	7.32	9.6	107
Kingscliff	0.95	7.08	9.6	82
Dreamtime Beach	1.11	7.90	9.6	102
Letitia Beach	1.11	7.30	9.6	87

3.4 Wind climate

Measured wind speeds and directions at Coolangatta Airport AWS was analysed over the period from 2003 until 2023. Seasonal wind roses are presented in Figure 15. Wind measurement statistics are presented in Table 6.

The wind data shows a predominance for south-westerly winds during winter and autumn. Spring and summer show a more bi-modal pattern with winds generally coming from either the north-eastern or south-western sectors. Maximum wind speeds of 18m/s were recorded at Coolangatta.

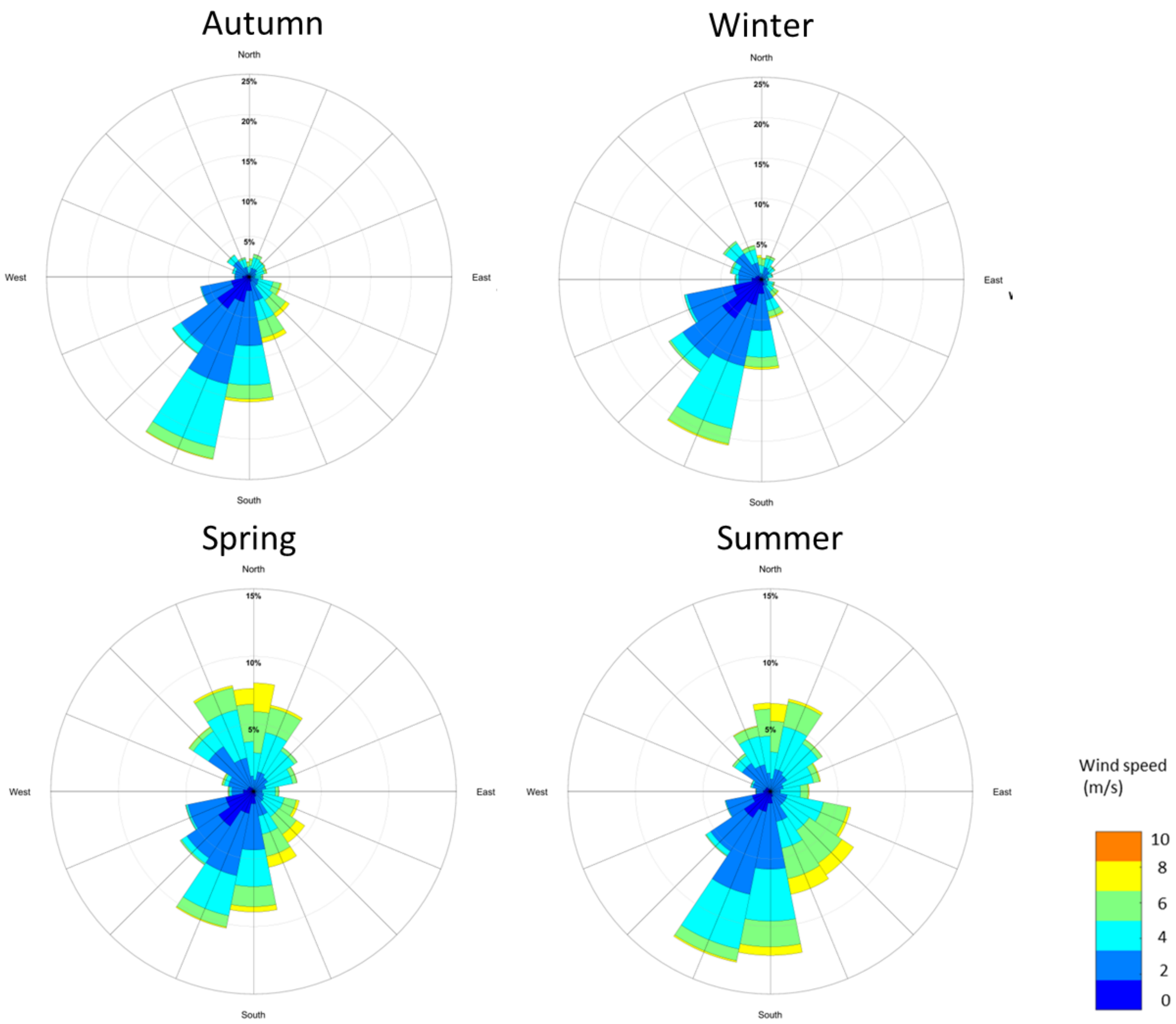


Figure 15: Wind roses of one-minute data for Coolangatta AWS from 2003 to 2023.

Table 6: Wind measurement statistics for observations between 2003 to 2023.

Parameter	Statistic	Coolangatta
Wind speed [m/s]	Mean	4.2
	20%ile	2.3
	90%ile	7.0
	Max	17.8

3.5 Tides and other water level variations

Tides in the project area are semi-diurnal with an open ocean mean spring tidal range of around 2m (MHL, 2020). Tidal planes for the Tweed-Ballina region (ocean) and Tweed River (estuary) tide gauges are provided in Table 7 and Table 8, respectively.

Table 7: Ocean tidal planes for Tweed region calculated for 2019-2020 (MHL, 2023).

Tidal plane	Height (metres relative to AHD)	
	Tweed Heads	Brunswick Heads
High High Water Solstice Springs (HHWSS)	0.973	1.065
Mean High Water Springs (MHWS)	0.663	0.719
Mean Sea Level (MSL)	0.039	0.076
Mean Low Water Springs (MLWS)	-0.584	-0.567
Indian Spring Low Water (ISLW)	-0.806	-0.814

Table 8: Tidal planes for various locations within Tweed River estuary and Cudgen Creek (MHL, 2023).

Tidal plane	Height (metres relative to AHD)				
	Tweed River at Tweed Heads	Tweed River at Dry dock	Tweed River at Letitia 2A	Tweed River at Barneys Point	Cudgen Creek at Kingscliff
High High Water Solstice Springs (HHWSS)	0.973	0.827	0.929	0.832	0.913
Mean High Water Springs (MHWS)	0.663	0.536	0.618	0.538	0.591
Mean Sea Level (MSL)	0.039	0.132	0.086	0.117	0.014
Mean Low Water Springs (MLWS)	-0.584	-0.269	-0.422	-0.303	-0.564
Indian Spring Low Water (ISLW)	-0.806	-0.502	-0.669	-0.513	-0.794

Along the NSW coast, ocean water levels[1] can also be influenced by other non-tidal variations such as:

- Storm surge - elevated water levels during storms typically including barometric effect and wind-driven surge
- Coastal trapped waves - long period waves with periods of days to weeks, generated by strong wind events on the southern Australian coastline and Bass Strait
- Tsunamis - shallow water progressive wave, potentially catastrophic, caused by underwater seismic activity
- Ocean circulation - ocean currents such as the East Australian Current (EAC) can raise the water level for extended periods by transporting large quantities of water onshore (e.g., migration of eddy currents along a coastline).

Table 9 presents the 25-year, 50-year and 100-year ARI water levels derived from the Tweed Heads (offshore) tide gauge between 1982 to 2019 (i.e., 37 years).

Table 9: Extreme water levels derived from Tweed Heads offshore tide gauge between 1982 to 2019 (98% confidence interval provided in brackets).

ARI	Water level (m AHD)
25 years	1.40 (1.36 to 1.45)
50 years	1.43 (1.38 to 1.49)
100 years ***(low confidence due to short data record)***	1.46 (1.39 to 1.52)

3.6 Sea level rise

Global mean sea levels have increased by approximately 0.2 m between 1901 and 2018 (BMT, 2022). More specifically, the Tweed region has seen an increase in mean sea level of 0.1 m between 1993 and 2022 (BMT, 2022). The latest advice from IPCC (AR6) on sea level rise (SLR) assesses the climate response to five illustrative socio-economic pathway (SSP) scenarios that cover the range of possible future development of anthropogenic drivers of climate. The report concludes that in the longer term, sea level is committed to rise for centuries to millennia due to continuing deep ocean warming and ice sheet melt and will remain elevated for thousands of years.

In the shorter term, it is certain that global mean sea level will continue to rise over the 21st century. The latest SLR (above 1995 - 2014 baseline) projections for Brunswick Heads, NSW for the 'likely' mean SLR ranges (17th to 83rd percentiles) by 2100 are (refer to Figure 16):

- 0.25-0.57m under the very low greenhouse gas (GHG) emissions scenario (SSP1-1.9)
- 0.29-0.63m under the low GHG emissions scenario (SSP1-2.6)
- 0.41-0.78m under the intermediate GHG emissions scenario (SSP2-4.5)

[1] The term 'ocean water levels' is used to refer to water levels offshore of wave breaking. Inshore of wave breaking additional non-astronomical processes can also influence water levels including wave setup and wave runup.

- 0.53-0.95m under the high GHG emissions scenario (SSP3-7.0)
- 0.61-1.08m under the very high GHG emissions scenario (SSP5-8.5).

The adopted SLR values for the coastal hazard assessment are presented in Table 10 (extracted for Brunswick Heads from IPCC AR6 Sea Level Projection Tool). Specifically, the very high emissions GHG scenario (SSP5-8.5) 83rd percentile SLR values of 0.21m by 2040, 0.56m by 2070 and 1.46m by 2120 are used as representative of an extreme but realistic case for the coastal and tidal inundation assessments (see Sections 6 and 7.3). For the probabilistic coastal erosion and recession hazard assessment, a Weibull distribution is fitted to the full range of adopted SLR values (see Section 5.3.5).

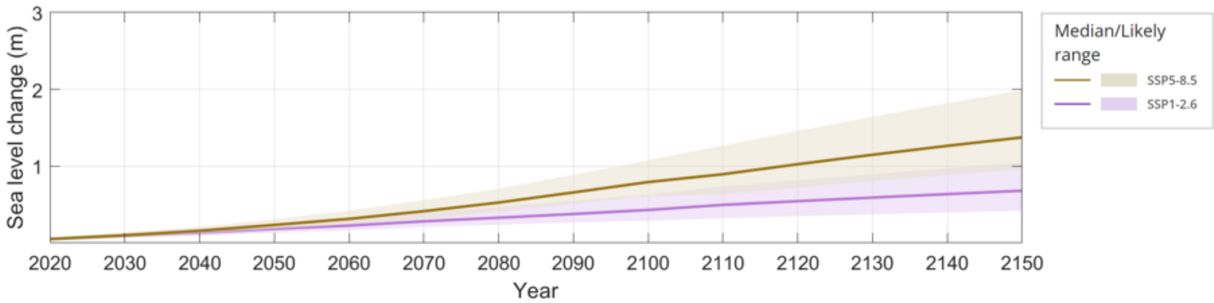


Figure 16: IPCC AR6 sea level rise projections (for Brunswick Heads, NSW) relative to 1995 - 2014 baseline for the low and very high future greenhouse gas emission scenarios (Garner et al., 2021).

Note: Shaded range represents the respective 17th and 83rd percentile ranges.

Table 10: SLR projections in metres relative to 1995 - 2014 baseline (for Brunswick Heads, NSW).

Quantile	2040	2050	2070	2100	2120	Comment
5th percentile	0.07	0.10	0.17	0.22	0.26	SSP1-2.6
17th percentile	0.09	0.13	0.21	0.29	0.35	SSP1-2.6
50th percentile	0.15	0.22	0.37	0.68	0.90	Mid-value between above (17th %ile) and below (83rd %ile) values
83rd percentile	0.21	0.31	0.56	1.08	1.46	SSP5-8.5
95th percentile	0.26	0.38	0.68	1.33	1.80	SSP5-8.5

3.7 Regional currents

The key nearshore currents acting on the Tweed Coast are as follows:

- Wave-driven currents – these include onshore and offshore directed currents driving cross-shore sand transport as well as longshore currents induced by wave breaking resulting in longshore sand transport:

  - Longshore currents on the Tweed Coast are predominantly from south to north due to the east to east-south-easterly wave climate. Limited southward directed wave-driven currents or sand transport is experienced along the Tweed coastal zone during northeast waves (Cardno, 2009).
  - Onshore directed currents during ambient swell conditions drive onshore movement of sand while offshore directed currents during high-energy wave conditions drive sand from the shore to the nearshore.
- Tidal currents – the tidal wave at the open coast was found to propagate east to west resulting in low current speeds that have little effect on sand transport (Jacobs, 2017). At the Tweed River entrance and adjacent areas, tidal currents are constricted and much higher. During typical conditions a concentrated seaward directed ebb jet is observed which may be deflected to the north or south under the influence of winds, waves, the East Australian Current and the local entrance morphology (Jacobs, 2017). Flood tide currents radiating into the river are much lower than peak ebb currents. During river flood events, fluvial currents exiting the river entrance can be multiples higher than tidal currents and move significant volumes of sand seaward.
- Wind-driven currents – shore-parallel currents due to wind stresses on the water surface are relatively minor in comparison to wave and tidal currents along the open coast and have little effect on sand transport. On the subaerial beach, strong winds can transport sand along the beach face and to the dunes (i.e., aeolian sand transport).
- East Australian Current (EAC) – this large-scale current runs south from the Great Barrier Reef to NSW along the edge of the Australian continental shelf. In the deeper nearshore at depths greater than 6m this ocean current typically flows in a south-easterly direction with variable low to moderate magnitude along Tweed Shire beaches. It was found that the EAC can interact with Point Danger and Cook Island resulting in clockwise circulation cells within the Letitia embayment which interfere with tidal currents and sand transport around the Tweed River entrance (Jacobs, 2017).

3.8 Rainfall

The mean annual rainfall observed at Tweed Heads Bowls Club between 1887 and 2022 was of 1,711mm. Figure 17 illustrates the mean monthly precipitation observed at Tweed Heads. Rainfall is unevenly distributed throughout the year with a high variability between seasons. The region receives most of its rainfall in summer and autumn, and experiences relatively dryer winters. Average monthly rainfall records between the years 1887 and 2022 ranged from a minimum of 64mm in September to a maximum of 245mm in March.

Rainfall varies significantly from one year to another as shown in Figure 18. For example, over the 35 year record period, a low of 688mm was recorded in 1902 and a high of 3,192mm was measured in 1906.

Much of the variability in precipitation is due to large-scale climate variations, with El Niño – Southern Oscillation playing a considerable role.

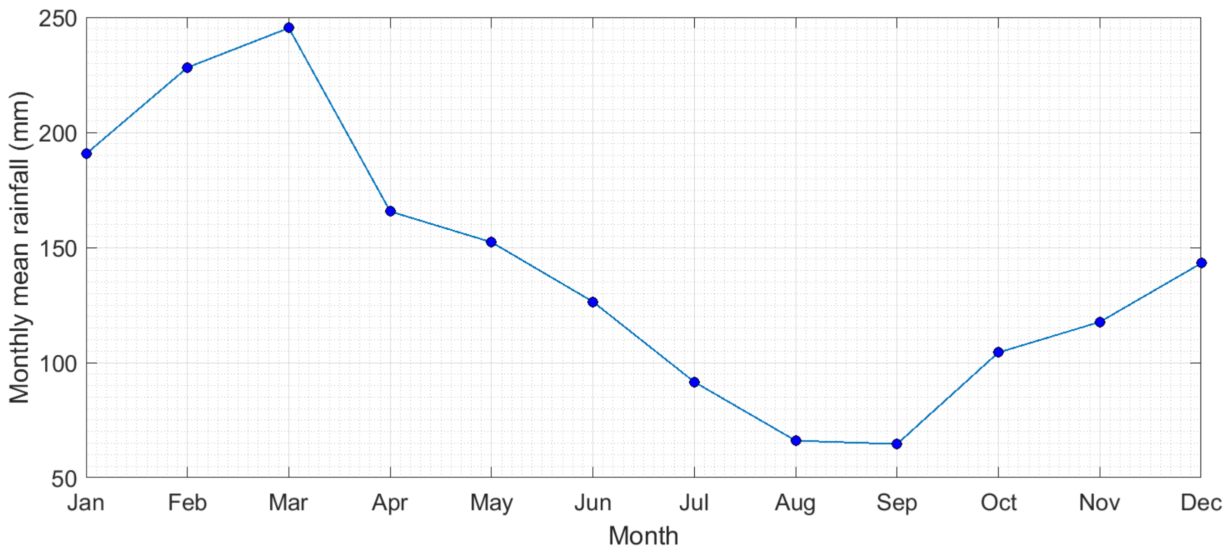


Figure 17: Mean Monthly rainfall observed at Tweed Heads Bowls Club (1887-2022).

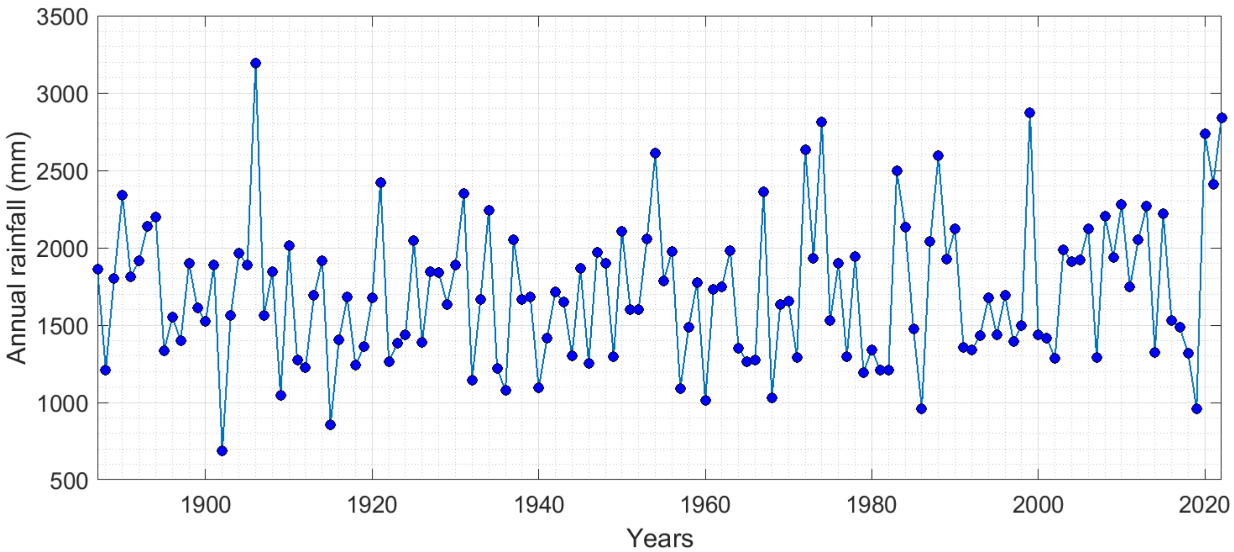


Figure 18: Annual rainfall at Tweed Heads Bowl Clubs (1887 – 2022).

3.9 Climate variability and projection

The southeast Australian coastline is impacted by natural climate variability. This is largely due to changes in atmospheric circulation patterns associated with the El Niño Southern Oscillation (ENSO) and the Interdecadal Pacific Oscillation (IPO). These fluctuations in climate variability are natural and driven by oscillations in sea surface temperature and occur on seasonal, interannual and decadal periods. Climate change however is the change in the average weather over decades to millions of years. Climate change may be driven by natural external forces like variations in solar radiation, internal processes like plate tectonics, or changes from anthropogenic forces such as global warming, which is the impact on climate from additional heat retained from increased amounts of carbon dioxide and other greenhouse gases. Circulation patterns associated with climate variability are impacted by climate change.

Correlation has been found between the Australian east coast wave climate and ENSO, reflected in the Southern Oscillation Index (SOI). Generally, there is an increase in the occurrence of tropical cyclones and tropical lows during the La Niña phase (positive SOI) for the Coral-Tasman Sea. During La Niña waves along northern NSW are bi-directional with southeast and easterly wave conditions. During the El Niño phase (negative SOI), there are generally fewer tropical lows and cyclones, and mid-latitude storms are dominant, resulting in a unidirectional south easterly wave climate (Mortlock and Goodwin, 2015; Goodwin et al., 2005). A timeseries of historical occurrence of El Niño and La Niña periods is shown in Figure 19.

Climate change is likely to force a continued expansion of the tropics which would maintain a strong coupling between the southeast Australian shelf and ENSO (Allen et al., 2014). In the period 1950 to 2019, the sea surface temperatures off the Tweed Coast have increased at a rate of 0.12 to 0.16°C/decade (BMT, 2022). Although the issue has been studied extensively, there is no consensus on exactly how a warming climate will influence ENSO (Mortlock and Goodwin, 2016). However, the expansion of the tropics with warming climate is expected to lead to a poleward shift in storm type, with more tropical origin storms than extra-tropical storms with a southern origin. The anticipated outcomes of these changes on the Eastern Australia wave climate would be an anti-clockwise rotation of the mean wave direction (Silva et al., 2021). In the study area, a decrease in mean offshore wave height as well as an anticlockwise rotation of around 5° in the mean wave direction has been projected (GCCM, 2020).

Climate change and associated impacts on the wave climate are likely to cause changes to the local currents and associated sand transport along the Tweed Shire coast. Over the next 100 years, a reduction in the longshore sand transport rate of 40% was projected for the Coffs Harbour to southeast Queensland region (Goodwin et al., 2016). However, there is considerable variability in the longshore sand transport projections, with a more recent study suggesting a lower reduction of up to 8.6% based on future wave climate projections (Vieira da Silva et al., 2023). Furthermore, Silva (2022) identified that current and future climate trends was likely to lead to an increase in the magnitude but a decrease in the frequency of headland bypassing events. These future sand transport changes will help inform the coastal sand budget in Section 4.

A notable component of the climate variability on decadal scales is found to be related to IPO. Helman & Tomlinson (2008) reported that major energy periods in the storm history of the east coast (e.g. 1946 to 1974) can be correlated with the negative (La Niña-like) phase of the IPO. The sea surface temperature anomaly associated with the negative phase (or cool phase in the eastern Pacific Ocean) of the IPO produces an increased frequency of East Coast Lows.

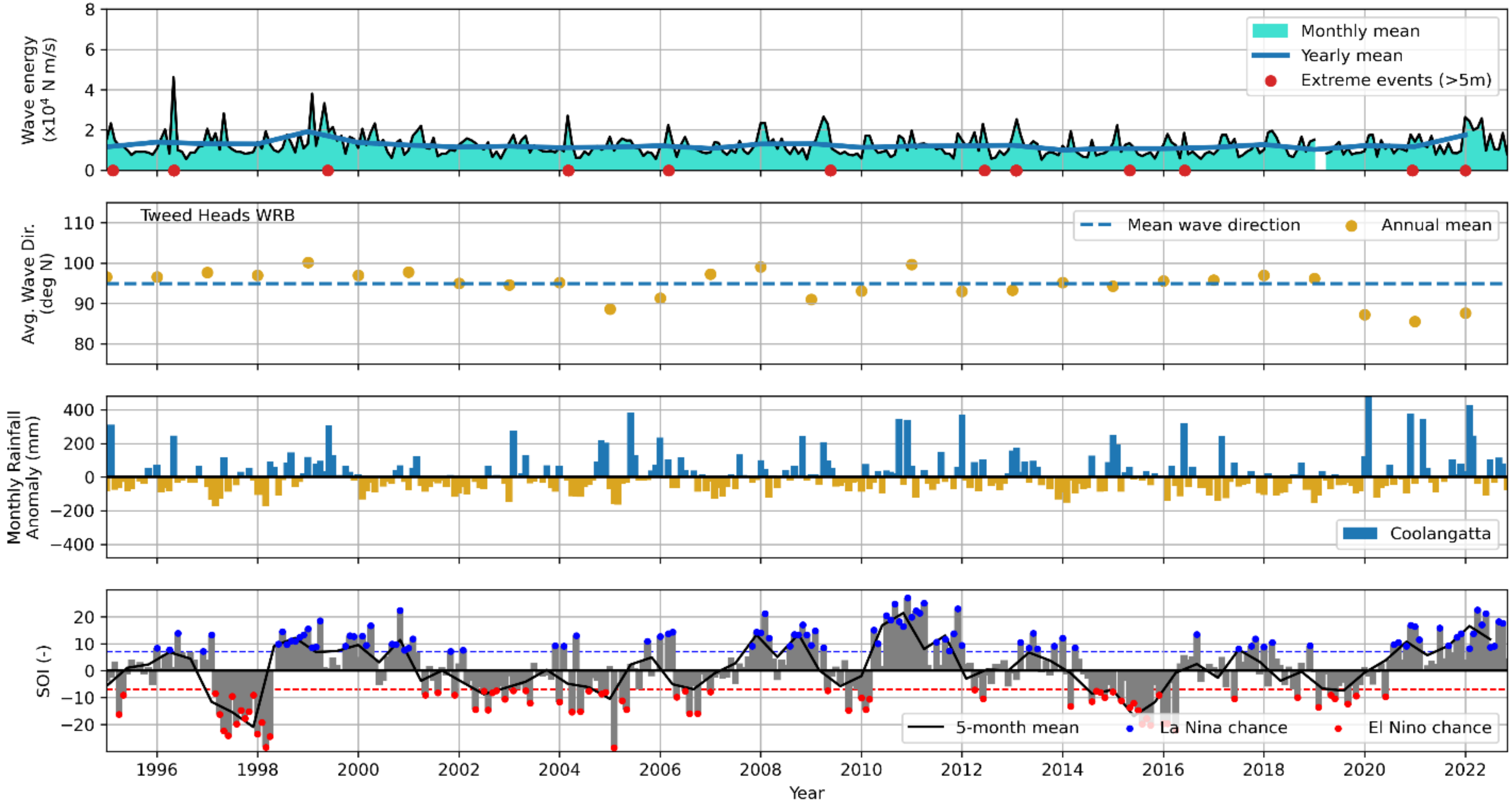


Figure 19: Timeseries of southern oscillation index (SOI) indicating periods of El Niño (red) and La Niña (blue) conditions along with wave conditions (top two panels) from Tweed Heads WRB and rainfall (3rd panel) from Coolangatta Airport.

4. Tweed Shire coastal sand budget

4.1 Overview

A coastal sediment budget is a quantitative analysis of the movement and distribution of sediment within a coastal region. Along the Tweed Shire LGA's open coast, the predominant sediment is sand. Developing a sand budget involves accounting for the sources of sand, such as erosion from coastal cliffs, discharge from rivers or onshore sand supply, and the processes that transport it, such as wave action or longshore sand movements. The coastal sand budget also includes the sinks or locations where sand is deposited, such as on the beach or in a coastal lagoon.

Coastal sand budgets are important for understanding the impact of coastal management practices on erosion and accretion patterns in the coastal zone. They can also help to identify areas of the coastline where erosion is occurring and where sand management strategies may be needed to prevent erosion or mitigate its effects. In addition, coastal sand budgets can be used to assess the impact of climate change on coastal processes, such as sea level rise and changes in wave patterns, and to predict how these changes may affect sand movement and distribution in the future.

4.2 Methodology

Analysis to determine the Tweed Shire coastal sand budget involved calculating historical sand volume changes in 6 beach compartments and 59 analysis cells across the study area's coastal profile (shown in Figure 21 and **Appendix A**), including:

- calculating volume changes between available coastal LiDAR data from November 2011 and August 2018
- converting DEA's mean annual shoreline positions to estimate volume change across the active coastal profile between 1988 and 2021 (refer Figure 20). This was done by multiplying the shoreline position change (relative to 2018) by:
    - the active profile height (i.e., between top of dune to the depth of closure, adopted as approximately 15m) [2]
    - alongshore length of the analysis (sediment) cell.

The annual volume change time series was validated against volume changes determined from the analysis of the 2011 and 2018 surveys. A reasonable agreement between the calculated and surveyed volumes was achieved, as shown in Figure 26 (Section 4.3.2).

The estimated volume changes are used to infer the rates and directions of sand movements. A quantified conceptual sand movement model is used to link together the drivers and volumes of annual sand movement (see Section 4.4).

In addition to the analysis presented in this section, the sand budget and conceptual coastal processes understanding has been informed by the supplementary data analysis (e.g., review of shoreline position and photogrammetry) presented in **Appendix A**.

[2] Actual depths of closure vary along the Tweed Shire and further assessment is provided in Section 5.3.5.

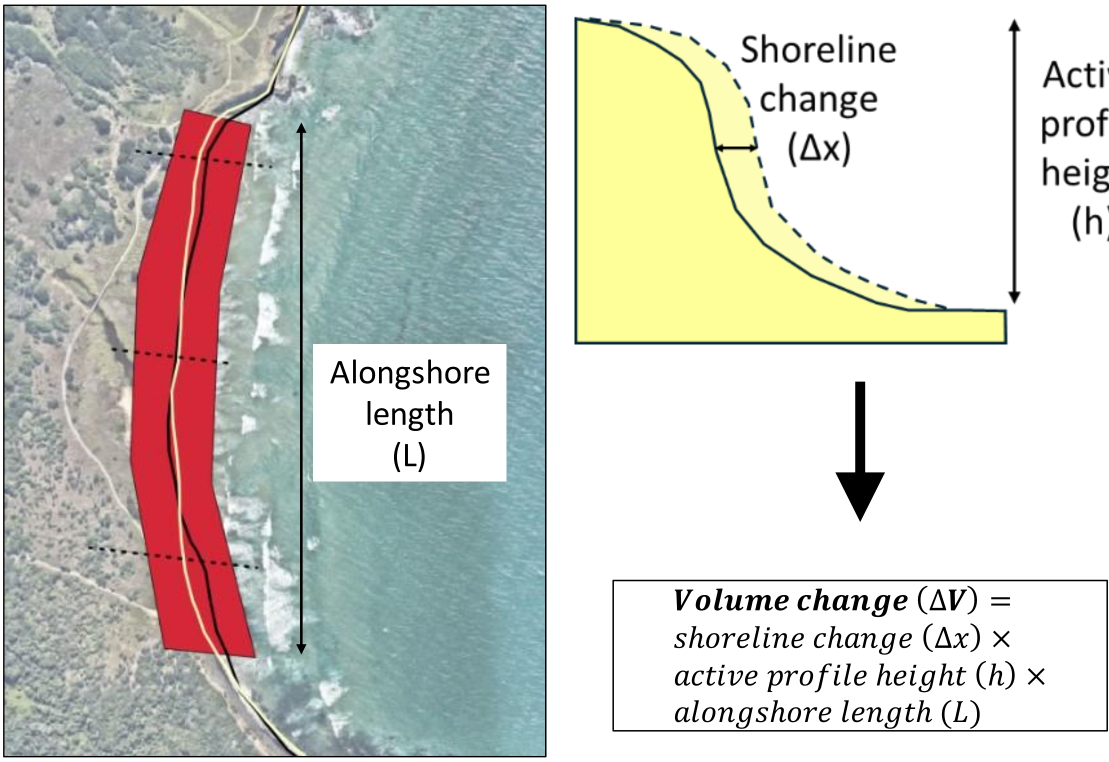


Figure 20: Schematic of volumetric analysis approach using shoreline change rate.

4.2.1 Analysis compartments

An assessment of the change in the sand volumes within the study are, from the southern to northern extent of the Tweed Shire LGA (from Wooyung to Point Danger) was undertaken adopting the 59 analysis cells shown in Figure 21. The extent and division of the cells were defined in consideration of previous assessments, survey extent, observed processes as well as the cross-shore divisions of the coastal profile (see Section 2.2). Cells were given a unique ID following *XX-A-B*, where *XX* is the beach cell, *A* is longshore beach sub-cell and *B* is cross-shore cell explained below:

- Subaerial beach *(1)*: which was adopted from approximately shoreline (or approximate 0m AHD contour) to the top of dune.
- Upper shoreface[3]: is the zone where under average conditions waves break and most wave energy is dissipated, commonly called the surf zone. Water level gradients, currents and sand movement are highest in this zone with the strong morphodynamic activity manifested in profile change and shoreline advance or retreat. On the upper shoreface timescales of profile change are in the order of hours to days to years.

  The upper shoreface was denoted *(2)* as the cross-shore identifier with depths less than around 12m.
- Lower shoreface: is the zone of the profile were waves shoal. The seaward extent is marked by the closure depth. Sand transport rates on the lower shoreface are typically small with the profile

[3] The shoreface is the zone seaward of the shoreline where offshore generated waves interact with the upward sloping seabed. It extends seaward to the closure depth where the influence of wave action on cross-shore sediment transport is on average minor compared to other influences.

responding to longer-term, annual-decade-millennium time scale changes in wave climate and sea level. The lower shoreface was denoted by *LS*.

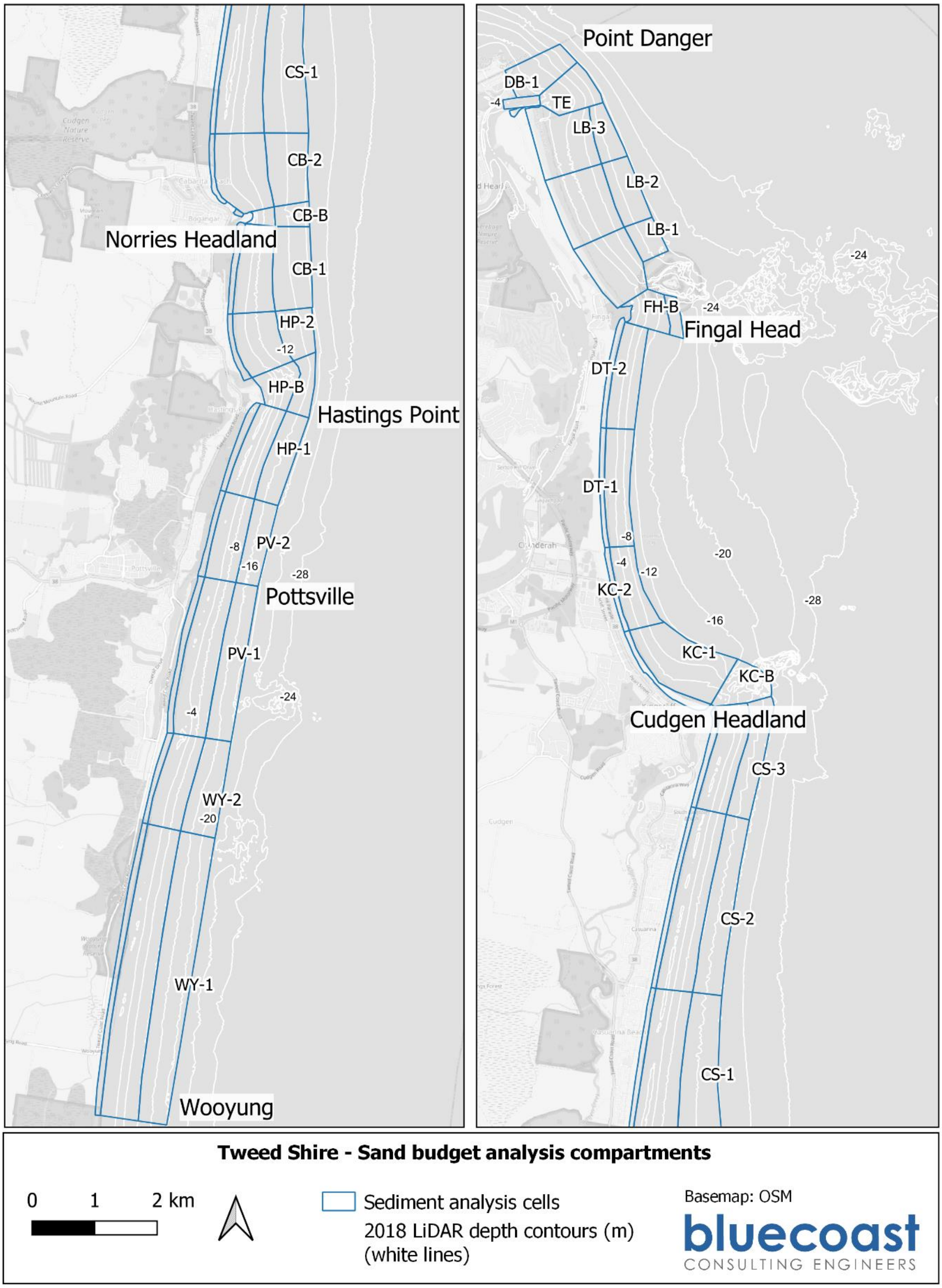


Figure 21: Sand budget analysis cells from Wooyung to Point Danger.

4.2.2 Time scales for change

The beaches along the Tweed Shire coast experience change over various time scales. This is illustrated in Figure 22 and described as:

- Long term changes occur over decades to centuries (and beyond) and are driven by persistent changes to sand budgets (e.g., reducing/increasing sand supply) and sea level rise.
- Medium term changes occur over years to decades and are driven by climatic cycles like ENSO and IPO and link to shifts in the wave climate.
- Short term changes can occur over days, weeks, months or years and are linked to storms, seasonal variations and ENSO fluctuation.

In the context of the sand budget analysis, it is important to understand these fluctuations (refer to Section 3.9). Surveys are undertaken at a point in time with the morphology captured reflecting the preceding conditions. Short to medium term influence may thus mask longer-term trends and care must be taken in interpreting the sand volume changes.

Figure 15 and Figure 24 show the two LiDAR surveys against time histories of the Interdecadal Pacific Oscillation (IPO) and Southern Oscillation Index (SOI used to track ENSO):

- 2011 survey was captured in an extreme La Niña SOI year both within an IPO El Niño like phase
- 2018 survey was neutral SOI year with the IPO transitioned to a La Niña like phase

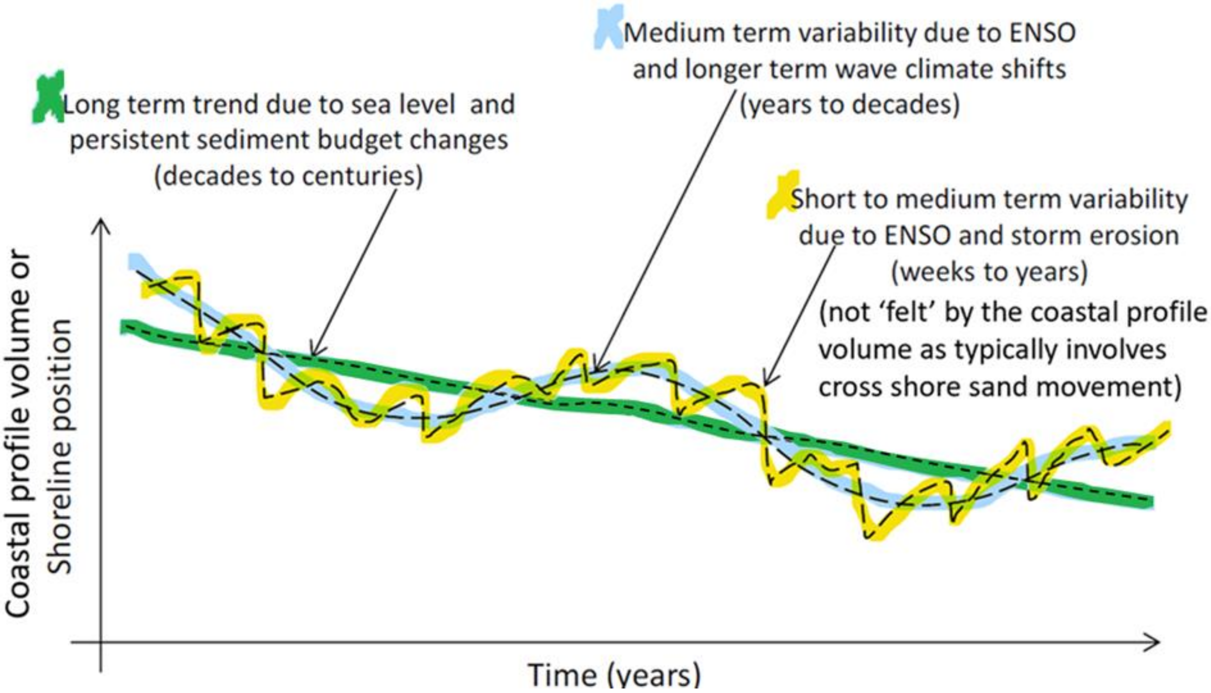


Figure 22: Conceptual illustration of time scales for beach changes (adapted from BMT WBM, 2013).

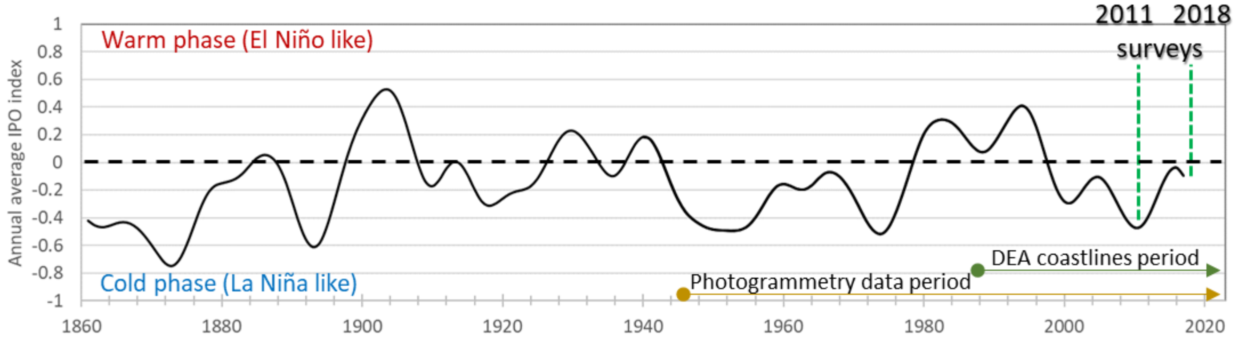


Figure 23: Annual average Interdecadal Pacific Oscillation index, 1860 to 2017 (data source: NOAA).

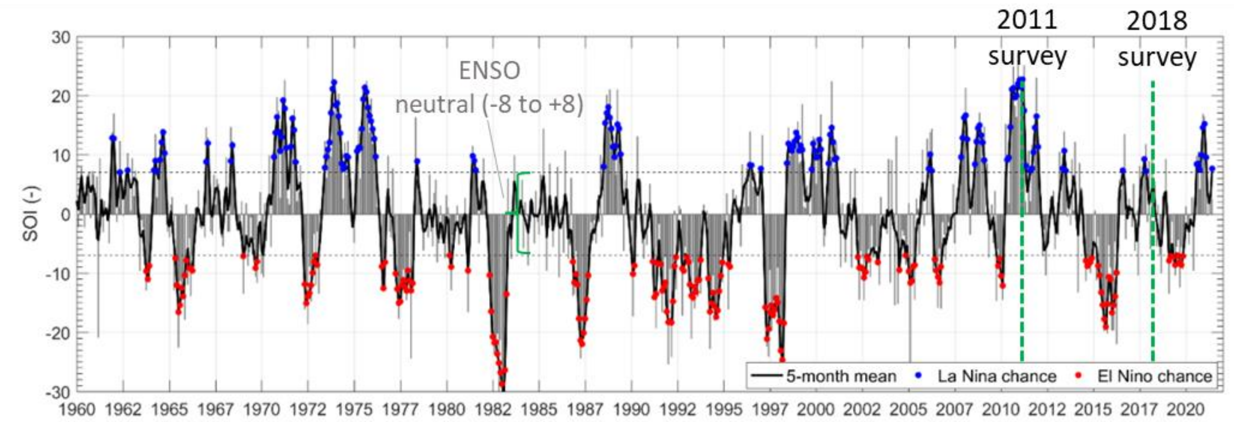


Figure 24: Monthly Southern Oscillation Index (ENSO), 1960 to 2022 (data source: BoM).

4.2.3 Error analysis

As noted in Section 1.5, the findings set out herein are subject to important assumptions and areas of uncertainty, including:

- Only limited survey data has been available for the study area and survey analysis was therefore undertaken over shorter time periods which may result in higher uncertainties in estimated long-term averages. Comparative volumetric analysis of available survey data has been used to inform the sand budget development and cross-checking of available longer-term data (i.e., photogrammetry and DEA coastlines).
- Mean annual shoreline data (DEA) was used to approximate long-term volume changes across the active profile for the sand budget and the rates of sand movement. These estimates are therefore subject to the accuracy of this dataset. Bishop-Taylor et al. (2021) conducted an extensive validation against independent coastal monitoring datasets to evaluate the positional accuracy and precision of the DEA shoreline data. Validations were performed using existing beach profile surveys where possible. The absolute mapping accuracy was found to be 7.3m, indicating a mean absolute error in mapping the median annual position. Based on the maximum envelope of observed shoreline position change in this dataset for the study area, the estimated error in shoreline positions and derived volume change is around 30%. Other error sources for calculation of absolute volume changes include the active profile height. However, the adopted 30% uncertainty range in estimated volume changes and associated sand transport rates is considered reasonable for the purposes of this study.

A quantitative comparison of calculated subaerial beach volumes using DEA shoreline and photogrammetry data was conducted for areas where overlapping data exist (refer Section 4.3.2).

4.3 Observed changes

4.3.1 Recent change (2011 to 2018)

This section provides a snapshot of the observed changes along the Tweed Shire coastline between 2011 and 2018. This period was selected due to the available coastal LiDAR data for all beaches in the study area in each of the two years. This period is also roughly representative as the recent period following the previous coastal hazard assessment (i.e., BMT WBM, 2013). The following is provided:

- Table 11 provides a summary of the sand volume changes between the two available surveys.
- Changes in surveyed levels relative to 2018 for the 2011 survey are mapped in Figure 25.
- A sand budget analysis based on the observed changes in each beach compartment is provided Table 12.

The seven-year period between 2011 and 2018 was characterised by significant coastal change that can be attributed to:

- Eroded subaerial beach condition at the start of this period due to successive storm events from 2009 to 2011 (NSW Coastal Panel, 2011).
- Climatic conditions influenced by dominant La Niña events between 2007 and 2013 coupled with an IPO cold phase (La Niña like) peaking in 2010 resulting in an extended period of large wave events arriving from the east.
- A preceding period of reduced sand supply into the study area's southern embayments leading to low upper shoreface sand volumes linked to a lack of headland bypassing events (see Section 4.5.2). This was followed by a period with large pulses of sand (sand waves) moving around the headlands into the southern embayments, particularly at Kingscliff Beach, in around 2011/2012.
- Passing of ex-Tropical Cyclone Oswald in January 2013 causing widespread subaerial beach erosion along the Tweed coast.
- A period of dominant El Niño conditions between 2014 to 2019 coinciding with a period of less significant storm events and rapid subaerial beach recovery leading to generally accreted (subaerial) beaches by the time of survey capture in 2018.

Table 11: Observed volume changes in each beach compartment between 2011 and 2018.

Beach compartment	Zone	Volume change relative to 2018 baseline (m^3)	
		2011	2018
Wooyung to Pottsville	Subaerial beach (Mooball beach only)	-63,845	0
	Upper shoreface	-1,165,320	0
	Lower shoreface	-1,776,625	0
	Subaerial beach	-185,045	0

Beach compartment	Zone	Volume change relative to 2018 baseline (m^3) 2011	2018
Pottsville to Hastings Point	Upper shoreface	-834,779	0
	Lower shoreface	-859,872	0
Hastings Point to Norries Headland	Subaerial beach	-21,892	0
	Upper shoreface	-326,289	0
	Lower shoreface	-548,583	0
Norries Headland to Cudgen Headland	Subaerial beach	-309,728	0
	Upper shoreface	-914,930	0
	Lower shoreface	-842,353	0
Cudgen Headland to Fingal Head	Subaerial beach	-594,215	0
	Upper shoreface	-725,420	0
Fingal Head Beach/ Letitia Beach	Subaerial beach & upper shoreface	-1,238,575	0
	Lower shoreface	-749,168	0
Duranbah Beach	Subaerial beach & upper shoreface	-283,038	0

Using the available survey data presented herein, the medium-term sand budget over the period between 2011 and 2018 was estimated for the study area's beach compartments. In order to estimate the sand movements within the study area, the following was assumed:

- 510,000m^3/yr of sand moving northward from the Byron Shire into the Wooyung Beach compartment based on long-term average rate estimated in Bluecoast (2023). While the assessed time periods in Bluecoast (2023) differ, it was assumed that there would be relatively minor variability in the long-term rate at the northern end of the Byron Shire (along New Brighton Beach) due to its open coast location.
- 598,000m^3/yr of sand moving northward at the Tweed Sand Bypass (TSB) jetty at Letitia Beach as determined in Bluecoast (2022) based on survey analysis over the period 2009 to 2020. As above, this time period slightly differs from the analysis period adopted herein but was considered to be reasonable as the northern boundary of the Tweed Shire sand budget analysis. The relatively small variation in annual sand bypassing volumes by TSB over these periods supports this assumption (refer to Bluecoast, 2022).

Under the above assumptions, a key finding for the Tweed Shire (medium-term) sand budget over this 7-year period is that all beaches in the study area were undergoing significant recovery since 2011. This was evidenced by the significant positive volume change within each beach compartment and increase in average elevations across the full (active) coastal profile. This suggests that there may have been a significant supply of sand from the lower shoreface that moved sand onshore. To balance the sand budget, an average onshore sand supply over this 7-year period was estimated at 25.8m^3/m (3.69m^3/m/year) across the study area. An onshore transport rate of such magnitude is untypical and likely not representative of a long-term average but also has been observed at other beaches in NSW during periods of post storm recovery (e.g., Harley et al., 2022[4]).

Comparison to the DEA coastlines and photogrammetry data over this period (see Section 4.3.2 and **Appendix A**) suggests that much of the recovery had already occurred within 1-3 years after the lowest subaerial beach volumes occurred in 2012/2013. This would result in even higher onshore sand transport rate in those years compared to the average rate (over 7-years) adopted herein. In the absence of more data, an average rate was assumed between 2011 and 2018 and across the study area, although this rate would likely differ from year to year and beach to beach.

Table 12: Tweed Shire sand budget for period 2011 to 2018.

Beach compartment [approx. length of sandy shoreline]	Total volume change (m^3/yr)[+ accretion]	Littoral transport IN (m^3/yr)	Littoral transport OUT (m^3/yr)	Lower shoreface sand supply (onshore transport) (m^3/yr) [3]
Wooyung Beach [6,240m]	+208,787	510,000 [1]	463,000	160,915
Pottsville Beach [5,490m]	+167,916	463,000	437,000	141,513
Hastings Point to Norries Headland [2,540m]	+52,023	437,000	451,000	65,635
Norries Headland to Cudgen Headland [8,870m]	+121,220	451,000	559,000	228,949
Cudgen Headland to Fingal Head [6,890m]	+154,117	559,000	598,000	177,685
Fingal Head Beach/ Letitia Beach [3,560m]	+30,083	598,000 [2]	*TBC*	7,120

Note:
1 Long-term average (net northward) sand transport rate adopted from Bluecoast (2023)
2 Long-term average (net northward) sand transport rate adopted from Bluecoast (2022)
3 Adopted average onshore sand transport rate of 25.8m^3/m/yr estimated from sand budget analysis undertaken herein (refer to description of this process provided in above paragraphs).

[4] Harley et al. (2022) suggest extreme storms can have a positive contribution to the nearshore sand budget by exchanging sediment between the lower and upper shoreface. Hence, single (or sequence of) large storm events can result in a net increase in sand volume across the active profile.

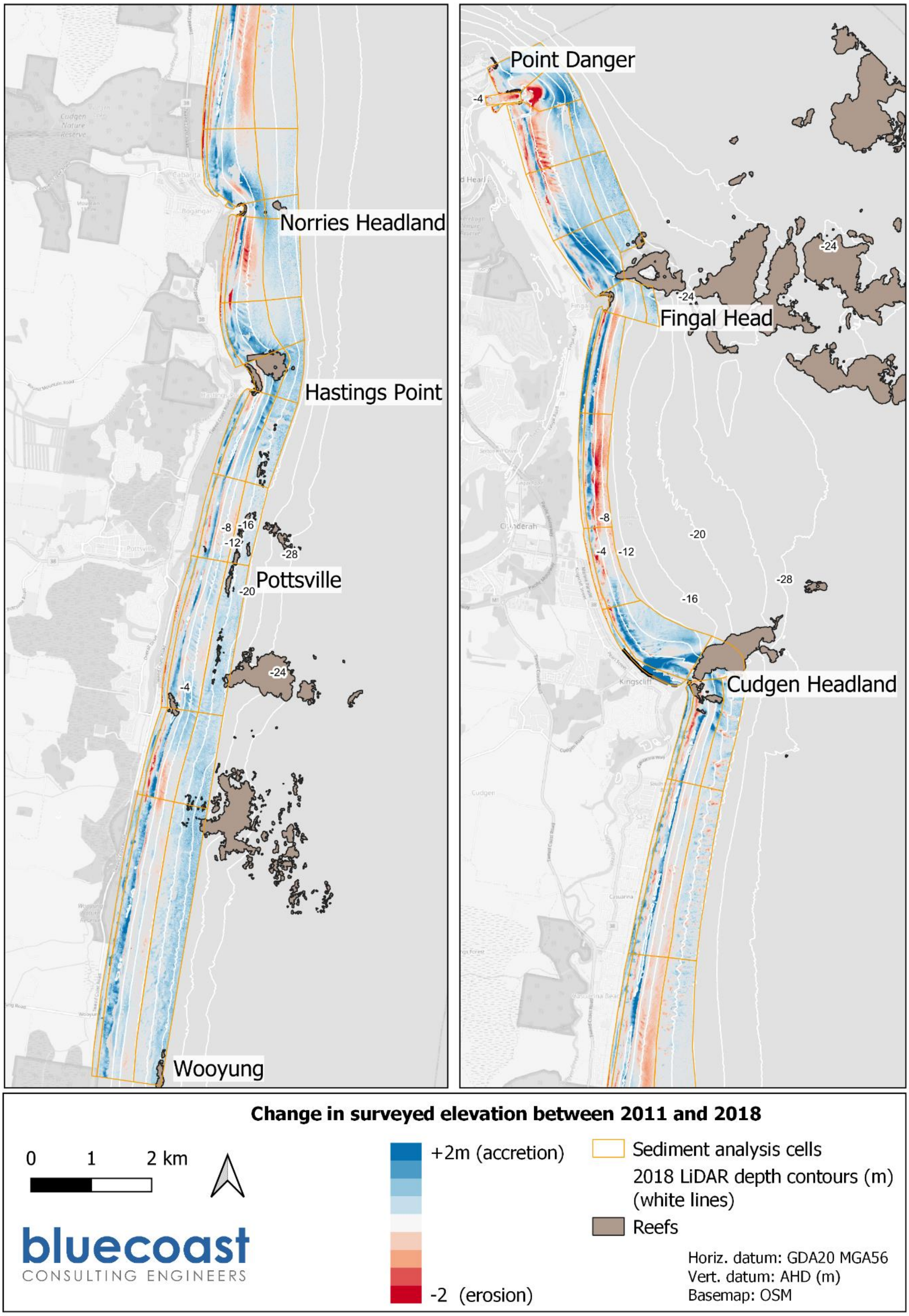


Figure 25: Surveyed elevation change along Tweed Shire coastline between 2011 and 2018.

4.3.2 Long term change

Limited data is available to quantify the long term behaviour of the Tweed Shire beaches. While photogrammetry derived subaerial beach profile data exists since 1947 its spatial and temporal resolution as well as human modification of the dune and subaerial beach (e.g., sand mining) restricts its use for estimating representative trends. Available survey data across the study area is limited to more recent periods (see Section 4.3.1) which is too short to estimate long term trends (see Section 4.2.2). To overcome some of these limitations, the DEA coastline satellite derived mean annual shoreline position data was used to analyse the longer term beach behaviour and associated sand budget. By adopting the DEA coastlines, the analysis is undertaken over a 33-year period from 1988 to 2021 and a timestep of one-year.

The 33-year period comprised several ENSO climate cycles and IPO phases and is expected to be representative of a wide range of climatic conditions. While the available data period remains relatively short when considering large scale climate patterns and the frequency of extreme storm events, it was considered useful for the purposes of this analysis. Cross checking against other available datasets throughout this period was undertaken to validate the approach. The following is provided:

- Table 13 presents estimated trends in subaerial beach volume change based on the photogrammetry data and concurrent trends in the mean annual shoreline positions from DEA coastlines.
- A timeseries of beach volume change relative to 2018 is presented in Figure 26. This includes annual beach volumes approximated from the DEA coastlines data (as described in Section 4.2) and available LiDAR data in 2011 and 2018.
- A long-term sand budget analysis based on the beach volume changes derived from DEA coastlines in each beach compartment is provided in Table 14.

The long-term sand budget analysis suggests that there is a net deficit of sand between Wooyung and Fingal Head of around 30,000m^3/yr. A long-term net loss of sand from the Tweed Shire beaches agrees with the previous studies. For example:

- BMT WBM (2013) estimated an average net rate of sand loss for the region between Clarence River to Gold Coast of 1.3 to 1.7m^3/m/yr including an onshore sand supply rate of around 1m^3/m/yr (which would imply a 39,000 to 51,000m^3/yr net sand loss from the 30km of sandy beaches between Wooyung and Fingal Head). BMT WBM (2013) adopted recession rates for Tweed Shire beaches ranging between 0.05 and 0.15m/yr with an allowance for higher rates at the southern end of each embayment and less than average at the northern end.
- Mariani et al. (2013) assessed the sand budget of the Norries Headland to Cudgen Headland compartment (referred to Cabarita-Casuarina-Salt compartment of 8km length) and referenced a wide range of sand deficit volumes due to higher sand transport out of the compartment to the north than what was estimated to move into the compartment from south. The stated range was 10,000 to 120,000m^3/yr (or 1.25 to 15m^3/m/yr) based on WBM (2001) and PWD (1982), respectively. Mariani et al. (2013) considered a portion of this littoral sand transport deficit to be offset by onshore sand transport in the order of 1 to 4m^3/m/yr (with a modal value of 1m^3/m/yr). In the absence of data-driven analysis in Mariani et al. (2013) there is low confidence whether their stated magnitude ranges are representative.

In the present study, the net deficit of sand was derived based on the following assumptions:

- Sand transport in and out of the analysis compartment (here between Wooyung and Fingal Head) are adopted from long term average rates presented in Bluecoast (2023) and Bluecoast (2022), respectively. Also refer to Section 4.3.1.

- Net onshore sand supply from the lower shoreface at a long-term average rate of 1.5m^3/m/yr as determined through the long-term sand budget analysis herein. This rate agrees with the range previously estimated by Patterson (2013). The study estimated that there remains some onshore sand supply from relict Holocene sand deposits on the lower shoreface at a rate of around 1-2m^3/m/yr based on regional coastline evolution modelling.

A net deficit of sand of 30,000m^3/yr over the 30km of beaches between Wooyung and Fingal Head equates to a loss of sand at around 1m^3/m/yr over the active coastal profile. Adopting an average height of the active coastal profile of around 15m, this would result in an average landward movement of the shoreline position of around 0.07m/yr across this area. This agrees well with the range of observed rates summarised in Table 13 (showing subaerial beach volume portion only) and further analysis presented in **Appendix A**. By exception, the observed beach volume and shoreline changes north of Fingal Head (i.e., Fingal Head Beach, Letitia Beach and Duranbah Beach) far exceed the average rates further south in the study area. This is due to the significant human interference with the construction (and extension) of the Tweed River training walls (see Section 2.1) and commencement of Tweed Sand Bypassing (TSB) activities in the late 1990s. In more recent years (since around 2009), the TSB operations were found to be in tune with the natural sand movements along Letitia Beach, maintaining the beach compartment in a new equilibrium (Bluecoast, 2022). That is, since 2009 erosion and accretion along Fingal Head Beach and Letitia Beach were predominantly linked to headland bypassing events and storms, not TSB operations.

Table 13: Longer-term trends in beach behaviour observed in photogrammetry and DEA coastlines data.

Beach compartment	Beach	Subaerial profile volume rate of change - photogrammetry (m^3/m/yr)		Average shoreline change rate - DEA Coastlines (m/yr)
		(1947-1962) to 2022	(1977-1987) to 2022	1988 to 2021
Wooyung	Wooyung Beach	- 0.23	0.10	-0.11
	Mooball Beach	- 0.66	0.26	-0.13
Pottsville	Pottsville Beach (south)	0.40	0.71	-0.12
	Pottsville Beach (north)	0.47	- 0.33	0.01
	Cudgera Beach	0.21	0.28	0.24
Hastings Point to Norries Headland	Maggies Beach (south)	- 0.78	- 0.80	-0.49
	Maggies Beach (north)	- 1.04	- 0.96	-0.31
Norries Headland to Cudgen Headland	Cabarita Beach	*No data*	4.97	0.1
	Casuarina Beach	*No data*	1.14	0.1
	South Kingscliff Beach (south)	- 0.02	- 0.19	0.04
	South Kingscliff Beach (north)	- 0.60	- 1.94	-0.03
Cudgen Headland to Fingal Head	Kingscliff Beach (south)	- 0.51	- 0.78	-0.05
	Kingscliff Beach (north)	- 0.14	- 1.16	-0.38
	Dreamtime Beach (south)	0.22	- 0.06	-0.4
	Dreamtime Beach (north)	0.44	0.85	0.1
Fingal Head to Point Danger	Fingal Head Beach	- 2.03	0.38	-1.48
	Letitia Beach (south)	- 3.30	- 6.34	-3.56
	Letitia Beach (north)	- 4.68	- 7.82	-3.52
	Duranbah Beach	-	-	-1.75

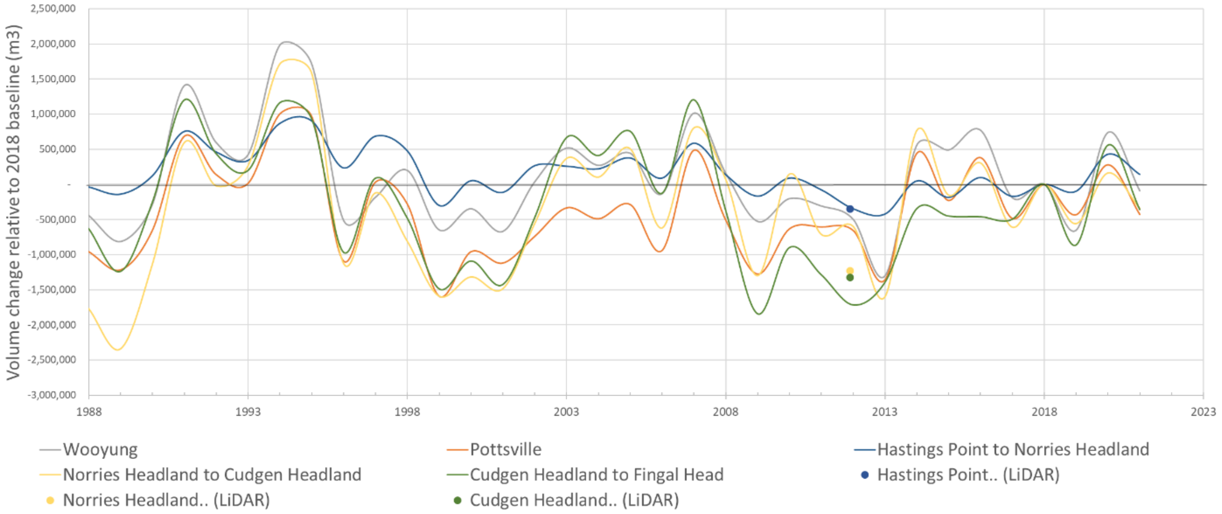


Figure 26: Estimated beach volume change within each beach compartment based on DEA coastlines.

Note: Available 2011 LiDAR volume estimates for respective beach compartments also shown as single points in matching colour. All volumes relative to 2018 baseline.

Table 14: Tweed Shire sand budget for period 1988 to 2021 (volume changes estimated from DEA coastlines).

Beach compartment [approx. length of sandy shoreline]	Total volume change (m^3/yr) [+ accretion]	Littoral transport IN (m^3/yr)	Littoral transport OUT (m^3/yr)	Lower shoreface sand supply (onshore transport) (m^3/yr) [3]
Wooyung Beach [6,240m]	-10,145	510,000 [1]	530,000	9,356
Pottsville Beach [5,490m]	+945	530,000	538,000	8,228
Hastings Point to Norries Headland [2,540m]	-14,015	538,000	556,000	3,816
Norries Headland to Cudgen Headland [8,870m]	+11,820	556,000	558,000	13,311
Cudgen Headland to Fingal Head [6,890m]	-17,326	558,000	598,000	10,331
Fingal Head Beach/ Letitia Beach [4] [3,560m]	*Not assessed*	598,000 [2]	*Not assessed*	*Not assessed*

Note: 1 Long-term average (net northward) sand transport rate adopted from Bluecoast (2023) 2 Long-term average (net northward) sand transport rate adopted from Bluecoast (2022) 3 Adopted average long term onshore sand transport rate of 1.5m^3/m/yr estimated from sand budget analysis undertaken herein. 4 Not assessed due to significant human modification by Tweed Sand Bypassing over this period.

4.4 Quantified conceptual sand movement model

Figure 27 provides a graphical overview of the quantified conceptual model of long-term average (net) sand movements (quantified model) across the Tweed Shire study area. This quantified model is based on the regional long-term sand budget and the assessment of each of the sand movement pathways, sources and sinks presented below in Section 4.5.

Based on observational data, previous literature and/or coastal processes knowledge, key factors that influence the observed sand volume changes and sand movements have been distilled. These key factors are described in the subsequent section and summarised as:

- Rate of **net longshore sand transport** (LST) and gradients in longshore transport rates.
- **Sand movement pathways** including the proportion that moves in an onshore direction from lower shoreface deposits.
- Variable embayment sand supply via **headland bypassing** around the study area's headlands and its effect of the quantities of sand in the southern embayments and shoreline positions.
- Past and current **coastal management interventions** and their interactions with the study area's natural sand movements.

Wherever possible, multiple lines of evidence have been used to cross-check, validate and provide greater confidence in the findings. Limitations are stated and uncertainty has been quantified for some of the findings.

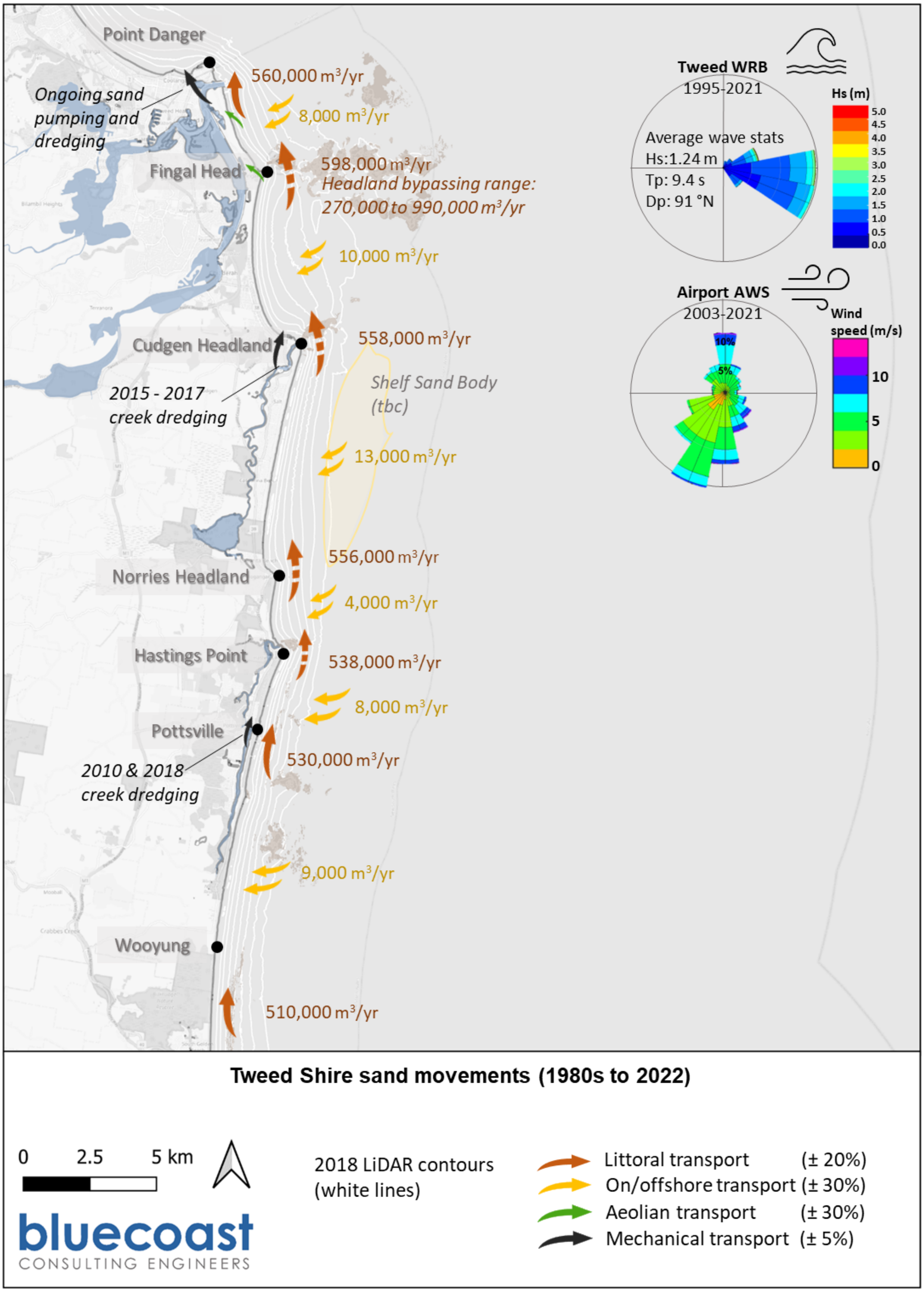


Figure 27: Quantified conceptual model of long-term net sand movements along Tweed Shire coastline.

4.5 Sand sources, sinks and pathways

4.5.1 Net longshore sand transport

Driven by wave action, longshore sand transport (LST) occurs predominately in the mid- to outer surf zone (within upper shoreface and subaerial beach) and normally inshore of the -4m depth contour. The dominant south-easterly offshore wave climate is oblique to the coastline orientation driving a net longshore movement of sand to the north along the 'Cape Byron to Ballina' and 'Tweed' sediment compartments. While the alongshore sediment transport may be directed either north or south depending on the prevailing wave direction, in the Tweed region the net sediment transport direction is to the north.

Longshore sand transport gradients are the dominant factor in the sand budget and shoreline changes in the region. However, there are no known measurements of LST rates in the region and previous studies present a wide divergence of estimates. The analysis of Patterson (2007; 2010; 2013) are considered the most recent and comprehensive undertaken in the region. Patterson used directional wave records, wave transformation modelling and longshore sand transport calculations to determine a gradient in the net longshore sand transport rate from about 150,000-200,000m^3/yr at the Clarence River to about 550,000m^3/yr at the Gold Coast. Other data-driven studies provided rates that were in general agreement with Patterson's calculated rates:

- Goodwin et al. (2013) used survey analysis (2002 and 2011 surveys) to estimate a net sand transport bypassing Cape Byron into the downdrift Byron embayment to be at least 350,000m^3/yr (±20%). A slightly higher rate of 400,000m^3/yr (±20%) was estimated by Bluecoast in subsequent analysis undertaken as part of the Byron Shire CMPs coastal hazard assessment (Bluecoast, 2023).
- Bluecoast (2022a) used sand pumping and dredging volumes and 11 full coastal profile surveys between 1972 to 2021 to calculate a net sand transport rate of approximately 560,000m^3/yr near the Tweed Sand Bypassing pumping jetty at the northern end of Letitia Beach.

While the longshore sand transport rates from Patterson (2013) are considered the most reliable and largely adopted herein, they are also noted as being many times greater than those presented in the PWD study (1978). PWD (1978) used field measurements of progradation following construction of the Brunswick River training walls to estimate that the net longshore transport rate at this Byron region was 110,000 to 120,000m^3/year. WRL (2011) considered the substantially higher rates adopted by Patterson (2010) warrants clarification and/or additional studies. To some extent additional clarification was presented in BMT WBM (2013).

The rates of longshore sand transport and along coast gradients adopted for this study are provided in Table 15.

Table 15: Adopted annual net longshore sand transport rates.

Location	Annual net longshore sand transport rate (m^3/yr)	Uncertainty (%)	Degree of annual variability
Clarence River	150,000[1]	±30%	Moderate
Cape Byron (headland bypassing)	400,000[2]	±20%	Extremely high

Location	Annual net longshore sand transport rate (m^3/yr)	Uncertainty (%)	Degree of annual variability
Byron Bay Main Beach	415,000[2]	±20%	High
Brunswick Heads	490,000[2]	±20%	Moderate
New Brighton Beach	510,000[2]	±20%	Moderate
Wooyung Beach	530,000	±20%	Moderate
Hastings Point (headland bypassing)	538,000	±20%	Moderate
Norries Headland (headland bypassing)	556,000	±20%	High
Cudgen Headland (headland bypassing)	558,000	±20%	High
Fingal Head (headland bypassing)	598,000	±20%	High
Letitia Beach TSB sand pumping jetty	560,000[1]	±25%	Moderate

Note:
1. Derived from literature, Bluecoast (2022), BMT (2020), BMT WBM (2013), Patterson (2013), Goodwin et al. (2013) and PWD (1978).
2. Based on sand budget analysis in Bluecoast (2023).

LST rates are highly variable responding to variation in the direction and energy in the offshore wave climate, which is sensitive to ENSO and other climate cycles of years, decades and longer timescales.

Typically, during dominant La Niña periods waves along northern NSW are bi-directional with southeast and easterly wave conditions. El Niño events are associated with a unidirectional south easterly wave climate (Mortlock and Goodwin, 2016). This wave climate variability, particularly the wave obliquity but also wave energy, largely controls the magnitude and direction of longshore sand transport along the study area's coast and headland bypassing (Silva et al., 2021). The alignment of the beach is therefore important when considering LST rates and how ENSO effects these. For example, along the updrift beaches of study area's headlands high rates of LST would be expected in El Niño events being driven by a more southern wave climate. Whereas in the downdrift (southern) embayments the higher energy and more eastern waves during La Niña events would be expected to drive higher LST rates.

Climate change is also likely to influence LST rates and their variability. The expansion of the tropics with warming climate is expected to lead to a poleward shift in storm type, with more tropical origin storms than extra-tropical storms with a southern origin. The anticipated outcomes of these changes on the Eastern Australia wave climate would be an anti-clockwise rotation of the mean wave direction and associated changes to sand movement (Silva et al., 2021). The mean wave height offshore of the Gold Coast, just north of the study area, is projected to decrease as well as an anticlockwise rotation of around 5° in the mean wave direction (GCCM, 2020). Such a shift would be expected to reduce net northerly LST along beaches updrift of the study area's headlands but could increase potential net northerly LST rates in the southern embayments.

4.5.2 Headland bypassing

Headland bypassing refers to the process by which sand is transported around a headland, or rocky outcrop on a coastline. Headland bypassing is an important process in shaping the coastline and can have significant impacts on the erosion and accretion of sand along the shoreline. In the Tweed Shire, headland bypassing is important in the context of coastal management, as understanding the dynamics of headland bypassing can help inform efforts to mitigate harmful erosion and other natural hazards in the southern embayments (e.g., Kingscliff Beach and Fingal Head Beach).

There are several factors that can influence headland bypassing, including the size, shape and orientation of the headland, the size and direction of waves, and the presence of other geological features such as sandbars or offshore reefs. The more prominent headlands along the Tweed Shire coastline (i.e., Norries Headland, Cudgen Headland and Fingal Head) have a significant influence on net northward littoral sand movements. Sand moving around these headlands, a process referred to headland bypassing, influences the supply of sand to the southern (downdrift) embayments as well as the way sand moves through these embayments.

Recent insights into headland bypassing in the local context are provided by the work of Silva et al. (2021) who undertook a detailed assessment of sand movements around Fingal Head. Using repeat hydrographic surveys and aerial images, the study identified two distinct headland bypassing processes:

- Sandbar-driven bypassing related to high-energy wave events. Between June 2018 and January 2020 hundreds of thousand cubic metres of sand was observed moving around Fingal Head by sandbar-driven bypassing during Tropical Cyclone Oma.
- Sand leaking around the headland following persistent low energy wave conditions and widening of the updrift beach (i.e., pre-loading of the apex) eventually resulted in sand leaking around the headland.

Sand supply to the southern embayments in the Tweed Shire is controlled by variations in the offshore wave climate which results in intermittent headland bypassing of pulses of sand around headlands. This is best demonstrated by comparing high resolution surveys encapsulating the start and end of such a headland bypassing event. Such comparison is presented in Section 4.3.1 with the largest change in surveyed elevations across the active profile and associated sand volume change observed along Kingscliff Beach and Fingal Head Beach over this 2011 to 2018 period.

4.5.3 Onshore sand movement

A net supply of sand to the nearshore is observed along many parts of the NSW coastline. This exchange of sand between the lower and upper shoreface contributes to the nearshore sand budget but may also supply sand to the longshore sand transport system. During the mid to late Holocene, when sea level was relatively stable, typical onshore sand transport rates of 1m^3/m/year were previously estimated along the NSW coastline (e.g., Cowell et al., 1995).

In the presence of large shelf sand bodies, the long-term rate of such onshore sand transport may be significantly higher. Kinsela et al. (2016) estimated that present-day onshore sand supply from the lower shoreface along some southeast Australian beaches could be in the order of 1-2m^3/m/year. This range of onshore sand supply was found to correlate well with the historic accretion observed along the Broken Head to Cape Byron beach compartment in the Byron Shire (Bluecoast, 2023). There has been minimal research on the presence of shelf sand bodies in the Tweed Shire. PWD (1982) raised that a large deposit of sand may be present on the lower shoreface off the Norries Headland to Cudgen Headland beach compartment (see Figure 28). Boyd et al (2004) and Roberts and Boyd (2004) also confirm relict sand deposits off the Tweed Shire coast in water depth of 30 to 60m. A higher onshore sand transport rate between Norries Headland and Cudgen Headland is supported by findings in BMT (2013) and the sand budged analysis completed herein. The latter adopted a long-term average onshore transport rate of 1.5m^3/m/year along this section of coast which is in line with Patterson (2013).

Harley et al. (2022) propose that with sea level rise, the exchange of sand that lowers the lower shoreface as sediment moves onshore can counteract, or even reverse, the effect of sea-level rise on the upper beach. The origin of this sand is beyond the usual depth of closure, so it is very likely that strong wave conditions are involved in this transport, as more typical waves are not expected to be able to shift sand at such depths. As described in Section 4.3.1, a positive sand budget was observed after post storm recovery along the Tweed Shire between 2011 and 2018 which may be due to this process.

Uncertainty remains if and how the present rates of onshore sand supply from the lower shoreface along the Tweed Shire coast will change with sea level rise over the next century.

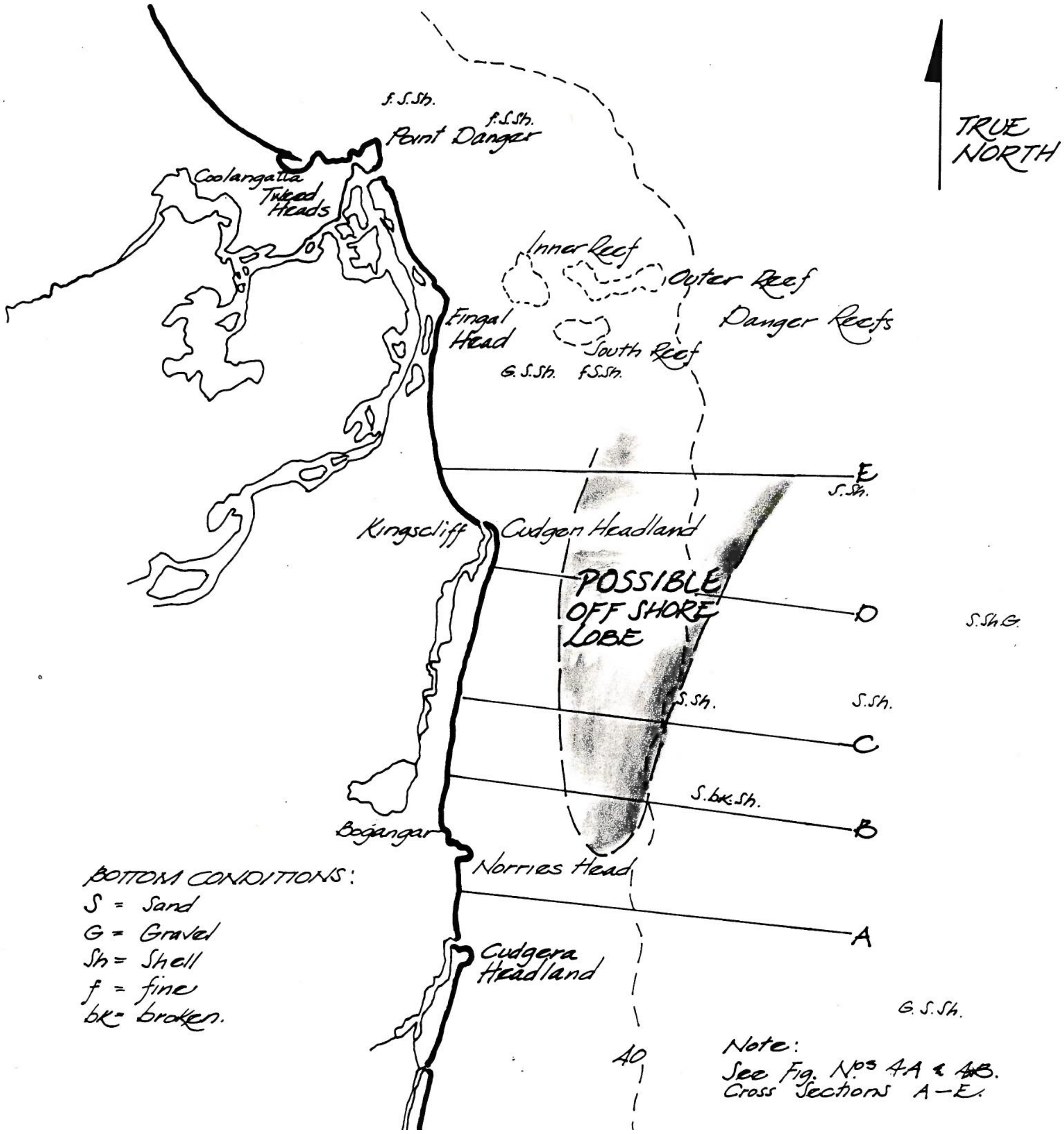


Figure 28: Sketch of possible shelf sand body offshore between Cabarita and Kingscliff (source: PWD, 1982).

4.5.4 Sand mining

Extensive sand mining occurred along the Tweed Shire coastline from the 1950s to 1980s. There is no available record of extracted sand quantities for specific locations. The extent of mineral extraction from 1947 to 1980 between Cudgen and Fingal headland is shown in Figure 29. BMT WBM (2013) also reported extensive sand mining occurred further south along Pottsville to Hastings Point (1960s) all the way to Cabarita Beach (1950s to 1970s), except for the area of Cabarita Township.

Sand mining included extraction of sand from dune and beach areas which led to a direct reduction of the local sand budget and resulted in reshaping of the dune and beach profile during that time. At present, the beach volumes and profiles have generally recovered from the sand mining impacts. Furthermore, areas that had been affected by sand mining had since been stabilised with vegetation and are no longer subject to wind-blown losses (BMT WBM, 2013).

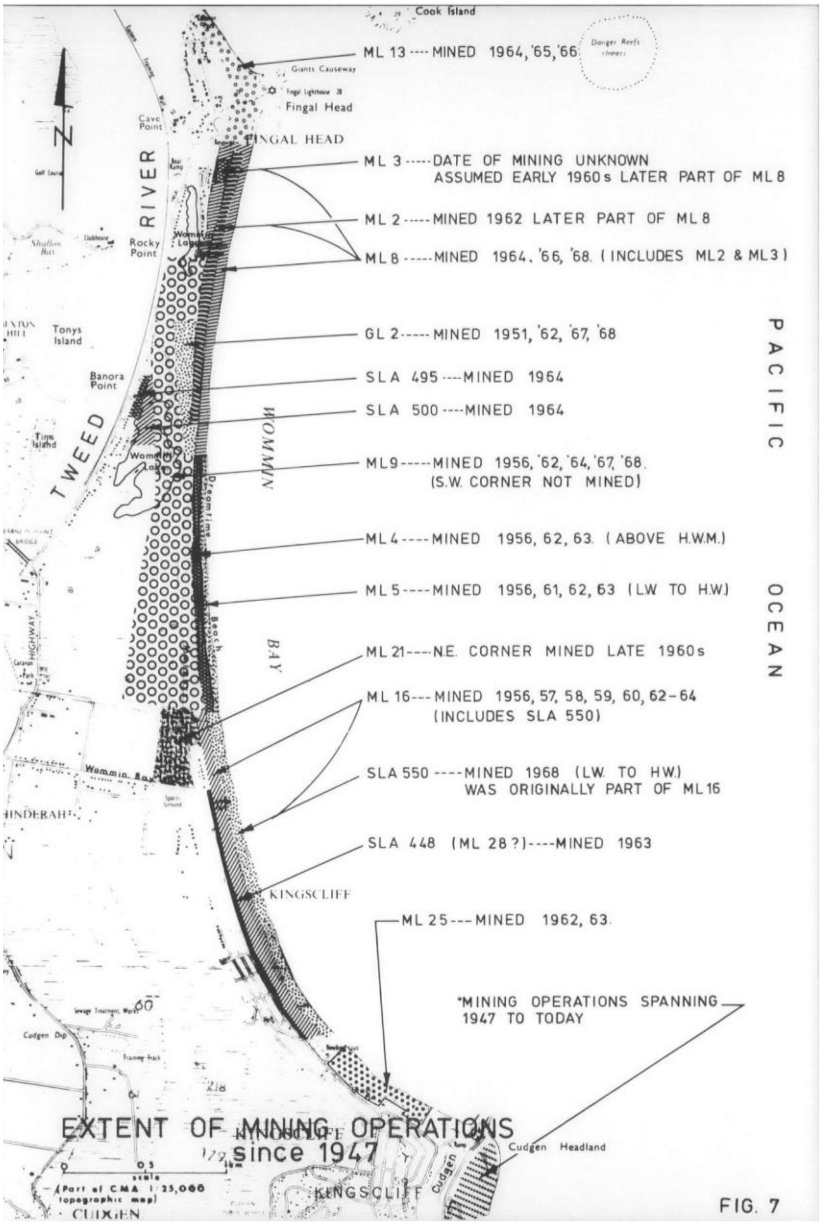


Figure 29: Extent of sand mining from 1947 to 1980 between Cudgen Headland to Fingal Head (source: PWD, 1980).

4.5.5 Dredging and beach nourishment

Dredging and beach nourishment in the Tweed Shire has been undertaken as one-off campaigns and more regularly by TSB as part of managing the Tweed River entrance. Known beach nourishment activities are presented in Table 16.

Table 16: Overview of know beach nourishment activities.

Placement location	Date	Sand volume	Sand source	Reason	Proponent/ reference
Pottsville Beach (immediate north of entrance)	2010	*Qty unknown*	Mooball Creek entrance	-	-
Pottsville Beach (immediate north of entrance)	October 2018	Around 2,000m^3	Mooball Creek entrance	Improve water quality and flood risk mitigation	Tweed Shire Council (TSC, 2018)
Kingscliff Beach	2015 - 2017	47,000m^3	Terranora Inlet and Cudgen Creek	Opportunistic nourishment from navigation dredging	NSW Department of Industry – Lands (BMT WBM, 2017)
Fingal Head Beach and Dreamtime Beach	August 2019 - October 2023	115,000m^3	Tweed River entrance	Ongoing entrance management	Tweed Sand Bypassing
Duranbah Beach	2001 - 2023	42,000m^3/year (sand pumping onto subaerial beach) 28,000m^3/year (nearshore dredge placements)	Tweed River entrance	Ongoing entrance management	Tweed Sand Bypassing

4.5.6 Coastal structures and their interactions with the shoreline

The historical timeline outlined in Section 2.1 provides details of the human modifications to the coastal barrier system in the study area. This includes the construction of the various creek/ river training walls and the Kingscliff seawalls. Coastal structures do not result in a change to the regional sand budget (i.e., they do not introduce or remove sand from the system). Structures, particularly those that interrupt longshore transport, can redistribute sand with corresponding amounts of accretion and erosion adjacent to the structure.

The interactions with the shoreline for coastal structures within the Tweed Shire are described as follows:

- Mooball Creek training walls – once built, the training walls rapidly changed the local sand movements which resulted in significant accretion of the updrift (southern) beaches and recession on the beaches to the north, while stabilising the alongshore position of the creek entrance. Following re-establishment of northward sand bypassing around the structures, the beach and dunes recovered. The localised impacts of the training walls are clearly noticeable in the observations; however such impacts were temporary. At present, subaerial beach volumes are likely primarily controlled by longshore sand supply and cross-shore storm response. Uncertainty remains around the future influence of the training walls and creek entrance to the behaviour of adjacent beaches.

- Cudgen Creek training walls – given the position of the training walls at the northern side of Sutherland Point, the structures practically extend this natural headland. As described in BMT WBM (2013), the structures have somewhat stabilised the southern end of Kingscliff Beach but also resulted in greater variability of sand volumes due to headland/ structure bypassing effects.
- Tweed River training walls – the extension of the training walls in the 1960s caused an accretion of Letitia Beach, especially in the north, and a clockwise rotation of the shoreline. TSB sand pumping and dredging reversed this trend and caused a retreat of the northern shoreline and an anti-clockwise rotation of Letitia Beach. The shoreline adjustment was rapid and completed by around 2008, when TSB operations started to align with the natural longshore sand transport rates. At present, the sand movements around the training walls and the behaviour of northern Letitia Beach and Duranbah Beach are predominantly controlled by ongoing TSB operations.
- Kingscliff seawalls (SLSC to Bowls Club) – the combined effect of the Kingscliff seawalls is to translate any net sand loss to the north. Unlike the shore-perpendicular training wall structures described above, the influence of seawalls on beach and shoreline behaviour is dependent on the beach levels. While the beach in front of the seawalls is in an accreted state, such influence is minimal. During an eroded state, including on coastlines suffering net sand loss, the seawalls can 'lock in' sand in the dunes that would have otherwise been released to supply the downdrift sections of beach. During storm events, coastal processes interacting with the seawalls can lead to exacerbated erosion along the immediate downdrift section of beach.

4.5.7 Bedrock outcrops and reefs

The geological and seabed characterisation for the Tweed Shire is described in Section 3.1. Bedrock outcrops, including the reefs off Pottsville Beach, Hastings Point, Cudgen Headland and Fingal Head are hard features that affect wave transformation and the movement of sand as well as influencing shoreline dynamics. Hard substrate also reduces the volume of sand that can be stored in the respective beach sections.

4.5.8 Estuaries

The three smaller coastal estuaries at Mooball Creek, Cudgera Creek and Cudgen Creek and the Tweed River estuary have their ocean entrances along the Tweed Shire coastline. With exception of Cudgera Creek, all entrances to these estuaries are controlled by rock training walls. The three creeks flow northward behind the coastal sand barrier. Previous literature and the available evidence reviewed herein suggest there are no net losses or gains of sand from, or to, the coastal compartment from these three estuaries.

The Tweed River entrance is managed by TSB which largely controls the sand transport in and out of this estuary. The river has been trapping marine sand until the late 1900s as the flood shoals adjusted to the initial building and extension of the training walls (Jacobs, 2017). It is uncertain how much sand is permanently entering the estuary, if any, as it is regularly removed by dredging or by flood events. Jacobs (2017) indicates that since TSB sand pumping started in 2001 a net sand movement from the river to the entrance is observed. BMT (2020) estimated that the net movement from the river is about 7,000m^3/year (equal to offshore losses near the entrance) which agrees with findings from sand budget analyses in Bluecoast (2022).

The lower estuaries and their entrances are expected to accumulate marine sand as a morphological response to sea level rise (Eysink, 1990). This flood tide delta aggradation will result in a net reduction in the sand budget of the active coastal zone that will likely result in some recession of beaches adjacent to estuary entrances in the Tweed Shire. At the Tweed River, the entrance morphology and associated sand movements likely remain predominantly controlled by the continuous operations of the TSB.

4.6 Conclusion

The key findings and implications of the sand budget for coastal management in the Tweed Shire are:

- The sand budget provides a tool to inform sound coastal management in the LGA and regionally. By considering sand volumes changes and movement over the full beach fluctuation zone, as defined in the CM Act, it promotes management actions that recognise the importance of sand in sustaining healthy beach systems. Recognition of the importance of longshore sand transport and variable sand supply along a coastline such at Tweed Shire, would be expected to lead to better coastal management outcomes.
- A net (long-term) loss of sand was estimated at around 30,000m3/year over the 30km of sandy beaches within the study area. The rate of sand loss varies alongshore and between beach compartments. No net sand loss was observed for the stretch of coast between Norries Headland and Cudgen Headland, possibly due to a higher rate of onshore sand supply from the lower shoreface in this area. Observed changes along the coast either side of the Tweed River entrance have been predominantly governed by TSB operations.
- The sand budget outcomes are used to inform the development of probabilistic coastal erosion and recession hazard lines (see Section 5). The calculated probabilistic coastal erosion and recession hazard extents provide another tool to inform coastal management. The role of such hazard lines is most important in quantifying the erosion risk to land along the coast to inform coastal planning. While there are several linkages between the sand budget outcomes and the erosion and recession hazard calculations, key considerations to quantifying the hazard extents include:
    - A net long-term sand loss along most of the Tweed Shire coastline results in shoreline recession which requires consideration in long-term shoreline change calculations as part of the hazard assessment.
    - High variability in sand supply to southern embayments at Cabarita Beach, Kingscliff Beach and Fingal Head Beach is observed due to headland bypassing processes resulting in fluctuating upper beach volumes and shoreline positions. It is important to account for the additional shoreline variability observed in these areas.
    - High variability in onshore sand transport rate over time, with potential of significantly increased (temporary) sand supply from lower shoreface observed following major storm events.
    - Possible higher long-term average sand supply from lower shoreface within Norries Headland to Cudgen Headland due to presence of relict shelf sand body resulting in stable beach compartment (no net sand deficit). Where uncertainty in future onshore sand supply rates exists, an allowance for variability in such rates needs to be considered in hazard projections.
    - In some areas, hard substrate reduces the volume of sand that can be stored within the coastal profile. The presence of shallow/ outcropping bedrock can also provide a level of erosion resistance dependent on the level and extent of hard substrate.

    - At present, the three estuaries of Mooball Creek, Cudgera Creek and Cudgen Creek are no net sink or source of marine sand to the Tweed Shire's sand budget. With sea level rise the sand budget at the estuary entrances (including Tweed River) may become unbalanced, which may contribute to recession of adjacent beaches. The Tweed River has been a net source of sand since commencement of TSB operations in late 1990s.

- Sand budget analysis relies on coastal topographic and bathymetric surveys. To improve future coastal sand budgets and reduce uncertainty wide-extent, high-resolution and accurate surveys will be needed. Technological advances in the future may make the acquisition of these important datasets more efficient. Wide-extent coastal surveys during a range of climate cycles would be beneficial (e.g., La Niña and El Niño phases).

5. Coastal erosion and recession hazard assessment

5.1 Overview

In line with the NSW Coastal Management Manual Part B (the Manual – OEH, 2018), a probabilistic coastal erosion and recession hazard assessment for the Tweed Shire coastline was undertaken. This section provides an overview of the approach and inputs to the hazard assessment as well as a review of the key assumptions and parameters used in the BMT WBM (2013) *Tweed Shire Coastal Hazards Assessment* study.

The adopted approach and inputs have been determined in collaboration with the Department of Planning and Environment (DPE) (now Department of Climate Change, Energy, the Environment and Water, DCCEEW) and Tweed Shire Council (i.e., the project team).

5.2 Approach

A probabilistic beach erosion and shoreline recession model is used for this study. The statistical model comprises a volumetric coastline response model that uses detailed terrain data and a parametrised sand budget to predict the potential range of present and future coastal erosion and recession hazards. The methodology has been adapted from previous probabilistic hazard models applied to Stockton Beach (Bluecoast, 2020), Lake Cathie (OEH, 2016; Kinsela et al., 2016) and a state-wide assessment (OEH, 2017b; Kinsela et al., 2017). An overview of the probabilistic coastal erosion and recession model is provided in Figure 30. For each of the 6 beach compartments shown in Figure 21 and described in Table 11, site-specific supporting analysis (including photogrammetry, shoreline position and survey analysis) and local context is presented in **Appendix A**.

The probabilistic hazard assessment is a risk analysis performed using a Monte Carlo simulation. For key input factors that have inherent uncertainty, a range of possible values are defined (i.e., a probability distribution). The simulation then calculates results over and over, each time using a different set of random values from the range of possible input values. The output is a probability distribution of erosion and shoreline recession hazard. Steps applied during the Tweed Shire coastal erosion and recession hazard assessment are:

1. <u>Inputs</u>

   Define spatially and time varying probability distributions describing the key factors of the sand budget and sea level rise. Individual probability distributions are defined for representative beach sub-compartments and, where required, across different time periods. Triangular probability distributions are used where higher uncertainty exists. These are described by a 'mode – most likely' value with 'minimum' and 'maximum' bounds. Where there is higher confidence around the mean and variances from observations, normal or gamma distributions are considered to provide a better representation of the shape and skewness of the distributions. The key factors considered for the Tweed Shire erosion hazard assessment include:

- Beach erosion due to storm events, long-term beach behaviour trends due to sand budget imbalances, changes to the wave climate or sea level rise, shorter-term variability in the sand budget (e.g., beach rotation, headland bypassing effects, storm clusters), onshore sand supply from the lower shoreface as well as beach and estuary response to sea level rise.
- Incorporation of erosion limiting/reducing/enhancing factors such as bedrock outcrops/reefs, coastal structures and associated downdrift shoreline impacts.

2. Calculations

The Monte Carlo simulation of coastal erosion uses one million (1,000,000) of individual calculations each with a different set of the key input parameters. The probabilistic calculations are carried out for each year of the planning period. Key steps include:

- The erosion/recession setback calculations are undertaken on a volumetric basis for a series of cross-shore profiles within the study area.
- Full profile recovery from beach erosion is assumed after each year. That is the calculations revert to the baseline profile before applying the sampled erosion and recession allowance for each year. Variations in the pre-storm beach profile conditions are included in the hazard model by including an allowance for shorter-term variability in the profile volumes (see Section 5.3.4).
- Calculation of post-storm zone of slope adjustment (ZSA) and extent of the zone of reduced foundation capacity (ZRFC) based on a deterministic model after Nielsen et al. (1992).

3. Outputs

The probability of exceedance of the landward position of the ZRFC are determined based on the one million results produced for each year of the adopted planning periods. Five planning timeframes have been adopted for reporting and mapping purposes of this study, including, immediate, 2040, 2050, 2070 and 2120. The 1%, 2%, 5% and 10% Annual Exceedance Probability (AEP) of the erosion hazard are then mapped for each planning timeframe. Some smoothing of the hazard lines is undertaken to avoid significant localised fluctuations in the erosion escarpment position that would be unlikely to be sustained in practice.

The adopted approach for the probabilistic coastal erosion and recession hazard assessment is considered suitable for planning purposes. The results should not be used for design purposes and interpretation of the results should consider the following assumptions and uncertainties:

- A regional hazard assessment was completed using the best available information on coastal processes and regional geology at the time of preparing the assessment. For example, the probabilistic erosion calculations may have missed localised, unresolved or unknown hard substrata which would influence actual coastal erosion.
- Current coastal management activities and engineered structures were assumed to be continued and adequately maintained over the assessment period unless otherwise specified (see Section 5.3.6 for details).
- Where possible the latest scientific evidence and advice has been adopted in this assessment, however uncertainty remains, particularly in the impacts of climate change on future sea levels and local coastal processes within the Tweed Shire. Uncertainty is somewhat dealt with by using a

probabilistic approach, but the results are dependent on the inputs and value ranges determined by the project team.

- Methods to predict the beach response to sea level rise are highly simplified and can be somewhat conservative. For the longer planning periods, the beach response to sea level rise typically provides the highest contributing factor to future recession governing the predicted landward hazard extent.

5.2.1 Previous studies

The previous coastal hazard assessment (BMT WBM, 2013) used a linear distance approach (rather than a detailed probabilistic volumetric approach) to calculating the erosion hazard extents from Mooball Creek in the south to Letitia Spit with immediate, 2050 (minimum, best and maximum estimates) and 2100 (minimum, best, maximum estimates) hazard lines calculated. The immediate hazard line used an accreted beach planform/ profile (from 2007 photogrammetry data) with an erosion storm demand of 200m^3/m applied to all beaches. Future hazard lines (2050 and 2100) were calculated based on a sea level rise recession distance (m) and long-term recession rate (m/yr) applied to this immediate hazard line for a minimum, best estimate and maximum combined recession rate. The sea level rise recession distances were 16m (Dreamtime Beach) to 90m (at Cabarita Beach and Kingscliff Beach) by 2100 based on the Bruun Rule and an adopted sea level rise of 0.34m by 2050 and 0.84 by 2100.

Using this approach, this study presented hazard extents which reached property areas at (south to north):

- Hastings Point far eastern properties east of Tweed Coast Road (near Peninsula Street) by 2100
- Cabarita properties near and east of Cypress Crescent by 2100
- Bogangar to South Kingscliff far eastern properties by 2100
- Kingscliff foreshore properties in the immediate (e.g. SLSC and bowls club) and Marine Parade by 2100 (particularly at southern end)
- Fingal Head foreshore property in the immediate (holiday park), Marine Parade by 2050 and Queen Street by 2100.

The probabilistic approach adopted herein builds upon this previous study by incorporating the latest datasets (e.g., latest topography and bathymetry, and IPCC sea level rise advice) and methods to provide an updated probabilistic coastal erosion and recession hazard assessment for the Tweed Shire coast.

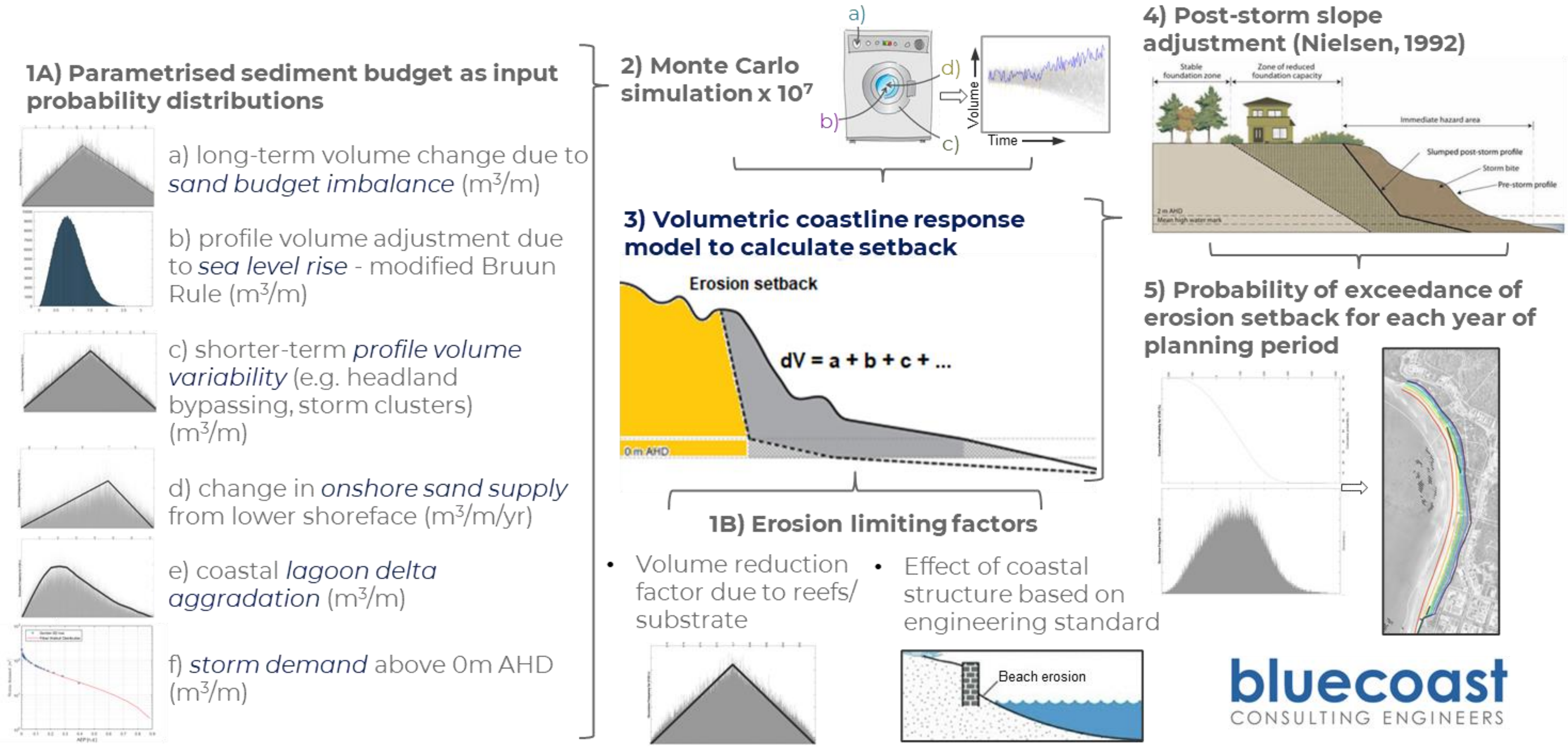


Figure 30: Overview of probabilistic coastal erosion and recession hazard model.

5.3 Adopted inputs and methodology

The following sections outline the key inputs for the Tweed Shire coastal erosion and recession hazard assessment. The input value ranges for the probabilistic model have been determined based on the Tweed Shire coastal sand budget (Section 4) and supporting analysis presented in **Appendix A**.

When the inputs are defined as a triangular probability distribution for the Monte Carlo simulation, the value range is described by the minimum (min), mode (mod), and maximum (max) values to represent the bounds of the distribution. It is noted, that for all input ranges the mapping of the hazard extents will always be skewed towards the more conservative limit of these ranges due to the adopted extreme exceedance probabilities (i.e., 1%, 2%, 5%, 10% AEP) for the mapping and presentation of results.

5.3.1 Assessment profiles

A total of 1,122 regular shore-normal profiles between Wooyung Beach in the south and Point Danger in the north (see Figure 43 for transect locations) were adopted for the erosion and recession calculations. The profiles are at 20m to 50m intervals depending on coastline complexity and coastal development and extent from landward areas seaward to approximately 30m water depth. Profile elevations were derived from LiDAR data as described in the following section. Maps showing the assessment profiles and beach areas are provided in **Appendix B.**

5.3.2 Baseline

The 2018 NSW Coastal LiDAR topographic and bathymetry data is used as the baseline for the coastal erosion and recession hazard assessment. This dataset is considered the most suitable baseline for the following reasons:

- Consists of high-quality contemporary survey data extending across the entire study area and full coastal profile.
- Is considered representative of a typical to accreted beach state across the Tweed Shire coastline. The 2018 Coastal LiDAR was captured between July to October 2018 during a neutral ENSO period.

More recent available topographic LiDAR data (e.g., 2023) only extents to the subaerial beach areas (not subaqueous) and was therefore not suitable as a baseline dataset for this assessment. Also, beach conditions over this more recent period within the study area have been affected by the pre-dominant La Niña climate conditions from 2020 to 2023. Similarly, adopting an ‘eroded’ baseline profile (e.g., using available LiDAR data from 2011) would result in potentially overly conservative hazard predictions. Instead, such shorter-term profile volume variability, including the effects of headland bypassing, is considered statistically as an input to the hazard model (see Section 5.3.4). In the most recent previous coastal hazard study (BMT WBM, 2013), an accreted profile from 2007 photogrammetry data was used as the baseline (see Section 5.2.1).

An example profile at Kingscliff Beach showing available survey data since 1985 (including 2018 LiDAR data for reference) is provided in Figure 31. Profiles showing available survey data for other beaches are shown in **Appendix A**.

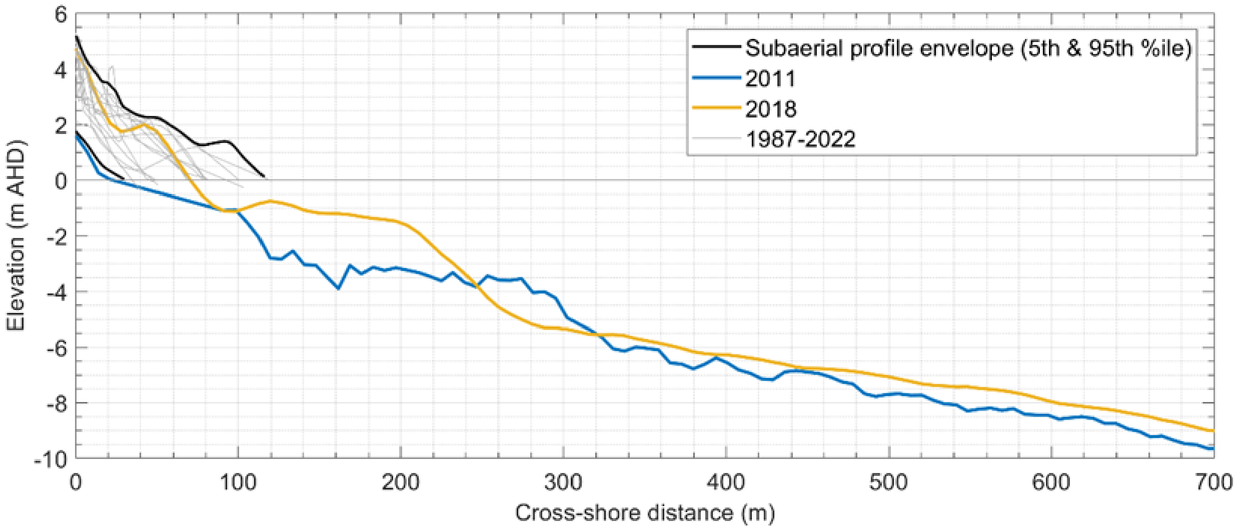


Figure 31: Example coastal profile envelope for Kingscliff Beach.

5.3.3 Beach erosion

Storm induced beach erosion volumes (or 'storm demand') for extreme events (~100-year ARI) observed along exposed NSW beaches typically ranges between 150 to 250m^3/m (Gordon, 1987). The 'storm demand' experienced by a section of beach is largely governed by storm intensity and duration as well as localised processes. A reduced storm demand can be experienced if the beach is already in an eroded state, bedrock or other less erodible substrate exists and/or due to lower wave exposure for sheltered beaches. The most recent previous coastal hazard study of the Tweed Shire coastline (BMT WBM, 2013) adopted a nominal storm demand volume for the entire region as 200m^3/m allowing for a reduced volume where justified based on photogrammetry data and/or wave exposure.

The full range of storm demands in the Tweed Shire with rare and frequent occurrence probabilities (i.e., less/more frequent than a 100-year ARI event) were estimated by curve-fitting to the commonly used distribution of storm demands in New South Wales by Gordon (1987). Figure 32 presents the relationship between storm demand and annual recurrence intervals in Gordon (1987) as well as examples of the adopted probability distributions as input for the coastal erosion and recession hazard assessment herein. To account for the varying exposure of sections of beach in the Tweed Shire, the probabilistic storm erosion calculations were undertaken as follows:

a. Review of observed storm demands at each section of beach (presented in **Appendix A**) to determine the minimum storm demand for a 100-year ARI event for each beach. This ensures that the 100-year ARI storm demand is at least as large as any previously observed storm events in the available photogrammetry data (up to 75-year record). For the purposes of this study, the estimated storm demand is intended to reflect a single storm event or a series of events occurring within a given year.

b. Selection of a representative maximum storm demand volume for a 100-year ARI storm event, based on Gordon (1987) as well as relative beach exposure. A triangular distribution representing the range (minimum to maximum) of 100-year ARI storm demand volumes was used to account for uncertainty in this value (presented in Table 17). For most beaches, this approach resulted in a modal value of 200m^3/m which is in line with the adopted storm demand volume in BMT WBM (2013) but allowing for a higher 'maximum' limit.

c. Scaling of the Gordon (1987) distribution of storm demands for open beach locations in New South Wales so that the 100-year ARI value aligns with the randomly sampled value from the triangular distribution in (b).

d. Extrapolation of the scaled Gordon (1987) storm demand distribution by fitting of a Weibull distribution[5] to estimate the full range of probabilities as input to the probabilistic erosion calculations.

The combined storm demand and recession volumes have been converted to horizontal erosion distances to the landward extent of the Zone of Slope Adjustment (ZSA) and Zone of Reduced Foundation Capacity (ZRFC) in accordance with the Wedge Failure Plane Model after Nielsen et al. (1992) (see Figure 33). These calculations are performed for each assessment profile location in the study area.

The slope adjustment model after Nielsen et al. (1992) is strictly only considered valid for dunes comprising homogenous sand. It is conservative, overly in some cases, for areas where coffee rock is present. In the absence of more appropriate design tools, its use is considered reasonable for the purpose of the erosion hazard assessment. A conservative discrete angle of repose of 33° was adopted which is representative of unconsolidated sand.

Table 17: Adopted input ranges for storm demand in the erosion and recession hazard model.

Compartment	Beach	Adopted 100-year ARI value range [min, mod, max]	Comment
Wooyung to Pottsville	All beaches	150, 200, 250	Minimum value for 100-year ARI event set to the maximum observed historic storm erosion volume of 150m^3/m (**Appendix A**). Maximum value set to 250m^3/m based on 'open coast' beach storm demand data from Gordon (1987). Some erosion extents may be limited by presence of bedrock in some areas which is considered separately (Section 5.3.7).
Pottsville to Hastings Point	All beaches	150, 200, 250	
Hastings Point to Norries Headland	All beaches	200, 250, 300	Minimum value set to the maximum observed historic storm erosion volume of 200m^3/m (**Appendix A**). Maximum value set to 300m^3/m based on high wave exposure, with the modal value set to the 250m^3/m based on Gordon (1987).
Norries Headland to Cudgen Headland	Cabarita Beach	125, 200, 250	Adopted a reduction in 'open beach values' for the minimum value due to wave sheltering effect by Norries Headland. Maximum value set to 250m^3/m based on Gordon (1987).

[5] Adopted Weibull fit parameters are *scale = 25.6120* and *shape = 0.8357*

Compartment	Beach	Adopted 100-year ARI value range [min, mod, max]	Comment
	Bogangar and Casuarina Beaches	150, 200, 250	As above (e.g., Wooyung to Pottsville), adopted a range based on observed historic storm erosion volumes (**Appendix A**) and Gordon (1987).
	South Kingscliff Beach	200, 250, 300	Minimum value set to the maximum observed historic storm erosion volume of 200m^3/m (**Appendix A**). Maximum value set to 300m^3/m based on high wave exposure, with the modal value set to the 250m^3/m based on Gordon (1987).
Cudgen Headland to Fingal Head	Kingscliff Beach	150, 200, 250	As above (e.g., Wooyung to Pottsville), adopted a range based on observed historic storm erosion volumes (**Appendix A**) and Gordon (1987).
	Dreamtime Beach	150, 200, 250	
Fingal Head to Point Danger	Fingal Head Beach	125, 200, 250	Adopted a reduction in ‘open beach values’ for the minimum value due to wave sheltering effect by Fingal Head and Cook Island evident in the observed historic storm erosion volumes presented in **Appendix A**. Maximum value set to 250m^3/m based on Gordon (1987).
	Letitia Beach	150, 200, 250	As above (e.g., Wooyung to Pottsville), adopted a range based on observed historic storm erosion volumes (**Appendix A**) and Gordon (1987).
	Duranbah Beach	200, 250, 300	Adopted exposed beach storm erosion value range due to known high wave exposure, similar to South Kingscliff Beach and Hastings Point to Norries Headland.

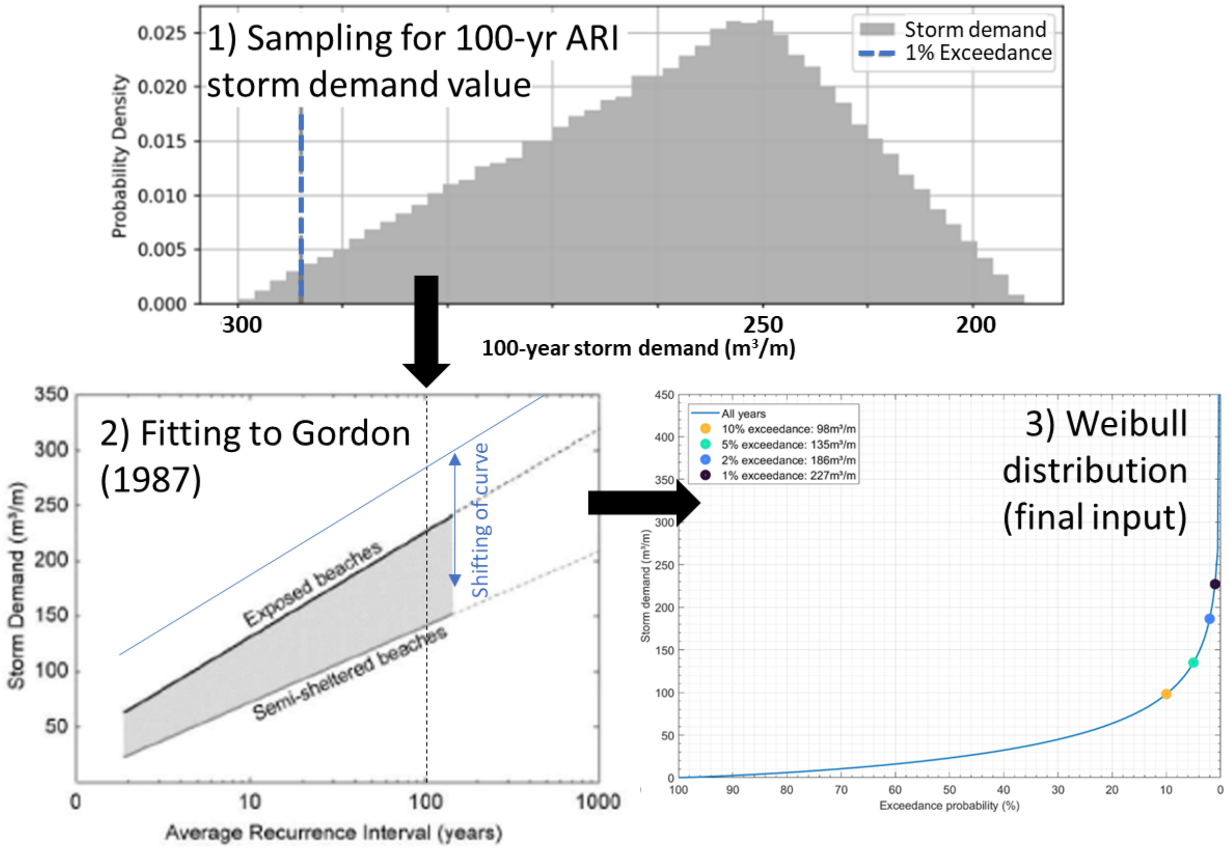


Figure 32: Example workflow for determining Weibull distribution of storm demand for a typical open beach (e.g., Wooyung Beach) as input to the erosion and recession hazard model.

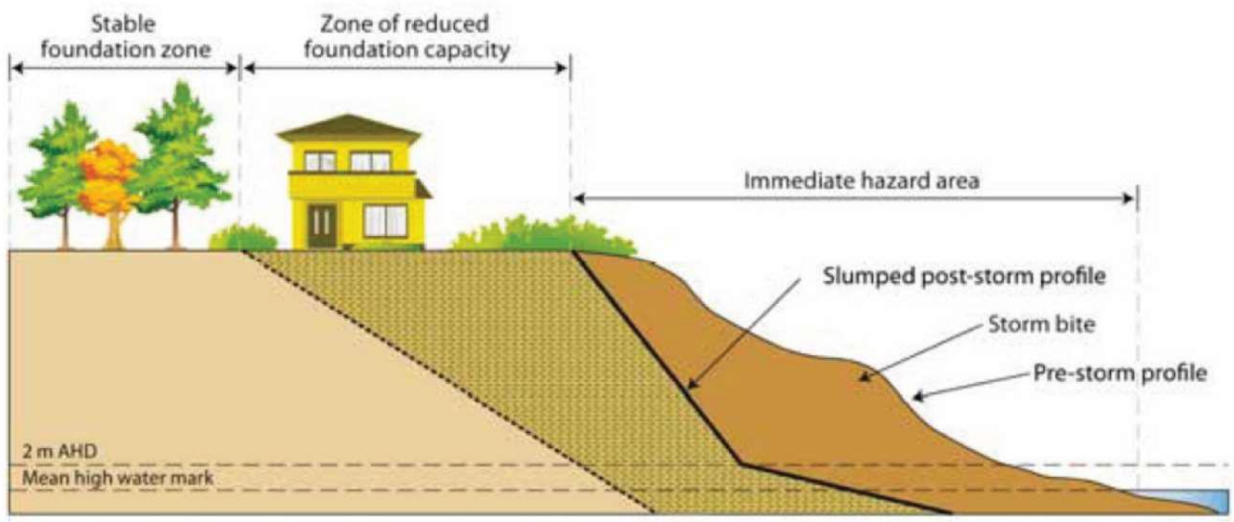


Figure 33: Wedge Failure Plane Model (NSW Coastal Risk Management Guide, 2010; after Nielson et al., 1992).

5.3.4 Sand budget allowances

Coastal profile response to long term trends and short-term variability in the Tweed Shire sand budget are a key input to the coastal erosion and recession hazard assessment. Consideration was given to the following processes:

- Long-term shoreline recession or accretion caused by sediment budget imbalances evident in historical data. For the Fingal Head to Point Danger compartment, the continuation of TSB operations was assumed.
- Shorter-term variability of the subaerial beach profile volume due to changes in headland bypassing, storm clusters, sand supply from lower shoreface, beach rotation and other processes linked to climate cycles.
- ‘Loss’ of marine sand from the active coastal zone due to tidal delta aggradation with sea level rise adjacent to estuary entrances in the Tweed Shire.

The adopted input values for these key sand budget allowances are further described in the following sections.

Long term beach volume trends

Long-term shoreline recession or accretion rates caused by sand budget imbalances have been determined based on the sand budget analysis (Section 4) as well as observations in subaerial beach volumes (photogrammetry) and mean annual shoreline positions (DEA coastlines), presented in **Appendix A**. For context, as described in Section 4.3.2, the sand budget analysis found a net (long-term) loss of sand of around 30,000m^3/year over the 30km of sandy beaches within the study area. As a regional average, this translates into a long-term volume change rate of around -1m^3/m/year across the full active coastal profile, or approximately -0.3 to -0.4m^3/m/year for the subaerial beach component only. This rate of sand loss varies alongshore and between beach compartments and multiple lines of evidence were used to inform the respective ranges adopted as input to the erosion and recession hazard model.

A summary of the range of long-term shoreline recession/ accretion rates (in units of subaerial profile volume change per metre per year) adopted in the erosion and recession hazard assessment in the form of triangular probability distributions is provided in Table 18. An example input probability distribution for a receding beach compartment (Kingscliff Beach) showing the full range of adopted input values for long-term beach volume trends is presented in Figure 34. Consistent with the presentation of results in Section 5.4, the values for the 1%, 2%, 5%, and 10% exceedance probabilities are provided as examples.

Table 18: Adopted input ranges for long term subaerial beach volume trends (recession/ accretion) in the erosion and recession hazard model.

Compartment	Beach	Long term subaerial volume change [min, mod, max] m^3/m/year	Comment
Wooyung to Pottsville	All beaches	-0.4, 0, +0.4	Beaches appear relatively stable. Adopted a range around zero to account for uncertainty in data quality. Lower range based on subaerial portion of regional average sand loss rate determined by sand budget analysis and ranges observed in photogrammetry data (see Section 4.3.2 and Appendix A).
Pottsville to Hastings Point	All beaches	-0.4, 0, +0.4	

Compartment	Beach	Long term subaerial volume change [min, mod, max] $m^3/m/year$	Comment
			BMT WBM (2013) also considered this section of coast to be reasonable stable but adopted a ‘best estimate’ recession rate of -0.05m/year (approx. -0.4m^3/m/year).
Hastings Point to Norries Headland	All beaches	-1.0, -0.7, -0.4	Beach appears to be receding. Adopted lower limit based on rates observed in photogrammetry data (Appendix A) and upper limit based on subaerial portion of regional average sand loss rate based on sand budget analysis. Modal value is mid-value between upper/ lower limits. BMT WBM (2013) previously adopted a range between -0.05 to -0.12m/year (~ -0.25 to -0.6m^3/m/year).
Norries Headland to Cudgen Headland	Cabarita Beach	-0.2, 0, +0.3	Beach appears relatively stable or accreting over longer term (high short term variability). Adopted a narrow range around zero to account for uncertainty in data quality but slightly skewed towards accretion based on observed behaviour (see Section 4.5.2 and Appendix A). BMT WBM (2013) also reported relative stability for this beach compartment but adopted a range of recession rates between -0.15 to -0.25m/year (~ -0.75 to -1.25m^3/m/year) to account for shorter term variability linked to ENSO (considered separately herein, refer Table 19).
	Bogangar and Casuarina Beaches	-0.2, 0, +0.3	As above. Although, this section of beach experiences less short term variability (considered in separate model input). BMT WBM (2013) previously adopted slightly lower rates compared to their Cabarita Beach range, with rates reduced by 0.025m/year for the central embayment and by 0.05m/year for the northern end.
	South Kingscliff Beach	-0.2, 0, +0.3	
Cudgen Headland to Fingal Head	Kingscliff Beach	-1.0, -0.7, -0.3 (p630 to p685, p696 to p793) -1.2, -0.9, -0.4 (p686 to p695)	Beach appears to be receding. Lower limit based on rates observed in DEA coastlines. Upper limit based on long term rate observed in photogrammetry data and regional sand budget. Modal value similar to BMT WBM (2013)’s best estimate (minimum/ maximum range -0.5 to -1m^3/m/year). Increased recession rates adopted for profiles within 200m of the northern end of

Compartment	Beach	Long term subaerial volume change [min, mod, max] $m^3/m/year$	Comment
			the Kingscliff seawalls. High short term variability at southern end of embayment.
	Dreamtime Beach	-0.7, -0.4, 0 (p794 to p889) -0.2, 0, +0.3 (p890 to p980)	Beach appears to be receding at the far southern end, becoming relatively stable or accreting to the north. Adopted a narrow range around zero in the north to account for uncertainty in data quality. Maximum range slightly skewed towards accretion based on observed behaviour (see Appendix A), however adopted conservative recession rates for more extreme probabilities in input distribution. Adopted value ranges agree well with estimated recession rates in BMT WBM (2013).
Fingal Head to Point Danger	Fingal Head Beach	0, 0, 0	Beach compartment in equilibrium with current TSB sand transfer activities and no net change observed in recent decade (Bluecoast, 2022). High short term variability at southern end of embayment linked to natural headland bypassing events (considered in separate model input). BMT WBM (2013) had previously adopted recession rates between -0.05 to -0.1m/year (~ -0.25 to -0.5m^3/m/year) for this section of coast.
	Letitia Beach	0, 0, 0	
	Duranbah Beach	0, 0, 0	As above, beach behaviour controlled by TSB operations. This beach was not included in BMT WBM (2013).

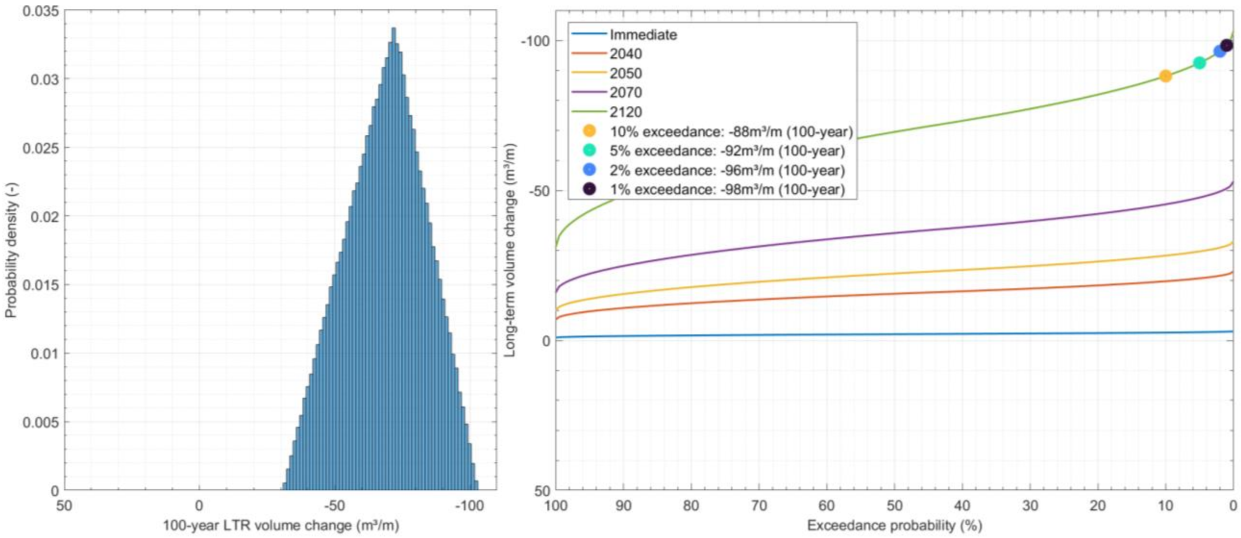


Figure 34: Example input triangular distribution (left) and associated cumulative distribution function (right) for long-term volume change for a receding beach (Kingscliff Beach).

Short term variability in beach volume

The sand budget analysis presented in Section 4 identifies observed short term changes in beach volumes that are influenced by various factors, such as the supply of sand due to processes like headland bypassing, beach rotation, storm clusters, offshore losses and other processes linked to climate cycles over timeframes from weeks to years. These fluctuations in beach volume are mainly observed at the southern areas of the various embayments (see Section 4.5.2) and have been taken into account in the coastal erosion and recession assessment. To account for future projections in climate variability influencing such beach volume fluctuations and associated uncertainty the range of beach volume fluctuation was increased for future planning periods. A 40% increase in the adopted short term subaerial beach profile volume variability by 2120 was applied to align with future projections of sediment transport variability due to climate change (e.g., Goodwin et al., 2016), refer Section 3.9 and 4.5.2.

For the purposes of the erosion and recession assessment, the effects of the abovementioned coastal processes are considered as a fluctuation in subaerial beach profile volume around the baseline profile (as described in Section 5.3.2). That is, the baseline beach profile is being "shifted" either seaward or landward based on the range of variability in profile volume that was adopted, whenever it is applicable. This allows accounting for the natural changes in beach volume that occur over periods from weeks to years and captures the uncertainty in the baseline profile. Notably, such short-term variations in beach profile volumes are considered independently from the effects of storm events. Additionally, for this assessment, this variability is treated as time-independent, meaning it is applied statistically each year without extending over consecutive years.

The adopted short term subaerial beach volume variability ranges and locations are provided in Table 19 with an example distribution for Kingscliff Beach presented in Figure 35.

Table 19: Adopted input ranges for short term beach volume variability in the erosion and recession hazard model.

Compartment	Beach	Short term subaerial volume variability relative to 2018 baseline [min, mod, max] m^3/m	Comment
Hastings Point to Norries Headland	Maggies Beach *Creek entrance to 700m north*	-80, 0, +100 (immediate) -100, 0, +120 (2070) -110, 0, +140 (2120)	Subaerial profile volume range between 2007 (highly accreted) to 2011 (highly eroded) relative to 2018.
Norries Headland to Cudgen Headland	Norries Cove	-100, -50, 0 (immediate) -120, -60, 0 (2070) -140, -70, 0 (2120)	Subaerial profile volume range between 2018 (highly accreted) to 2013 (highly eroded) relative to 2018. Modal value is mid-value between 2018 and 2013.
	Cabarita Beach	-100, 0, +120 (immediate) -120, 0, +140 (2070) -140, 0, +170 (2120)	Subaerial profile volume range between 2010 (highly accreted) to 2016 (highly eroded) relative to 2018.
Cudgen Headland to Fingal Head	Kingscliff Beach *Northern training wall to Bowls Club seawall* (p630 to p740)	-250, -125, 0 (immediate) -300, -150, 0 (2070) -350, -175, 0 (2120)	Subaerial profile volume range between 2018 (highly accreted) to 2011 (highly eroded) relative to 2018. Modal value is mid-value between 2018 and 2011.
Fingal Head to Point Danger	Fingal Head Beach	-120, 0, +50 (immediate) -140, 0, +60 (2070) -170, 0, +70 (2120)	Subaerial profile volume range between 2020 (highly accreted) to 2013 (highly eroded) relative to 2018.

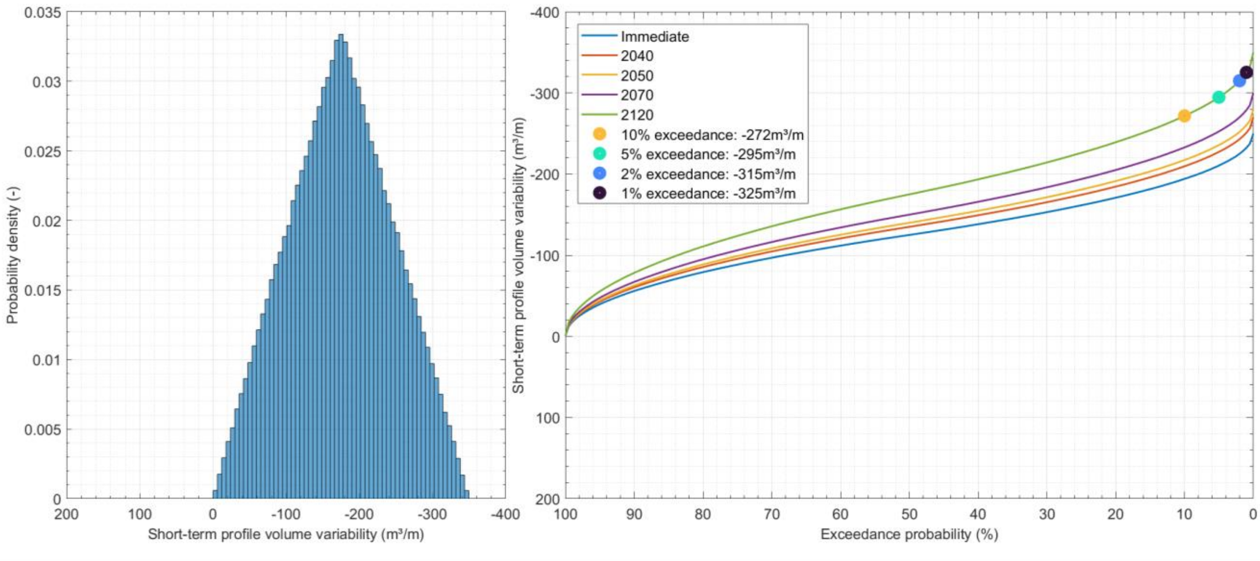


Figure 35: Example input triangular distribution (left) and associated cumulative distribution function (right) for short-term profile variability (Kingscliff Beach).

Change in onshore sand supply

As described in Section 4.5.3, at present, an onshore sand supply from the lower to upper shoreface likely occurs along all beaches in the study area. This contributes to the nearshore sand budget and is captured in historic observed beach behaviour.

For the Norries Headland to Cudgen Headland compartment, a relatively higher rate of onshore sand transport was estimated due to the influence of a relic shelf sand body. Rising sea levels or depleting sand volumes may alter the current onshore supply from such offshore sand resources. With uncertainty in the future sand supply via this pathway, an allowance for changes in the long-term rate of sand transport has been included in the erosion and recession hazard assessment (see Table 20). This included a range of change in onshore sand supply to the subaerial beach using a triangular probability distribution as follows:

- No change to the rate of onshore sand supply for the immediate planning period.
- Uncertainty range increased for later planning periods due to limited knowledge of the offshore shelf sand body and future change to upper shoreface sand supply rate with sea level rise. The lower limit for the range of onshore sand supply rates was modified so that the total long term beach volume change (excluding sea level rise effects) for the respective compartment is more closely aligned with neighbouring beaches (e.g. Cabarita Beach would convert from a stable to net receding beach).
- Linear interpolation of adopted value ranges between time periods presented in Table 20.

The input probability distribution showing the full range of adopted input values for the change in onshore sand supply is shown in Figure 36. Consistent with the presentation of results in Section 5.4, the values for the 1%, 2%, 5%, and 10% exceedance probabilities are provided as examples.

Table 20: Adopted input ranges for triangular distribution of changes to onshore sand supply in the erosion and recession hazard model.

Compartment	Beach	Change in onshore sand transport rate (m^3/m/year) [min, mod, max]
Norries Headland to Cudgen Headland	Cabarita Beach	0, 0, 0 (immediate)
	Bogangar and Casuarina Beaches	-0.4, 0, +0.4 (2070)
	South Kingscliff Beach	-0.8, 0, +0.8 (2120)

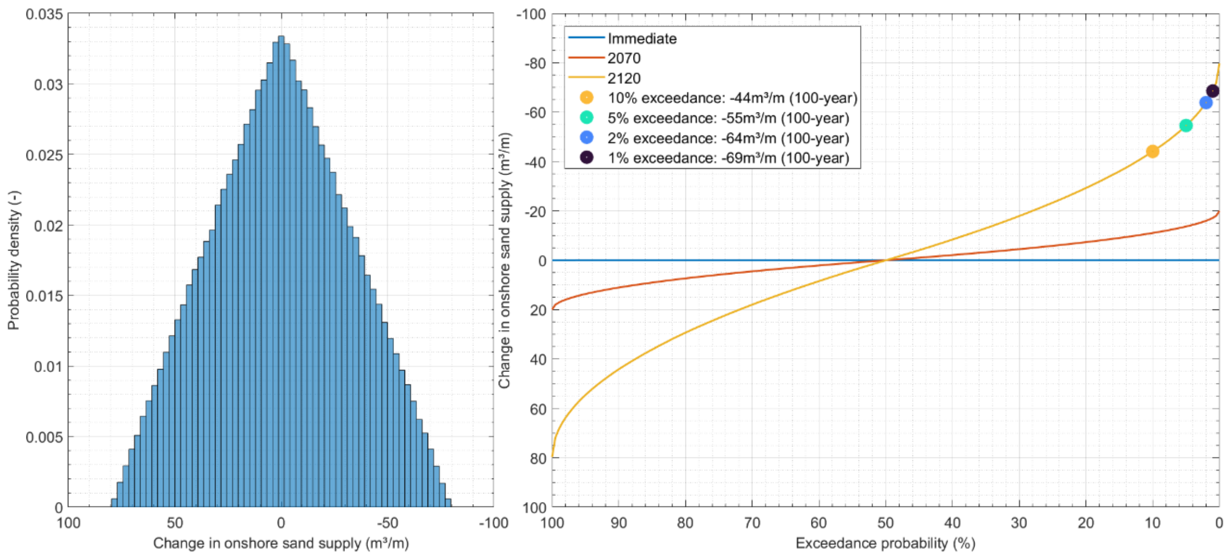


Figure 36: Example input triangular distribution (left) and associated cumulative distribution function (right) for change in onshore sand supply for Norries Headland to Cudgen Headland.

Estuaries

As described in Section 4.5.8, a net 'loss' of marine sand from the active coastal zone due to flood tide delta aggradation at estuary entrances with sea level rise will likely result in some recession of adjacent beaches. The sand volume losses are considered in the coastal erosion and recession hazard model in a simplistic way by multiplying the active submerged flood delta area by the projected sea level rise, after Kinsela et al. (2016). The profile volume reduction is applied to each of the analysis beach profiles within adjacent updrift and downdrift compartments of the estuary entrances, except the Tweed River where any adjacent beach compartments are controlled by TSB operations. For example, a 0.5m sea level rise over a 50,000m^2 flood tide delta area would equate to a 25m^3/m sand volume loss along a 1,000m stretch of beach.

The adopted active submerged flood delta area for each estuary and length of affected sandy beach adjacent to estuary entrance are provided in Table 21. The approximate active flood tide delta area (including entrance berm) was estimated based on recent and historical aerial imagery (see Figure 37). For example, active flood tide delta area for Mooball Creek was estimated to extend from the entrance training walls to near the Tweed Coast Road bridge. The approximated area was applied as the modal value for a triangular distribution with a ±20% uncertainty range.

Table 21: Proposed ranges of active flood tide delta areas in square metres (m^2).

Estuary	Min	Mode	Max	Alongshore length of affected beach (m) (profile #)	Example profile volume loss range (m^3/m) for 0.50m SLR [min, mod, max]	Comment
Mooball Creek	40,000	50,000	60,000	1,000 (p237 – p256)	20, 25, 30	Estimated active flood tide delta area from aerial imagery.
Cudgera Creek	48,000	60,000	72,000	800 (p313 – p351)	30, 37.5, 45	
Cudgen Creek	40,000	50,000	60,000	1,250 (p611 – p665)	16, 20, 24	

Figure 37: Flood tide delta areas (black hashed area) and affected beach (blue line) for Mooball (left), Cudgera (middle) and Cudgen (right) Creek.

5.3.5 Sea level rise recession

Coastal profile adjustments due to SLR are assessed using a volumetric approach following the principles in Bruun (1962, 1986). This considers an upward and landward shift of the equilibrium profile with SLR. The active volume of sand that is redistributed by this process is limited to the profile part between the active dune height and the depth of closure. The depth of closure describes the seaward limit of the active zone of sediment transport. This depth depends on the timescale of interest, with the inner depth of closure representative of the seaward limit of the littoral transport zone, where there is no significant change in seabed elevation, on a yearly timescale. A conceptual diagram describing the adopted approach to estimating the profile response to SLR is provided in Figure 38.

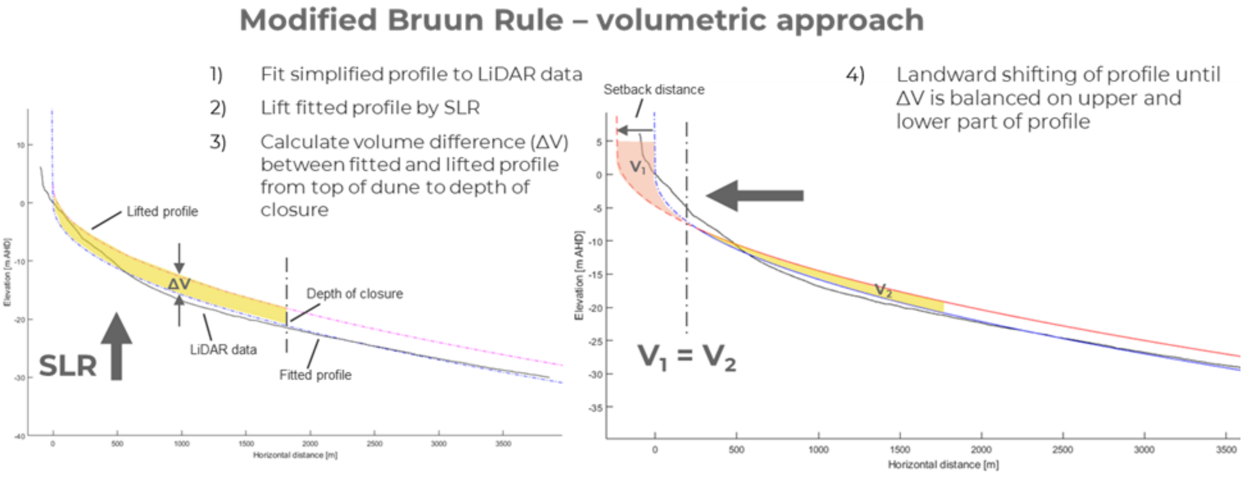


Figure 38: Diagram describing adopted sea level rise recession calculation.

The adopted SLR distribution is based on the IPCC AR6 projection for Brunswick Heads (Garner et al., 2021) presented in Table 10 for five example time periods. Brunswick Heads was chosen for this analysis as the SLR projection values were marginally larger (i.e., more conservative) than the values at the closest other SLR projection site at Tweed Heads. It is worth noting that the 2100 value adopted by BMT WBM (2013) of 0.84m is well below the 95th percentile value adopted here (1.33m). The full distribution for every year in the planning periods was established by fitting a Weibull distribution[6] to the quantiles extracted from the IPCC AR6 projections (Table 10) to extrapolate to higher and lower quantiles. The adopted SLR values relative to the 2018 baseline (Section 5.3.2) is provided in Table 22. An example input probability distribution for year 2120 is shown in Figure 39. Consistent with the presentation of results in Section 5.4, the values for the 1%, 2%, 5%, and 10% exceedance probabilities are provided as examples.

Table 22: Adopted input values for sea level rise (m) values based in the erosion and recession hazard model.

Beach	Exceedance probability (%)	2040	2050	2070	2120
All beaches	**1**	0.17	0.30	0.63	1.95
	2	0.16	0.28	0.60	1.82
	5	0.15	0.26	0.55	1.62
	10	0.14	0.24	0.50	1.44

[6] Adopted Weibull fit parameters are *scale = 1.3625* and *shape = 2.1781*

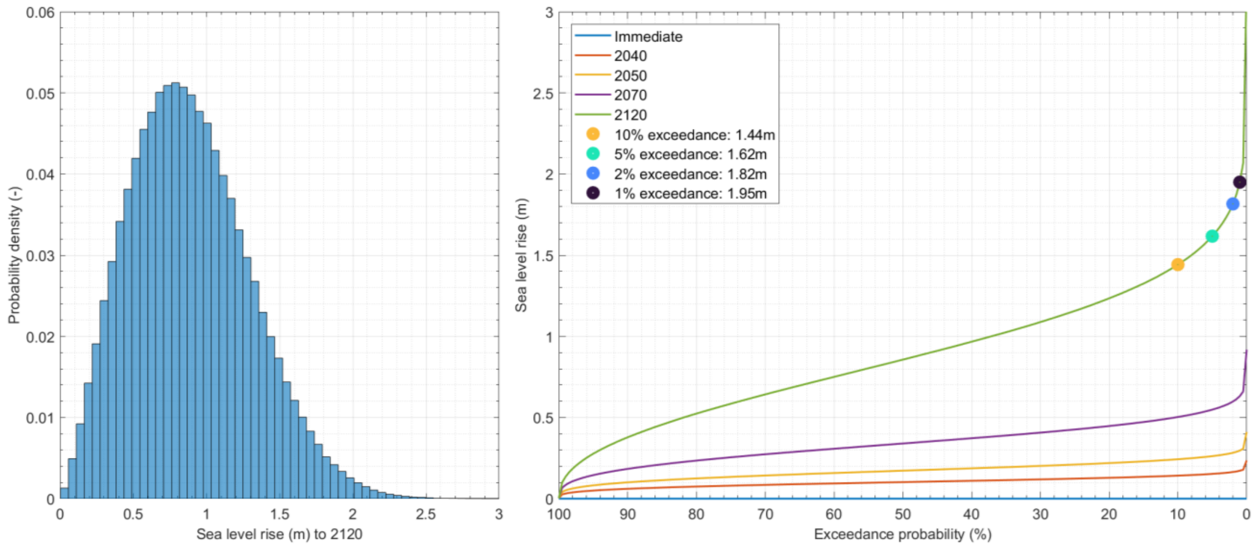


Figure 39: Example of adopted Weibull distribution (left) and associated cumulative distribution function (right) fitted to IPCC AR6 sea level rise projections for year 2120.

The adopted depth of closure values used to generate triangular probability distributions as input to the SLR recession calculation are presented in Table 23. The local depth of closure values were determined following consideration of the following data sources:

- Available coastal profile data (e.g., 2011 and 2018 LiDAR bathymetry datasets) and associated profile shape.
- The seaward extent of the outer nearshore sand area (PWD, 1987) as a representation of the active profile extent (see Section 3.1.3).
- Inner and outer depth of closure values calculated using the Hallermeier (1983) method and nearshore wave data from the NSW Nearshore Wave Tool (MHL).
- Previous studies in the region such as BMT WBM (2013) and Bluecoast (2022).

A triangular distribution for depth of closure value range was adopted to represent the seaward limit of the active beach profile over the adopted planning periods and associated uncertainty. Modal values were taken as the best estimate of the depth of closure based on the above data sources, with a ±15 to 20% range applied to determine the minimum and maximum values for the triangular distribution.

Depth of closure was found to be similar at all 'open coast' beaches with similar wave exposure and active profiles, including all beaches between Wooyung and Hastings Point, Maggies Beach to South Kingscliff Beach (Cudgen Headland), Dreamtime Beach, Letitia Beach and Duranbah Beach. For more sheltered beaches (Hastings Point, Kingscliff Beach, Fingal Head Beach) in the lee of extensive offshore reef and/or headlands, a reduced depth of closure modal value was adopted. An example input distribution for depth of closure values at an open beach is presented in Figure 40.

For all beaches, the adopted modal value for closure depth was between 18 and 24m. This compares well with previous studies in the region, such as approximately 20m on the northern Gold Coast (Patterson & Nielson, 2016), 20 to 24m on the Illawarra coast (Kinsela et al., 2022), approximately 22m used previously for the Tweed Shire Coast (BMT WBM, 2013) and 16 to 20m at Letitia Beach (Bluecoast, 2022).

Table 23: Estimated depth of closure values for Tweed Shire beaches.

<table>
<tr><th rowspan="2">Location</th><th colspan="2">Calculated Hallermeier (1983) closure depths</th><th>Estimated from 2011 and 2018 survey profiles</th><th>Adopted closure depth [min, mod, max]</th><th rowspan="2">Comments</th></tr>
<tr><th>Inner (m)</th><th>Outer (m)</th><th>(m below AHD)</th><th>(m)</th></tr>
<tr><td>‘Open coast’ Beaches
Wooyung Beach to Cudgera Beach
Maggies Beach to South Kingscliff Beach
Dreamtime Beach
Letitia Beach to Duranbah Beach</td><td>6 to 7</td><td>26 to 27</td><td>17 to 22</td><td>18, 22, 26</td><td>Modal value for ‘open coast’ beaches aligns with previous studies (BMT WBM, 2013) and approximate seaward extent of outer nearshore sand (PWD, 1978) with ±15% uncertainty range.</td></tr>
<tr><td>Hastings Point</td><td>7</td><td>29*</td><td>20</td><td>16, 20, 24</td><td>Reduced exposure due to offshore reefs and Hastings Point headland. Adopted modal value estimated from beach profile shape with ±20% uncertainty range.</td></tr>
<tr><td>Kingscliff Beach</td><td>6</td><td>24</td><td>18</td><td>8, 10, 12 (p630 to p724)
12, 14, 16 (p725 to p740)
14, 18, 22 (p741 to p793)</td><td>Values derived from repeat bathymetry survey, interpretation of profile slopes and geology.
Depth of active profile influenced by presence of offshore reefs, Cudgen Headland and embayment planform.</td></tr>
<tr><td>Fingal Head Beach</td><td>8</td><td>30*</td><td>16 to 20</td><td>16, 20, 24</td><td>Reduced exposure due to offshore reefs and Fingal Head.
Adopted modal value estimated from beach profile shape and previous study (Bluecoast, 2022) with ±20% uncertainty.</td></tr>
</table>

Note: *Nearshore wave data appears to overestimate wave exposure at headland and reef locations (see **Appendix A** for wave exposure) resulting in an overestimate of the Hallermeier (1983) depth of closure. For these locations, modal depth of closure was weighted more strongly to the survey data and previous studies.

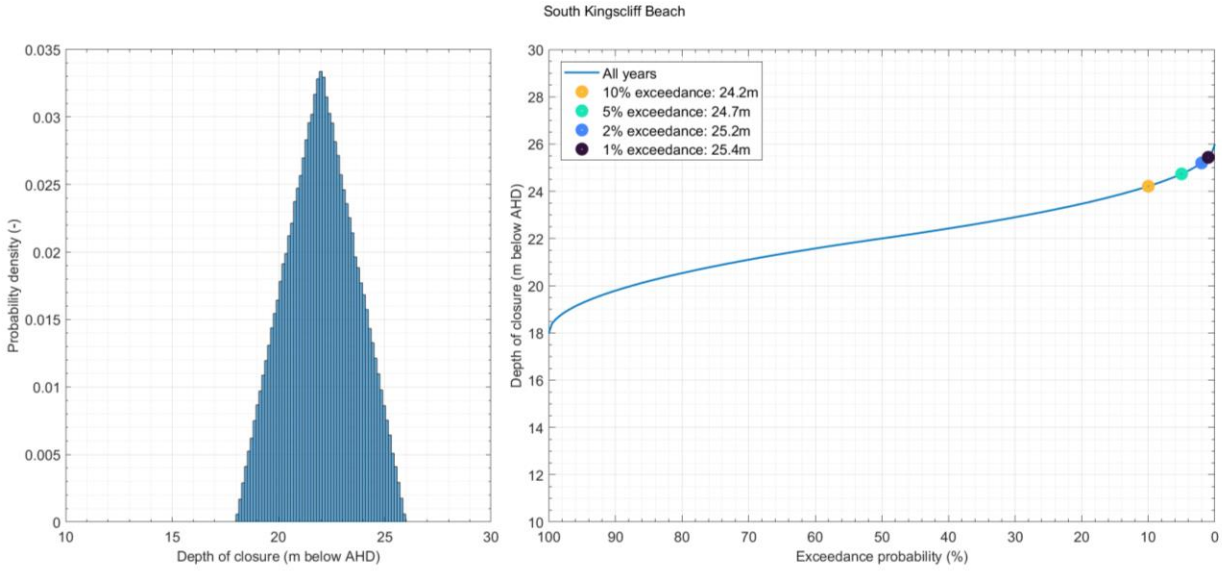


Figure 40: Example input distribution for depth of closure (South Kingscliff Beach).

5.3.6 Coastal structures

In general, protective structures would be expected to limit (either entirely or partially) the amount of erosion landward of the structures including during extreme events. The ability of the existing protective structures to limit the amount of landward erosion that occurs during extreme erosion events would depend on the structure type, design standard and structural and functional condition of the structure (now and in the future).

Various types of seawalls and revetments exist along the Tweed Shire coast, particularly at Kingscliff Beach, refer to Section 4.5.6. Table 24 provides a summary of the existing coastal protection structures along the Tweed Shire coast and their assumed design standards. Figure 41 shows the location and structure group (engineering standard) of the structures at Kingscliff Beach.

As described in Section 4.5.6, seawalls and revetments can locally increase the erosion and recession hazard at adjacent sections of beach. Where relevant, this has been considered separately in the adopted long term beach volume trends presented in Table 18.

Table 24: Existing coastal protection structures included in the coastal erosion and recession hazard assessment.

Structure group	Locations	Comment
Category 1 – engineered seawall	• Kingscliff Beach Holiday Park • Kingscliff Bowls Club • Cudgen Headland SLSC, Kingscliff	Rock and concrete structures designed to engineering standard. These structures are considered non erodible for this hazard assessment.
Category 2 – engineered structure with low design standard	• Faulks Park, Kingscliff (between Cudgen Creek training walls and Cudgen Headland SLSC)	Includes geotextile sand container (geobags) revetments and rock structures with low design life. These structures are considered fully erodible as part of this hazard assessment.

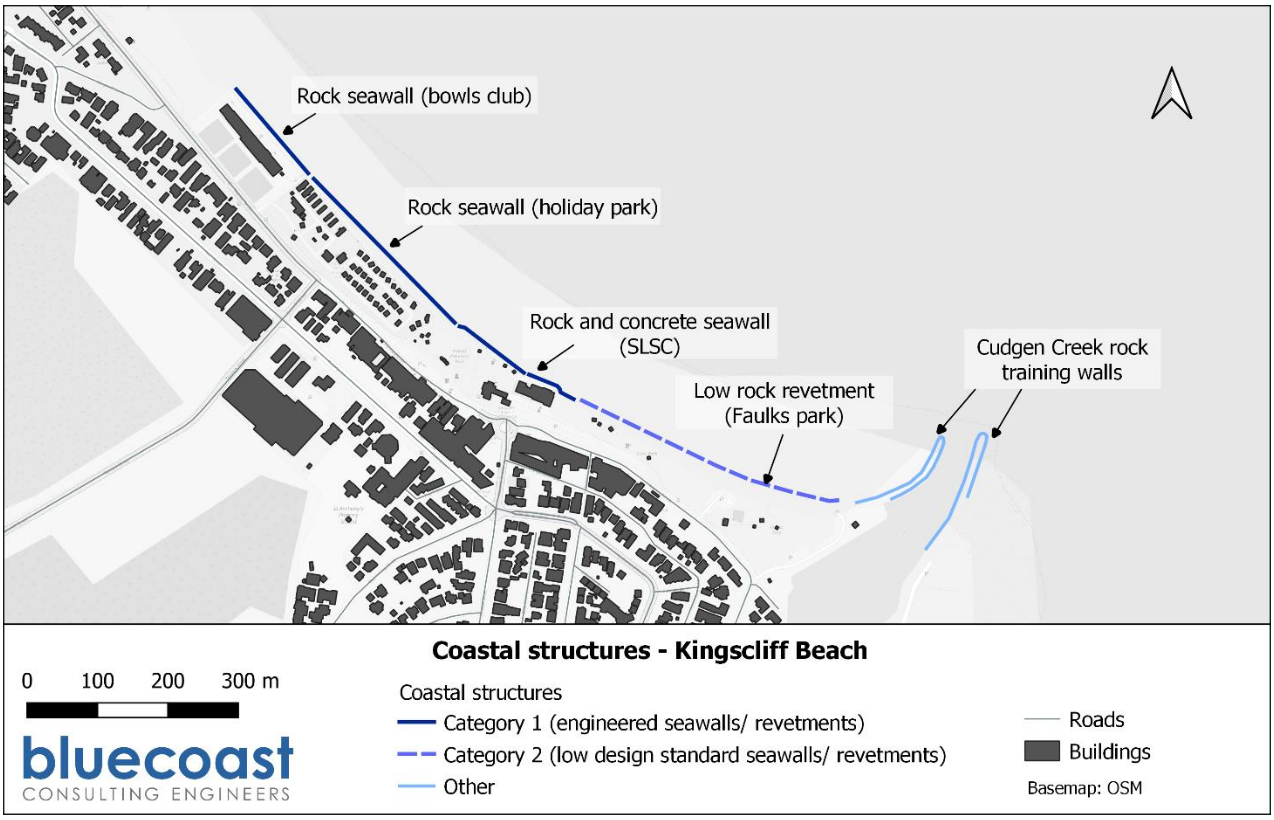


Figure 41: Map of existing coastal structures at Kingscliff Beach.

This coastal erosion and recession hazard assessment considers the category 1 coastal structures as non-erodible for this hazard assessment, limiting the landward extent of the coastal erosion and recession hazard. For comparison purposes, however, separate hazard assessment results are provided for the case where these structures are no longer present (i.e., fully erodible).

For areas downdrift of the Kingscliff seawalls (north of bowls club), the erosion and recession rates are likely to be higher due to seawall end effects from reduced sand supply (NSW Coastal Panel, 2011). These end effects have been applied to the sand budget allowances in this hazard assessment (see Section 5.3.4) within 200m of the end of the seawall.

5.3.7 Substrate effects

The presence of shallow/ outcropping bedrock within the coastal profile is evident along parts of the Tweed Shire coast (see Section 3.1 and Section 4.5.7). This bedrock can provide a level of erosion resistance dependent on the coverage of bedrock in the beach profile. The effect of substrate was considered in determining the erosion and recession hazard extents on sandy coastlines along the Tweed Shire coast. Note that the headlands in the study area have been considered separately in Morrison Geotechnic (2021).

Where shallow or outcropping bedrock are known to be present within the dune face, upper beach or surf zone a reduction in the storm erosion volumes has been applied in the probabilistic model. Given the uncertainty in the level of erosion resistance, a triangular distribution for a range of reduction ‘factors’ was used (see Figure 42) based on the values presented in Table 25. An example input probability distribution showing the full range of adopted input values of reduction ‘factors’ is presented in Figure 42. Consistent with the presentation of results in Section 5.4, the values for the 1%, 2%, 5%, and 10% exceedance probabilities are provided as examples. The adopted input range was determined from an analysis of the known hard substrate extent along each affected cross-shore profile. The maximum extent of hard substrate across the active profile was approximately 40% for beach profiles (near Hastings Point and South Kingscliff Beach) but closer to 20% in most cases. The erosion limiting factors were considered as follows:

- Scaling of the erosion volumes was applied to all beach profiles within areas where there is evidence for the presence of shallow or outcropping bedrock based on regional geology data, previous reports and review of aerial imagery (see Figure 43).
- Where there is evidence of nearshore reefs, this was accounted for in the calculation of sea level rise profile adjustments (see Section 5.3.5). This was adopted in consideration of the reduced accommodation volume for sand being exchanged across the shoreface (Woodroffe et al., 2012). Similar to the scaling of the storm erosion volumes, the reduction factors in Table 25 have been applied to reduce the respective profile volume allowances. This scaling was applied to all beach profiles within areas where there is evidence for the presence of nearshore reefs based on regional geology data, previous reports and review of aerial imagery (see Figure 43).

Table 25: Adopted coastal response scaling factors for substrate effects.

Probability distribution parameter	Erosion/recession reduction factor (-)
Minimum	0.6
Mode	0.8
Maximum	1.0 (no effect)

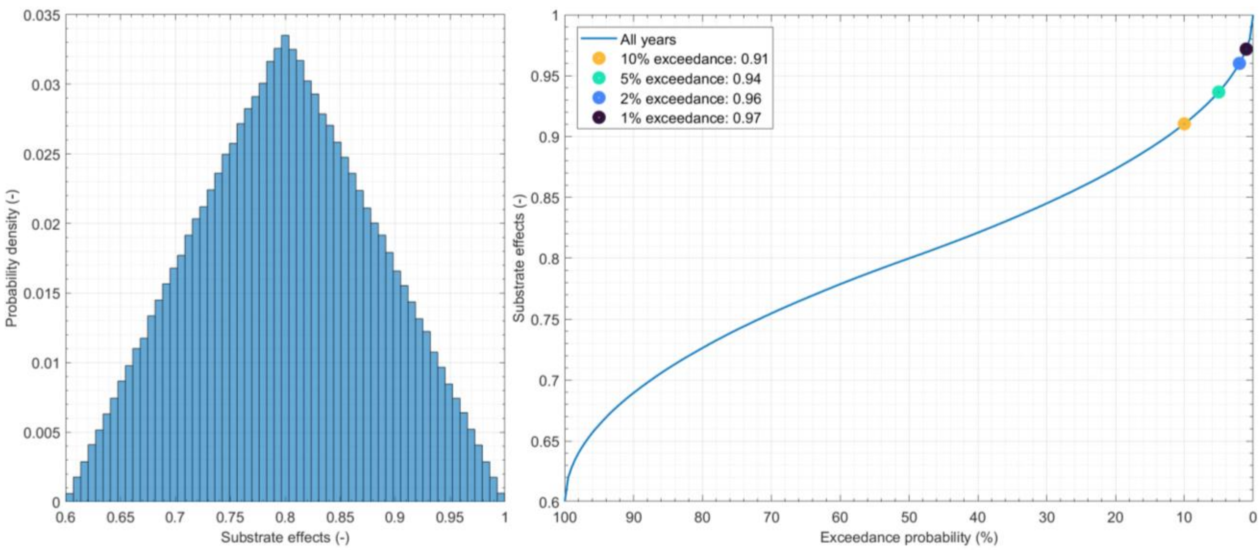


Figure 42: Input triangular distribution (left) and associated cumulative distribution function (right) of reduction 'factors' for substrate effects.

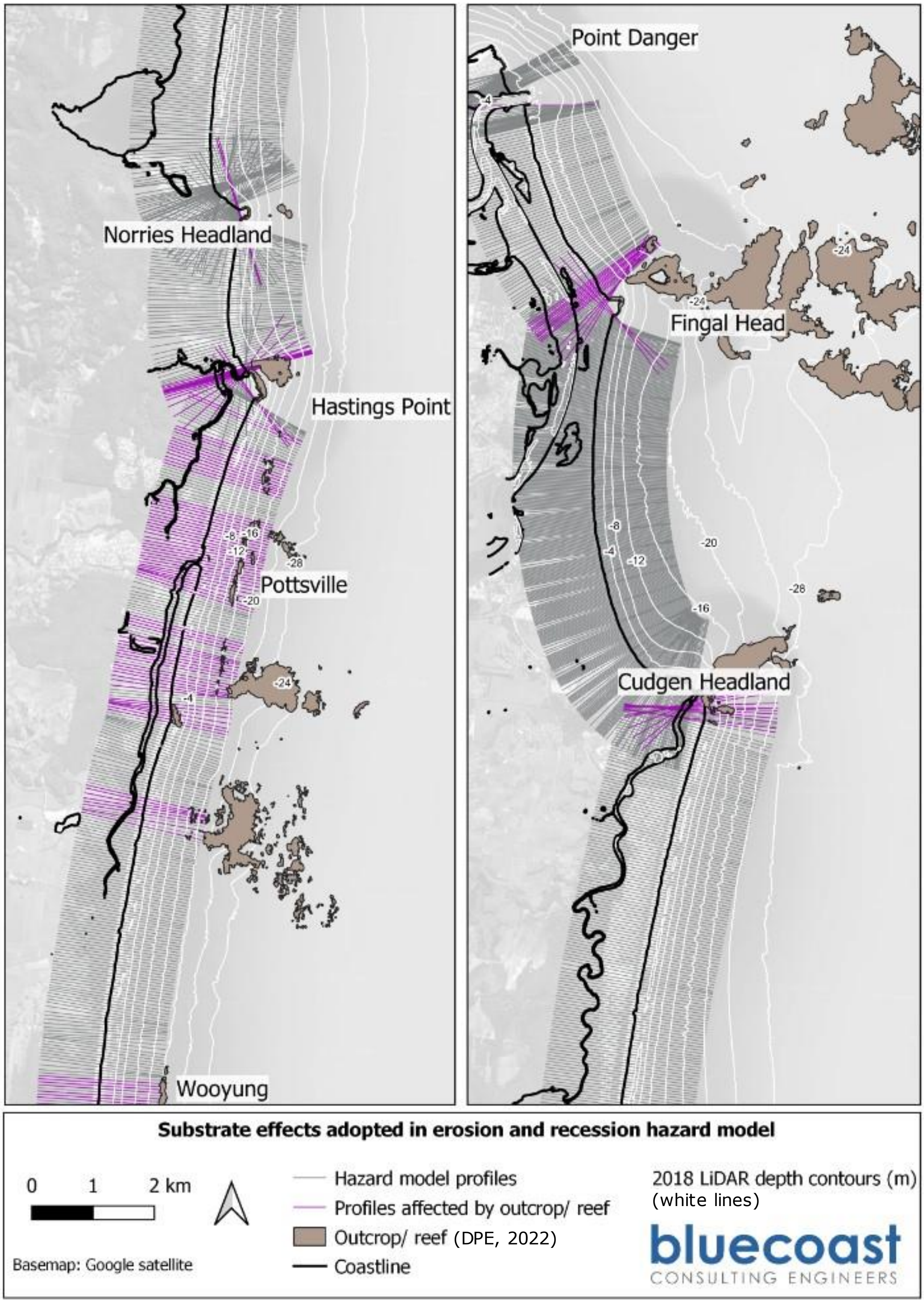


Figure 43: Adopted extents of shallow bedrock and reefs in the erosion and recession hazard model.

5.3.8 Summary of inputs

Individual probability distributions for representative sections of beach and, where required, across different time periods were defined as input to the probabilistic coastal erosion and recession hazard assessment. A summary of the adopted inputs is provided below and in Table 26.

- Long-term subaerial volume change - triangular distribution for long-term shoreline recession or accretion rates (m^3/m/year) based on sand budget analysis as well as review of photogrammetry beach profile and satellite derived shoreline data. Where relevant, recession rates have been increased by 25% to account for end effects immediately downdrift of existing seawalls (i.e., Kingscliff).
- Storm erosion volume - Weibull distribution for storm demand volumes (m^3/m) generated from a triangular distribution of estimated 100-year ARI value range based on photogrammetry data analysis and Gordon (1987).
- Sea level rise recession rates (m^3/m/year) were based on a modified Bruun rule using:
    - Sea level rise - Weibull distribution for sea level rise values (m) based on the IPCC AR6 projections.
    - Depth of closure - triangular distribution for depth of closure values informed by Hallermeier (1983) calculations, review of sediment characteristics and surveyed beach profiles.
- Change in onshore sand transport - triangular distribution for changes in the contemporary long-term rate of onshore sand transport has been included at sections of beach influenced by the presence of large shelf sand bodies. For later planning periods an uncertainty range is used which either increases or decreases this sand supply rate accounting for limited knowledge in potential changes to this sand transport pathway.
- Short-term variability in profile volume - triangular distribution for short-term variability in the subaerial beach volume (m^3/m) based on sand budget analysis. Potential future changes to the sand budget associated with climate change are considered in this profile volume variability for later planning periods.
- Substrate scaling - triangular distribution for scaling factors to be applied to the storm demand volumes (where non/less erodible substrate exists in upper beach/dune face) and calculation of sea level rise recession (where nearshore reefs occupy the beach profile) at relevant beach sections in the study area.
- Estuary sink - triangular distribution for sand volume losses (m^3/m) at beaches adjacent to coastal entrances due to flood tide delta aggradation with sea level rise. Adopted values based on an assessment of the active flood tide delta area (m^2) for each estuary in the study area multiplied by sea level rise (Weibull distribution – as above). A ±20% uncertainty range was used to create the triangular distribution of flood tide delta area inputs. This sand volume loss was applied to an alongshore section of beach determined based on a review of historic entrance behaviour and satellite derived shoreline data.

Table 26: Summary of adopted inputs (minimum, modal, maximum) for the erosion and recession hazard assessment.

Compartment	Beach (profile #)	Long-term subaerial volume change m^3/m/year	100-year ARI storm erosion volume range m^3/m	Depth of closure range m	Change in onshore transport rate m^3/m/year	Short-term variability in profile volume m^3/m	Substrate scaling factors -	Estuary sink – active delta area/ length of beach section (profile #) m^2/m
Wooyung to Pottsville	All beaches (p1 to p247)	-0.4, 0, +0.4	150, 200, 250	18, 22, 26	*not applicable*	0, 0, 0	0.6, 0.8, 1.0	*not applicable*
Pottsville to Hastings Point	All beaches (p248 to p312)	-0.4, 0, +0.4	150, 200, 250	18, 22, 26	*not applicable*	0, 0, 0	0.6, 0.8, 1.0	40, 50, 60 (p248 – p256)
Hastings Point to Norries Headland	Hastings Point (p313 to p341)	-1.0, -0.7, -0.4	200, 250, 300	16, 20, 24	*not applicable*	-80, 0, +100 (immediate) -100, 0, +120 (2070) -110, 0, +140 (2120)	0.6, 0.8, 1.0	60, 75, 90 (p313 – p341)
	Maggies Beach (p342 to p392)	-1.0, -0.7, -0.4	200, 250, 300	18, 22, 26		0, 0, 0	*not applicable*	60, 75, 90 (p341 – p351)
Norries Headland to Cudgen Headland	Cabarita Beach (p393 to p458)	-0.2, 0, +0.3	125, 200, 250	18, 22, 26	0, 0, 0 (immediate) -0.4, 0, 0.4 (2070) -0.8, 0, 0.8 (2120)	-100, 0, +120 (immediate) -120, 0, +140 (2070) -140, 0, +170 (2120)	*not applicable*	*not applicable*

Compartment	Beach (profile #)	Long-term subaerial volume change m³/m/year	100-year ARI storm erosion volume range m³/m	Depth of closure range m	Change in onshore transport rate m³/m/year	Short-term variability in profile volume m³/m	Substrate scaling factors -	Estuary sink – active delta area/ length of beach section (profile #) m²/m
	Bogangar Beach (p459 to p483)	-0.2, 0, +0.3	150, 200, 250	18, 22, 26	0, 0, 0 (immediate) -0.4, 0, 0.4 (2070) -0.8, 0, 0.8 (2120)	0, 0, 0	*not applicable*	*not applicable*
	Casuarina Beach (p484 to p529)		150, 200, 250			0, 0, 0	*not applicable*	*not applicable*
	South Kingscliff Beach (p530 to p629)		200, 250, 300			0, 0, 0	0.6, 0.8, 1.0	32, 40, 48 (p611 – p622)
Cudgen Headland to Fingal Head	Kingscliff Beach (p630 to p793)	-1.0, -0.7, -0.3 -1.2, -0.9, -0.4 (p686 to p695)^	150, 200, 250	8, 10, 12 (p630 to p724) 12, 14, 16 (p725 to p740) 14, 18, 22 (p741 to p793)	*not applicable*	-250, -125, 0 (immediate) -300, -125, 0 (2070) -350, -175, 0 (2120) (p630 to p740 only)	0.6, 0.8, 1.0	32, 40, 48 (p633 to p665)
	Dreamtime Beach (p794 to p980)	-0.7, -0.4, 0 (p794 to p889) -0.2, 0, +0.3 (p890 to p980)		18, 22, 26		0, 0, 0	*not applicable*	*not applicable*

Compartment	Beach (profile #)	Long-term subaerial volume change m³/m/year	100-year ARI storm erosion volume range m³/m	Depth of closure range m	Change in onshore transport rate m³/m/year	Short-term variability in profile volume m³/m	Substrate scaling factors -	Estuary sink – active delta area/ length of beach section (profile #) m²/m
Fingal Head to Point Danger	Fingal Head Beach (p981 to p1026)	0, 0, 0	125, 200, 250	16, 20, 24	*not applicable*	-120, 0, +50 (immediate) -140, 0, +60 (2070) -170, 0. +70 (2120)	0.6, 0.8, 1.0	*not applicable*
	Letitia Beach (p1027 to p1083)		150, 200, 250	18, 22, 26		0, 0, 0	*not applicable*	*not applicable**
	Duranbah Beach (p1084 to p1122)		200, 250, 300	18, 22, 26		0, 0, 0	*not applicable*	*not applicable**

Note: *Tweed River estuary sink not considered due to ongoing TSB operations. ^Increased by 25% for end effects along 200m beach section downdrift of Kingscliff seawalls.

5.4 Results

The probability of exceedance of the landward position of the Zone of Reduced Foundation Capacity (ZRFC) was determined based on the several million results produced for each year of the adopted planning periods. The following results from the erosion and recession hazard assessment are provided:

- The probabilistic hazard model results are presented as a series of maps in the map compendium of this report. The probability exceedance curves for each beach section are provided in **Appendix B**.
- By exception, at southern Kingscliff (between Cudgen Creek and Surf Club) and Duranbah Beach, the results present the Zone of Slope Adjustment (ZSA, instead of ZRFC) due to the steep bedrock topography. For these locations, calculation of the ZRFC is not valid and would result in unrealistic mapping of the hazard extents. Where regional geology data (or other evidence) suggests that erosion and recession may be limited by hard substrate, the actual hazard extents are subject to confirmation through site-specific geotechnical assessment (as shown in map compendium in Section 9).
- GIS layers indicating the landward extent of the erosion and recession hazard for the above exceedance probabilities and planning timeframes have been produced and provided in digital format.

The probabilistic coastal erosion and recession hazard assessment suggests that public and private assets are located within the immediate hazard extent at Kingscliff Beach and Fingal Head Beach at the holiday park. By 2120, the hazard extents would affect a considerably larger number of additional public and private assets and foreshore area including assets at Pottsville Beach (north), Hastings Point, Cabarita Beach, Casuarina Beach to South Kingscliff, Kingscliff Beach, Dreamtime Beach and Fingal Head Beach. A detailed asset exposure and risk assessment, including possible consequences, has been completed and is presented in Section 8.

6. Coastal inundation assessment

6.1 Overview

In line with the NSW Coastal Management Manual Part B (the Manual), a coastal inundation hazard assessment for the Tweed Shire coastline was undertaken.

The coastal inundation assessment is limited to the storm-related flooding by seawater due to elevated ocean water levels (storm surge) and wave processes (see Figure 44) along the open coast. Coastal inundation, as an action of the sea, is distinguished from more traditional definitions of flooding which are typically associated with rainfall and runoff (i.e., freshwater flooding). Flooding from rainfall and catchment runoff within the Tweed Shire is not included in this assessment and has been previously assessed in relevant catchment flood studies. A tidal inundation assessment for the Tweed Shire’s estuaries has been undertaken in Section 7.3 and in BMT (2019). Inundation around the estuaries as a result from combined tide and storm surge levels (storm tide) are discussed in Section 7.3.3.

The two main components that contribute to the coastal inundation hazard are:

- a ‘quasi-static’ component (tide, storm surge and wave setup)
- a wave-driven ‘dynamic’ component (wave runup, overwash and overtopping).

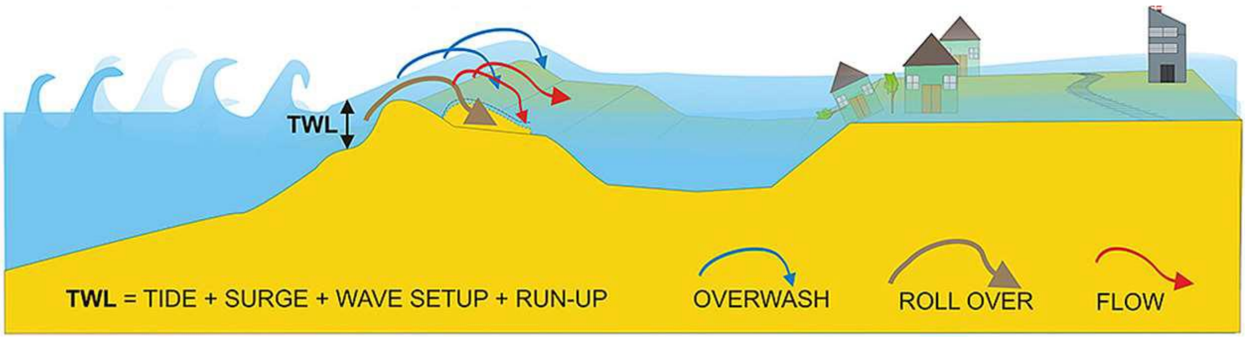


Figure 44: Schematic showing combined inundation by the total water level (TWL) comprising the 'quasi-static' and 'dynamic' components (source: Fernandez-Montblanc et al., 2020).

A high-level first-pass coastal inundation hazard assessment has been completed for the entire Tweed Shire open coast. This includes identifying areas potentially exposed to coastal inundation based on calculation of total water level derived using empirical formulae for wave runup levels for regular shore-normal coastal profiles along the entire Tweed Shire coast. A previous study by BMT WBM (2013) identified Kingscliff Beach, Fingal Head Beach and lower dune crest between Norries Headland and Cudgen Headland as regions where coastal inundation may occur.

For areas that are identified to be potentially exposed to coastal inundation, it is recommended that a detailed assessment be undertaken. A suitable assessment methodology would allow to better predict the landward extent (and depth) of the coastal inundation hazard for current and future scenarios.

6.2 Approach

The total water levels for the first-pass coastal inundation assessment are determined using the following data sources:

- 24-year hindcast of nearshore wave data derived from the NSW Coastal Wave Model (OEH, 2017a) at 10m depth every 100m along the entire Tweed Shire (provided by Manly Hydraulics Laboratory). The data period extends from November 1999 to June 2023.
- Local water level data from the Tweed Offshore tide gauge from 1982 to 2019.
- Shore-normal coastal profile elevation data derived from the 2018 Coastal LiDAR data (5m resolution).
- IPCC AR6 sea level rise projections (see Section 3.6). For future planning horizons, sea level rise was considered deterministically (i.e., a single value per planning horizon) for the coastal inundation assessment. The 83rd percentile of the adopted ranges presented in Table 9 was used. This provides a balance between being conservative and accounting for potential high-end scenarios and is a representative or central point within the range of possible outcomes.

Mase's (1989) wave runup model was applied to calculate wave runup and total water level along the coast at each beach profile. This model has been validated in other NSW open coast locations (e.g., Collaroy-Narrabeen Beach and Wamberal Beach; MHL, 2020; MHL, 2021) and was found to outperform other available wave runup models. The wave runup model and adopted assessment approach was further validated by Bluecoast against wave runup measurements at Wamberal Beach, NSW (see example results in Figure 45). The validation exercise suggests that overall, the model results showed a suitable degree of accuracy in predicting wave runup levels.

It is important to note that this first pass coastal inundation assessment is a high-level regional assessment subject to the limitations of the approach and data used. The results may be used to identify areas along the coast potentially exposed to coastal inundation and should be interpreted with consideration of the following limitations:

- The nearshore wave data derived from the NSW Coastal Wave Model (OEH, 2017a) provide a practical dataset to inform this assessment, however, uncertainty in the accuracy of the modelled nearshore wave data, particularly in the representation of extreme wave heights, remains. DCCEEW is currently undertaking an update to the nearshore wave dataset, including further validation.
- Morphological response of the beach during the storm as well as long-term adjustment to sea level rise and recession have not been included herein. Any landward or vertical movement of the coastal barrier (e.g., dune) would also affect the inundation extents. Changes to the nearshore bathymetry due to profile adjustments as well as higher sea levels may change nearshore wave processes that could exacerbate the inundation risk.
- The accuracy of the Digital Elevation Model (2018 Coastal LiDAR) used herein is stated as IHO 1B and has a 5x5m horizontal resolution which may not be sufficient to precisely describe coastal barrier elevations and steeper slopes.
- The mapped wave runup levels and overwash distances have been calculated at regular cross-shore profiles. For mapping purposes, linear interpolation of the results was undertaken between cross-shore profiles.

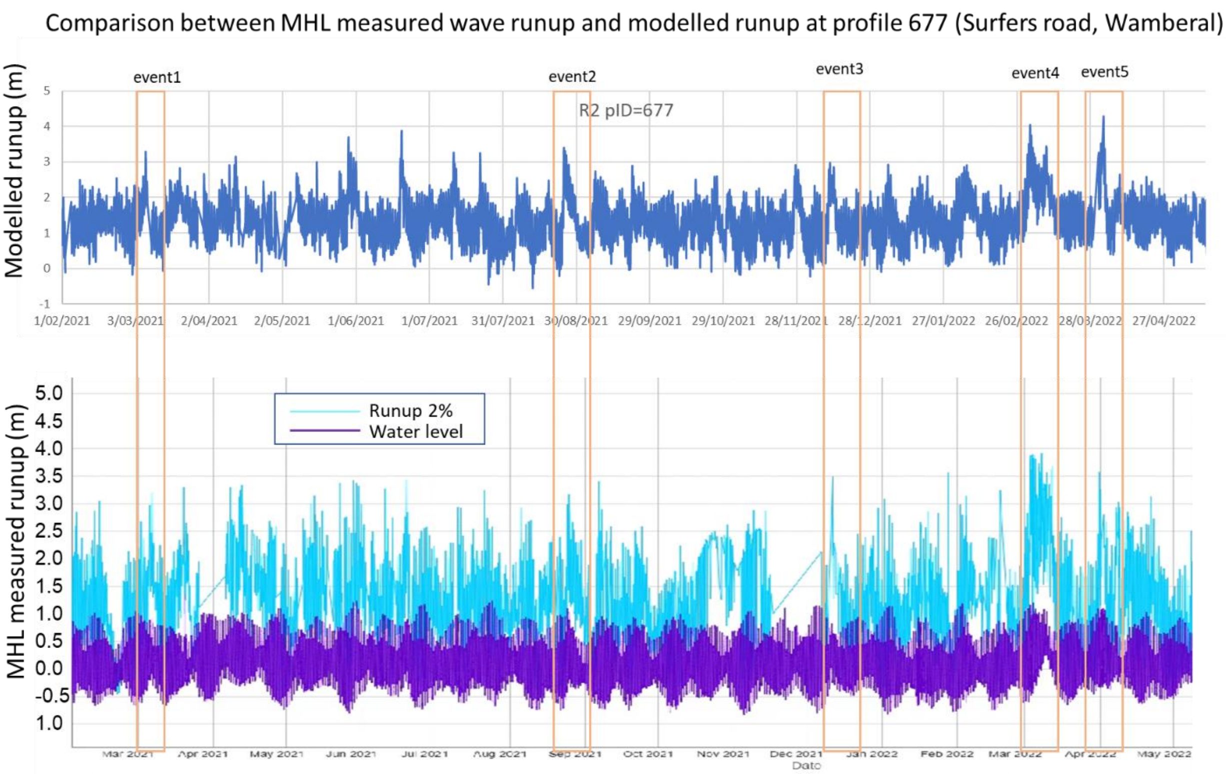


Figure 45: Validation of adopted wave runup calculation approach against measurements at Wamberal, NSW.

Mase's (1989) formula provides mean and maximum wave runup statistics (R_{mean}, R_{max}) and runup levels that are exceeded by 2% of waves ($R_{2\%}$). The adopted formulae are provided below:

$$\boldsymbol{R_p = H_0 a_p I^{b_p}}$$

where R_p is the runup height (m) for the p quantile or statistic value desired (e.g. R_{max}, $R_{2\%}$), H_0 is the deepwater significant wave height (m), a_p and b_p are coefficients which depend on the statistic p (see Table 27) and I is the Iribarren number (i.e., the surf similarity parameter):

$$I = \frac{\tan \alpha}{\sqrt{\left(\frac{H_0}{L_0}\right)}}$$

where tan α is the subaerial beach slope (m/m) and L_0 is the deepwater wavelength (m). For this study, H_0 and L_0 are calculated using the nearshore wave hindcast data for each beach profile.

Table 27: Wave runup coefficients (Mase, 1989).

Runup scenario	a_p	b_p
R_{mean}	0.88	0.69
$R_{2\%}$	1.86	0.71
R_{max}	2.32	0.77

When the wave runup exceeds the crest level of the coastal barrier (e.g., dune), the wave continues to propagate inland of the crest (overwashes). An empirical formula was used to estimate the wave overwash distance based on the rate of wave energy dissipation as it propagates inland as a wave bore. The following equation is used to estimate the maximum propagation distance of the wave bore (Cox & Machemehl, 1986):

$$X_p = \frac{T\sqrt{g}}{5}\sqrt{R_p - Y_0}$$

where X_p is the bore propagation distance landward from the crest (m) for statistic p, R is the wave runup level for the statistic p (m AHD), Y_0 is the coastal barrier crest level (m AHD), T is the peak wave period (s) and g is the gravitational constant (9.81m/s^2). For this coastal inundation assessment, we use the 99th percentile peak wave period measured at the Tweed Heads WRB of 15s. The overwash inland extent was then mapped based on the crest position of the coastal barrier and this bore propagation distance.

The crest level (Y_0) for each beach profile was defined as the first peak in elevation (i.e., the local maximum) that is at least 2.5 m AHD along each beach profile. Where there are known coastal seawalls or revetments, the crest level was set to the level of the structure.

The resulting 24-year hindcast of total water levels (including wave runup) for each profile location was further analysed as follows:

- Calculate wave runup statistics and determine maximum levels.
- Calculate total water level for 2040, 2070 and 2120 planning timeframes considering the sea level rise projections in Table 10 (83rd percentile values of the very high GHG emissions scenario).
- Determine where calculated wave runup exceeds coastal barrier height and estimate overwash extents based on bore propagation equation.
- Extract the calculated statistics for each profile to map the alongshore variation in wave runup levels and overwash.

6.3 Results

Coastal inundation maps showing the wave runup limit for different percentiles and sea level rise scenarios are presented in the map compendium in Section 9 of this report. A summary of first-pass inundation assessment results for the immediate planning timeframe is presented in Table 28.

Table 28: Summary of first-pass coastal inundation assessment for present day scenario.

Beach	Maximum wave runup level (m AHD)	Typical dune crest elevation* (m AHD)	Overwashes dune/ structure?	Affects public/ private development?
Wooyung Beach	5.3	5.0	Yes	No
Mooball Beach	5.3	5.0	Yes	No
Pottsville Beach (south)	5.0	4.0	Yes	No
Pottsville Beach (north)	6.2	4.0	Yes	No
Cudgera Beach	5.7	4.0	Yes	No
Hastings Point	4.9	4.5	Yes	No
Maggies Beach	6.0	4.5	Yes	No
Cabarita Beach	6.7	4.5	Yes	No
Bogangar Beach	5.4	4.5	Yes	No
Casuarina Beach	5.3	5.0	Yes	No
South Kingscliff Beach	6.1	6.5	No	No
Kingscliff Beach	6.0	5.0	Yes	Yes
Dreamtime Beach	6.5	6.5	Yes	No
Fingal Head Beach	6.6	5.0	Yes	Yes
Letitia Beach	5.5	4.5	Yes	No
Duranbah Beach	5.6	5.0	Yes	No

Note: *Minimum typical dune elevation along beach section at which overwash occurs.

This first pass assessment highlights that wave runup can result in dune overwash possible along most beaches. However, due to most development sites being set back from the dune along the Tweed Shire coast, developed areas identified as to be exposed to coastal inundation are limited to the following sections of beach:

- Kingscliff Beach between the Cudgen Headland SLSC and the holiday park at the northern end of Kingscliff.
- Fingal Head Beach at the holiday park.
- The impact of dune overwash at Cudgera Creek entrance is discussed further in Section 7.

It is recommended that further detailed coastal inundation assessments are considered in future (as required) to better understand the extent of coastal inundation for present and future scenarios, including for areas:

- Potentially exposed to coastal inundation based on the first pass assessment.
- Where significant changes in the beach and dune profile (and elevation) are experienced due to beach recession or implementation of coastal management activities.
- Where significant coastal development is planned to occur.

7. Estuary hazard assessment

7.1 Overview

The CM Act 2016 defines three coastal hazards related to estuaries:

- **Coastal entrance instability** – entrance dynamics and the condition of the entrance at a coastal lake or waterway which may affect flood hazards, beach and foreshore erosion hazards as well as the estuary flushing and associated water quality.
- **Tidal inundation** – inundation of land surrounding estuaries by tidal action under average meteorological conditions. Tidal inundation may include shorter-term incursion of seawater onto low-lying land during an elevated water level event such as a king tide or more permanent inundation due to land subsidence, changes in tidal range or sea level rise.
- **Erosion and inundation of foreshores** – hazards related to estuary bank erosion and foreshore inundation due to the combination of coastal and estuarine processes with erosion or inundation a result of tidal waters and the action of waves (including the interaction of those waters with catchment floodwaters).

This section provides a data-driven assessment of the three coastal hazards related the Tweed Shire coastal estuaries (not including the Tweed River estuary). This includes the three coastal creeks of Mooball Creek, Cudgera Creek and Cudgen Creek. The main characteristics of these estuaries and associated catchments are provided in Table 29.

The three estuaries are tidal estuaries with entrances that are partially infilled with marine sand forming highly mobile flood tide deltas. If not trained, entrance shape constantly changes in response to alongshore sediment transport, tidal flows, storms, and catchment flooding. If the entrance position is fixed by training walls (i.e., Mooball Creek and Cudgen Creek), estuary hydraulics and sediment transport patterns are generally modified, influencing beach and bank erosion, catchment flooding and tidal dynamics. The entrance conditions, such as the level of shoaling, affect a range of factors such as estuary water levels, flushing, water quality, salinity and coastal sediment dynamics.

A high level assessment of potential impacts on ecology and groundwater for each of the three estuaries due to sea level rise is presented in Section 7.5.

Table 29: Overview of characteristics of estuaries in study area.

Estuary name	Catchment area (km^2)*	Estuary group/ type**	Estuary area (km^2)*	Estuary volume (ML)*	Average depth (m)*	Tidal limit (km upstream from the entrance)***	Entrance characteristics
Mooball Creek	109	Wave dominated estuary/ riverine barrier estuary	0.5	351	0.7	10.6	• Trained entrance since 1967
Cudgera Creek	61	Wave dominated estuary/ riverine barrier estuary	0.5	250	0.6	5.3	• Untrained entrance • Headland-controlled on southern side
Cudgen Creek	69	Wave dominated estuary/ riverine barrier estuary	2.1	2,371	1.1	> 10	• Trained entrance since 1967

Note:
* Source: https://www.environment.nsw.gov.au/topics/water/estuaries/
** After Roy et al. (2001) classification of south-east Australian estuaries.
*** After MHL (2012) Cudgera Creek and Mooball Creek and MHL (1994) Cudgen Creek/ Lake tidal data collection report

7.2 Coastal entrance instability

An assessment of the coastal entrance instability of the three coastal creeks of Mooball Creek, Cudgera Creek and Cudgen Creek has been undertaken. BMT WBM (2013) *Tweed Shire Coastal Hazards Assessment* and Hydrosphere (2013) *CZMP for Tweed Coast Estuaries* reports previously reviewed the entrance instability hazard for all three estuaries. In summary, they identified that:

- Mooball Creek entrance is relatively stable due to the entrance training walls built in the 1960s. However, the desktop review by Hydrosphere (2013) found that the entrance has exhibited complete closure during low tide on occasions due to shoaling and there is a possible risk of breakthrough of the sand spit to the south of the Mooball Creek entrance in the future due to long term coastal recession and a narrow beach/ dune separating Mooball Creek from the ocean.
- Cudgera Creek entrance is stable on the southern side due to the rocky outcrops associated with Hastings Point but there has previously been channel migration to the north. The creek entrance is vulnerable to overtopping during major storm events from wave runup due to low dune crests on the northern sand spit. BMT WBM (2013) specifically identified the entrance instability hazard area as the area to the south of the Peninsula Street beach entrance/ access point due to possible channel migration and coastal erosion and/or coastal inundation.
- Cudgen Creek entrance is stable due to the entrance training walls built in 1967. Significant shoaling of the entrance area between the training walls is observed.

The existing training walls are considered to be maintained by the NSW Government and/or Tweed Shire Council over the planning timeframes herein. An assessment of the entrance behaviour at Mooball Creek, Cudgera Creek and Cudgen Creek was undertaken and is reported in the following sections. This assessment includes:

- A review of the geomorphic structure and geology of the lower estuary and entrance area
- Analysis of historic entrance behaviour in consideration of climatic conditions and anthropogenic influences
- Projection of possible future entrance behaviour.

Along with previous literature, the following data was used to complete the targeted entrance instability assessment:

- 2018 coastal LiDAR (DPE), 2007 creek digital elevation model (DEM) from the BMT WBM (2009) tidal modelling study and other available survey data
- NSW Seamless Geology database
- Satellite-derived annual shoreline position (DEA coastlines) between 1988 and 2021
- Historic aerial imagery available since 1962
- Estuary water level data provided by MHL.

7.2.1 Mooball Creek

An overview of the modern geomorphic setting and geology of the Mooball Creek entrance at Pottsville is presented in Figure 46. Alongshore elevation profiles from the latest topographic/ bathymetric surveys of the entrance (2007, 2011 and 2018) are shown in Figure 47. A series of aerial photographs of Mooball Creek entrance is provided in Figure 48.

Based on the available evidence, the following observations on the entrance behaviour were made:

- The entrance is predominantly in an open state. However, associated with natural climate variability, creek entrance closure is known to occur at Mooball Creek. The creek entrance closed most recently in October 2018 due to Pottsville Beach and Cudgera Beach being in a largely accreted state after a period of dominant El Niño conditions between 2014 to 2019. Associated with this dominant El Niño period, there was reduced rainfall across much of eastern Australia (BOM, 2018) likely reducing streamflow from Mooball Creek. Low streamflow and accreted beach states may cause Mooball Creek entrance to close again in the future, most likely during multi-year El Niño climate conditions. However, natural processes such as increased rainfall and reduced sand volumes along adjacent beaches as part of the local climate variability (see Section 3.9) can re-open the channel to maintain a predominantly open entrance.

- The entrance area has remained in the same alongshore position since the training walls were completed in 1967. Sections of the training walls have been damaged in previous storm events and Council is currently planning repairs to ensure the structures continue functioning into the future. Although the creek entrance is trained, infilling of the creek entrance associated with wave-driven onshore sand transport can cause the effective width of the entrance channel to become narrower at times. When the creek entrance narrows, the creek channel is generally located along the northern training wall (e.g., Figure 47 and 1997 aerial image in Figure 48).

- The beach on the western bank of the Mooball Creek entrance at Ambrose Brown Park (inside the entrance) varies in morphology significantly through time (Figure 48). Shoreline analysis (Figure 46) shows that between 1988 and 1998, the beach widened by up to 30m as a new equilibrium was established post-training walls. Since 1998, the beach has been more stable with yearly beach width averages varying by only up to 10m associated with shifts in the weather and wave climate cycles (e.g., reduced beach widths since 2020 associated with pre-dominant La Niña conditions and heavy rainfall).

- Large ocean swells have been observed to cause long-wave propagation into the creek entrance which can result in rapid water level changes in the lower estuary. This increased water level from ocean waves, which is dependent on the level of shoaling between the training walls, may lead to erosion along the lower estuary foreshore.

- The sand budget completed herein (Section 4) has confirmed that the section of the coast adjacent to the entrance is relatively stable or experiencing some long-term accretion (i.e., net sand gain). Hence, over the short to medium term, it is not expected that the entrance behaviour will change significantly. In the longer term, recession associated with sea level rise leads to a potential risk of entrance breakthrough to the south of the present entrance area.

- A narrow section along Mooball Beach to the south of the current entrance position near the Sheens Creek and Mooball Creek junction south of the Black Rocks Bridge has the potential for entrance breakthrough in the future (Figure 49). Along the beach for approximately 200m, the width of the vegetated area between the eastern bank of Mooball Creek and the beach is only 90 to 100m and the present day dune crest is relatively low at approximately 5.5 to 6.0m AHD. The land behind the dune crest slopes down towards Tweed Coast Road and then sharply from the road to the creek with a rock revetment to prevent bank erosion (Figure 49). Present day coastal inundation results (Section 6.3) suggest that overwash does not present an immediate breakthrough hazard. However, erosion and recession hazard modelling (Section 5.4) suggests there may be a future breakthrough hazard by 2120, albeit at a low exceedance probability (less than 5%). It is noted that with sea level rise the sand spit would typically be expected to roll back in a landward direction, i.e., the barrier would recede in its current alignment, rebuilding further landward. However, the position of the sand spit and much of the lower estuary is largely fixed due to development, including roads and bridges. If maintained into the future, this development is expected to restrict the ability for the estuary to naturally adjust its morphology to sea level rise.

Due to the fixed entrance position in the short to medium term and stable adjacent shorelines, the entrance is not expected to create a significant hazard at present. The largest change in estuary morphology in the short to medium term is likely to continue to occur along the western bank at Ambrose Brown Park, with a highly variable shoreline position associated with weather and wave climate cycles. In the longer term, entrance breakthrough is possible well to the south of the current entrance location which may lead to a change in the Mooball Creek entrance behaviour.

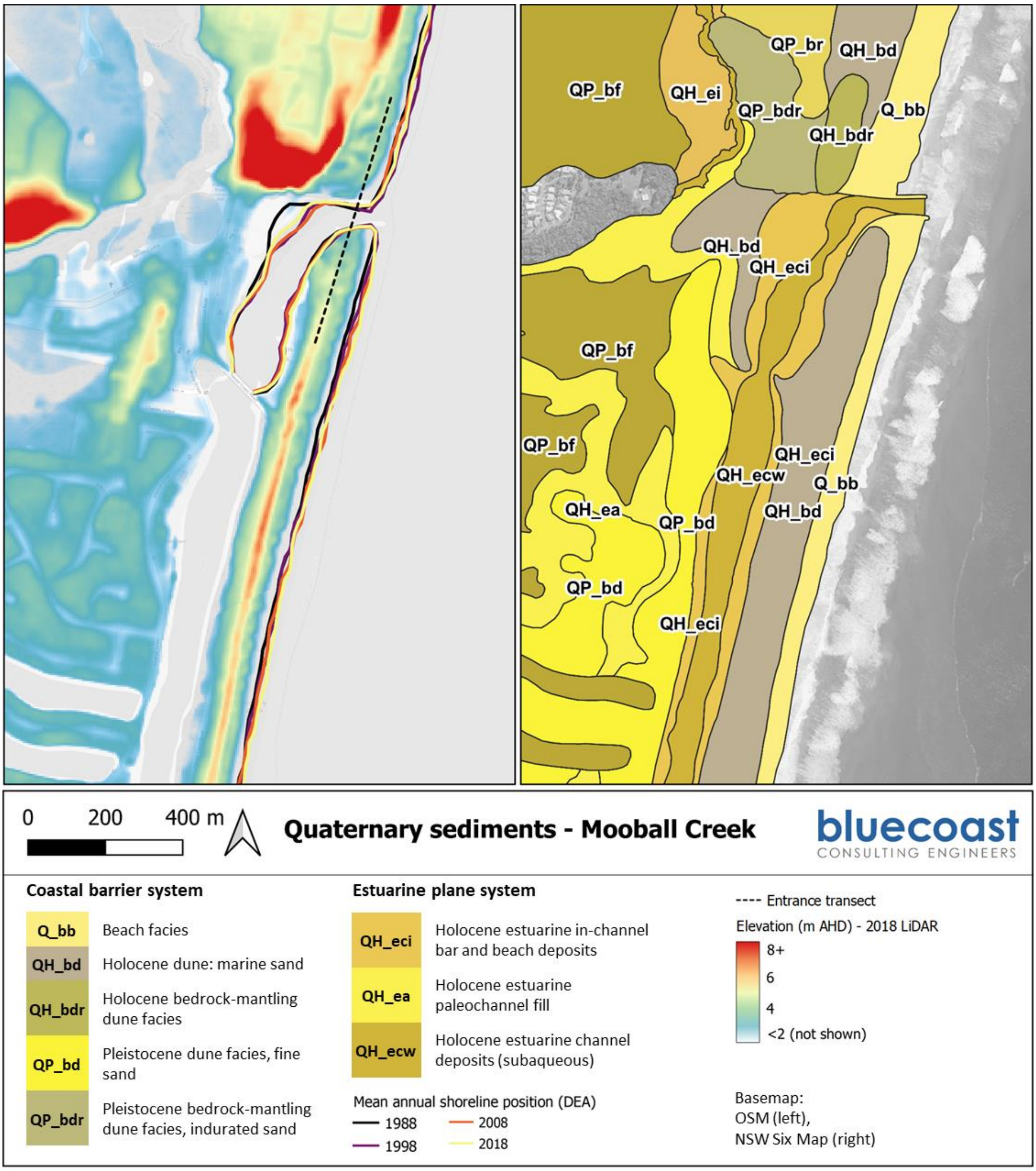


Figure 46: Geomorphic overview and Quaternary geology and sediments surrounding Mooball Creek entrance.

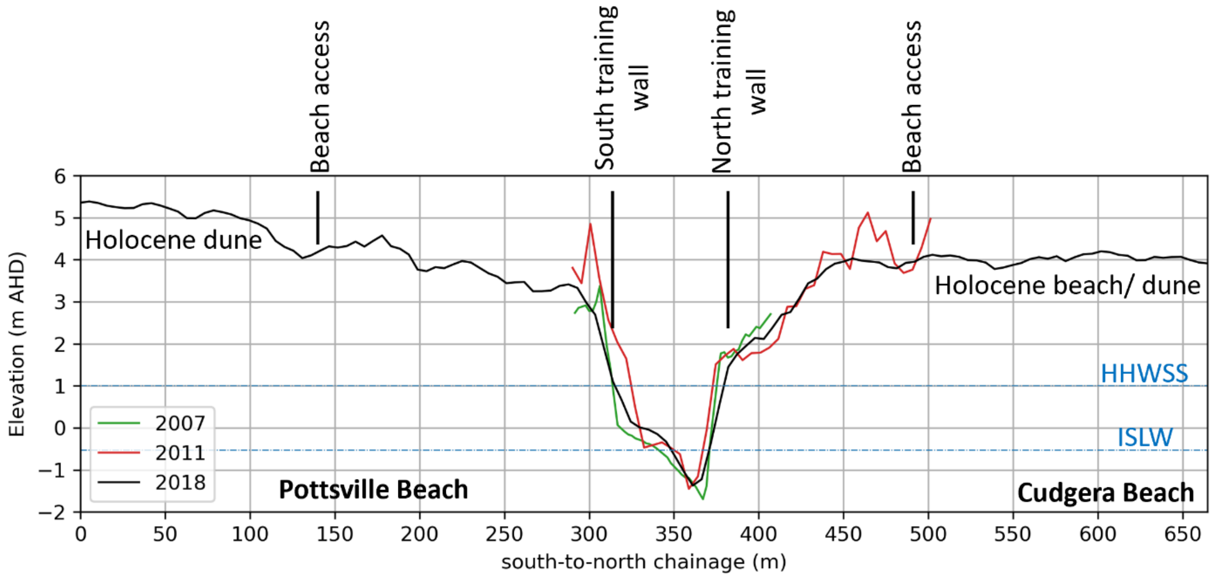


Figure 47: Alongshore elevation profile across Mooball Creek entrance derived from survey data.

Note: Transect location shown in Figure 47.

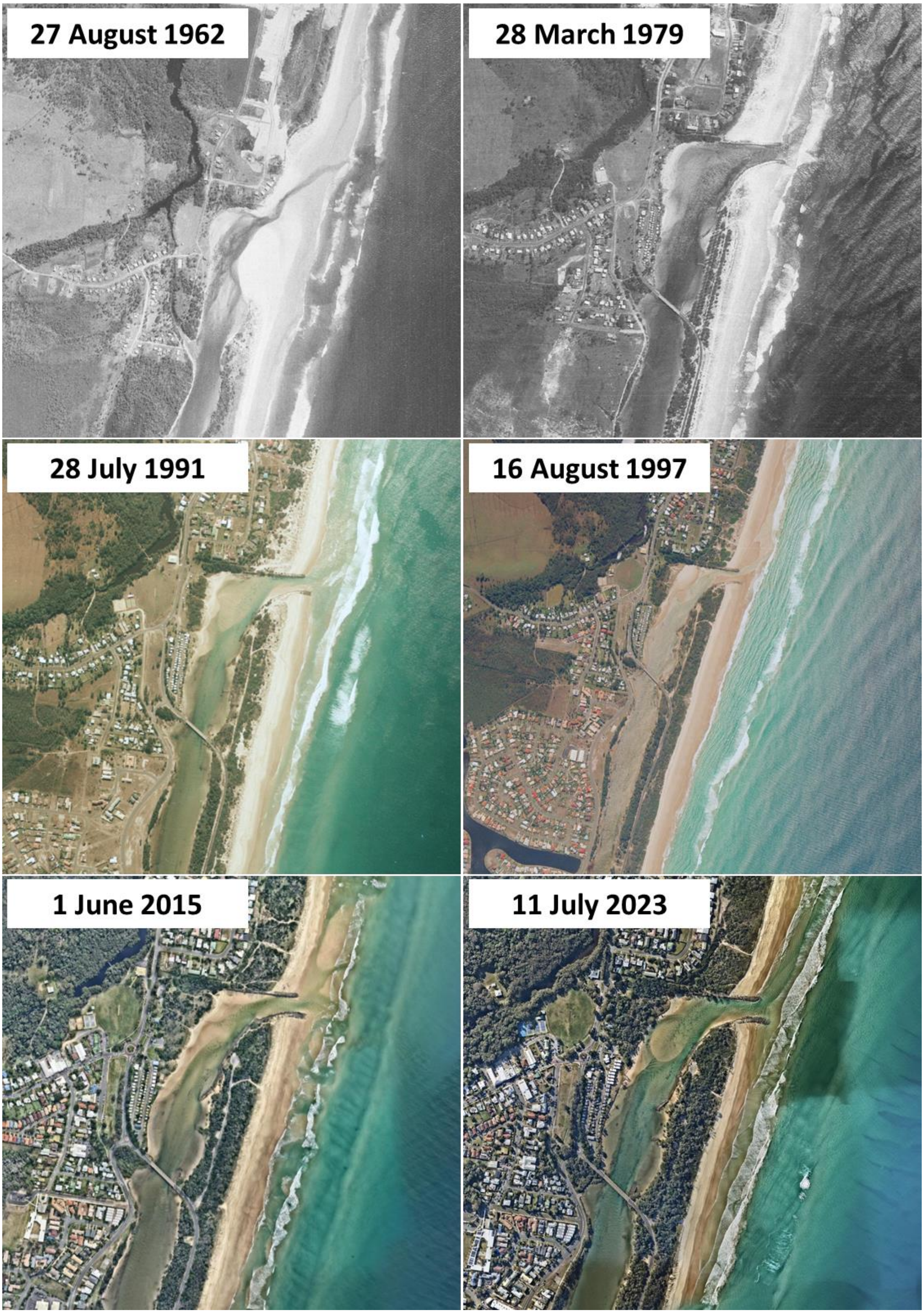


Figure 48: Aerial photographs of Mooball Creek entrance between 1962 and 2023.

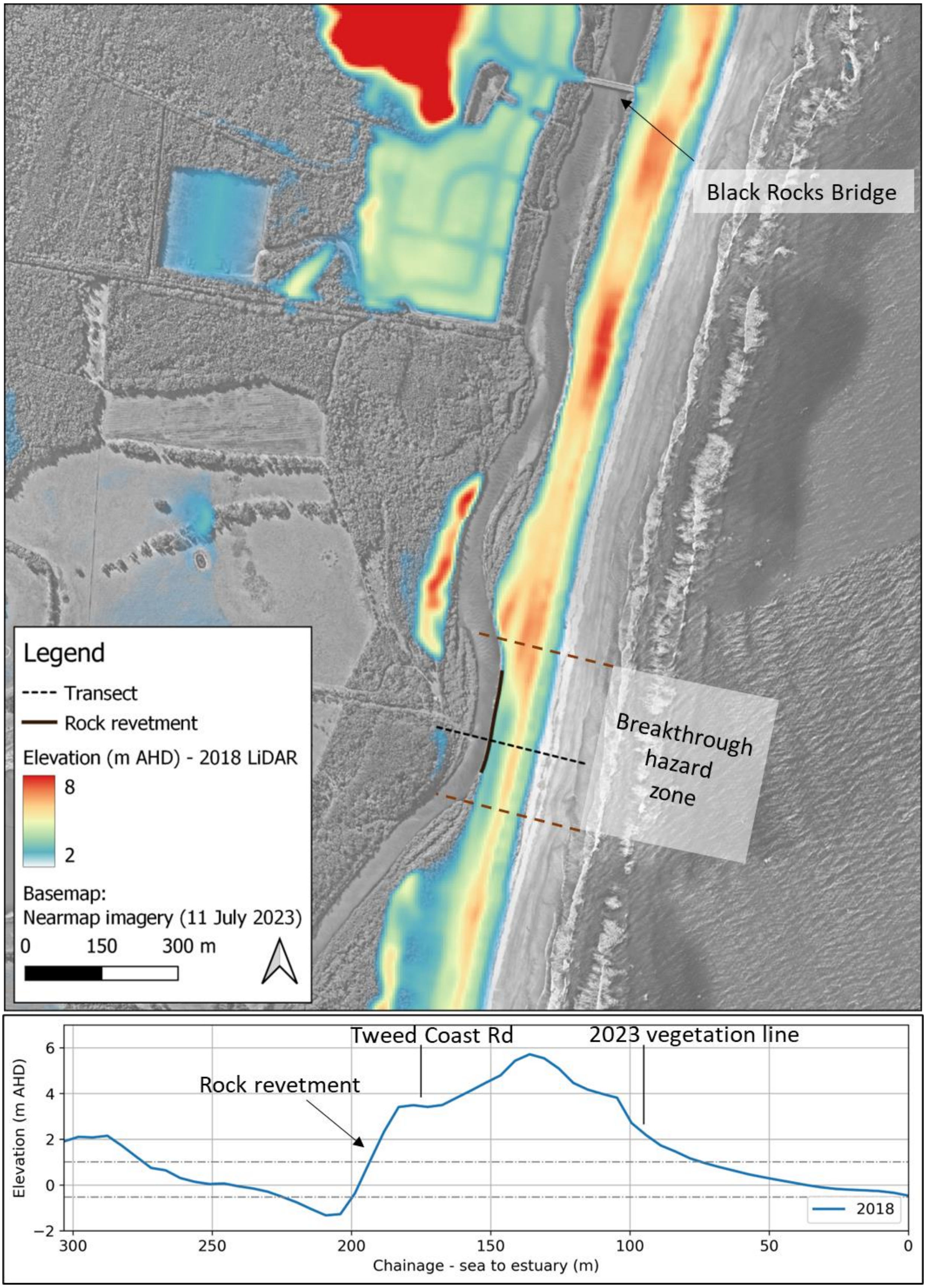


Figure 49: Overview of Mooball Creek breakthrough hazard zone.

7.2.2 Cudgera Creek

An overview of the modern geomorphic setting and geology of the Cudgera Creek entrance at Hastings Point is presented in Figure 50. Alongshore elevation profiles from the latest topographic/ bathymetric surveys of the entrance (2007, 2011 and 2018) are shown in Figure 51. A series of aerial photographs of Cudgera Creek entrance is provided in Figure 52.

Based on the available evidence, the following observations on the entrance behaviour were made:

- The entrance is predominantly in an open state. However, the deepest point of the creek entrance is approximately -0.6m AHD at its narrowest point (Figure 51) which is only 0.2m below the ISLW tide level according to water level recordings from 2007 to 2008 at the creek entrance (MHL, 2012). Similar to other Tweed coastal creeks, periods of accretion and low creek flows associated with natural climate variability may lead to temporary closures of the creek entrance (Hydrosphere, 2013).
- The entrance is relatively stable, with little to no alongshore migration of the entrance channel observed over the last 60 years identified through aerial imagery and mapped shoreline positions (Figure 50). The morphology of the northern sand spit, however, suggests that the channel has been further north of its current position in recent history. Aerial imagery (Figure 52) also shows that the width of this sand spit varies through time, likely in response to beach erosion events and bank erosion on its western side. Further, wave runup during extreme storm events could lead to dune overwash of the dune crests on the northern side of the creek entrance based on the first-pass coastal inundation assessment (refer Section 6) and the relatively low height of the dune crest (Figure 51). Overwash of the northern sand spit would lead to a wider creek entrance and a change in the lower estuary morphology and hydrodynamics as well as possible entrance channel migration.
- The sand budget completed herein (Section 4) has shown this section of the coast is experiencing long-term recession (i.e., net sand loss). This may lead to an increase in the frequency of dune overwash events on the northern spit in the future and resulting changes in the lower estuary morphology and hydrodynamics as discussed above.

At Cudgera Creek entrance, dune overwash is a current hazard which may lead to changes to the lower estuary morphology and hydrodynamics such as a widening of the creek entrance. The frequency of dune overwash may increase in the future associated with net sand loss to the adjacent beaches. Due to the relatively shallow creek entrance at present, entrance closure is also possible associated with natural climate variability.

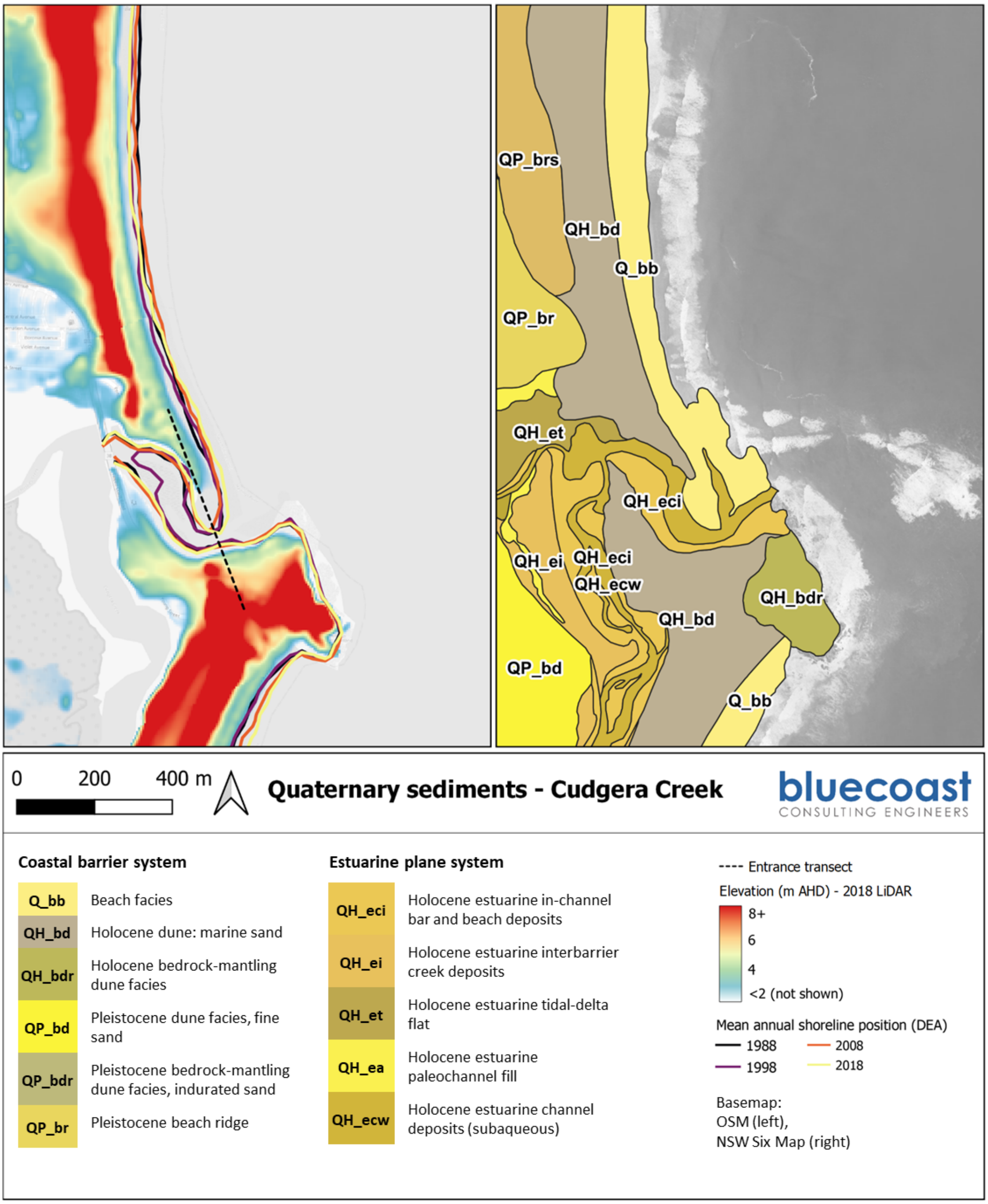


Figure 50: Geomorphic overview and Quaternary geology and sediments surrounding Cudgera Creek entrance.

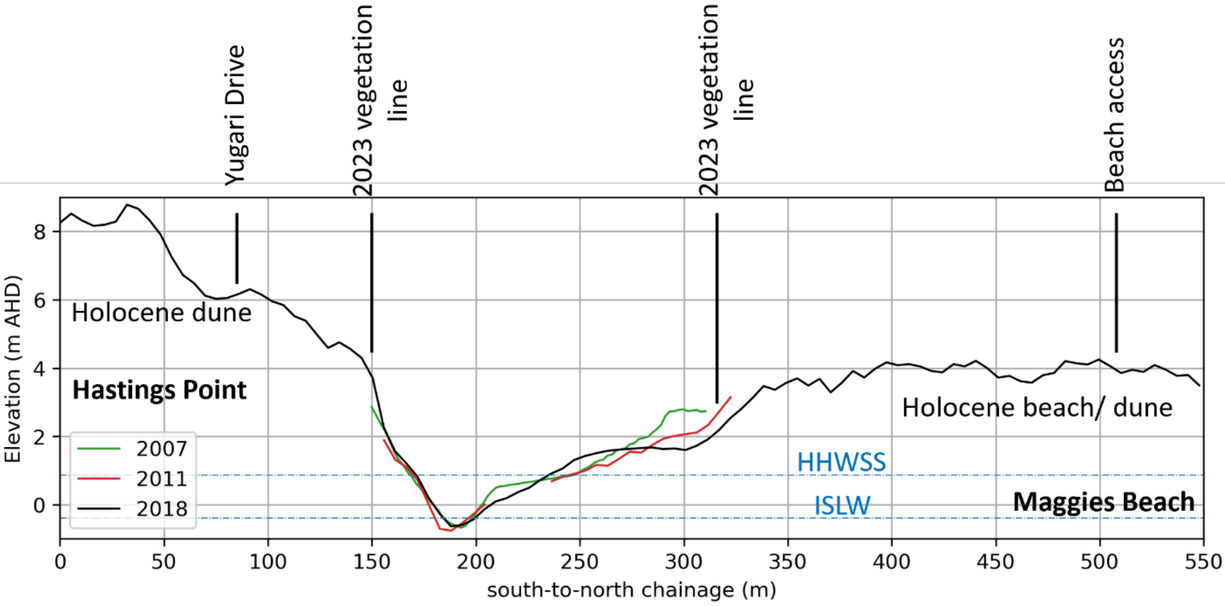


Figure 51: Alongshore elevation profile across Cudgera Creek entrance derived from survey data.

Note: Transect location shown in Figure 50.

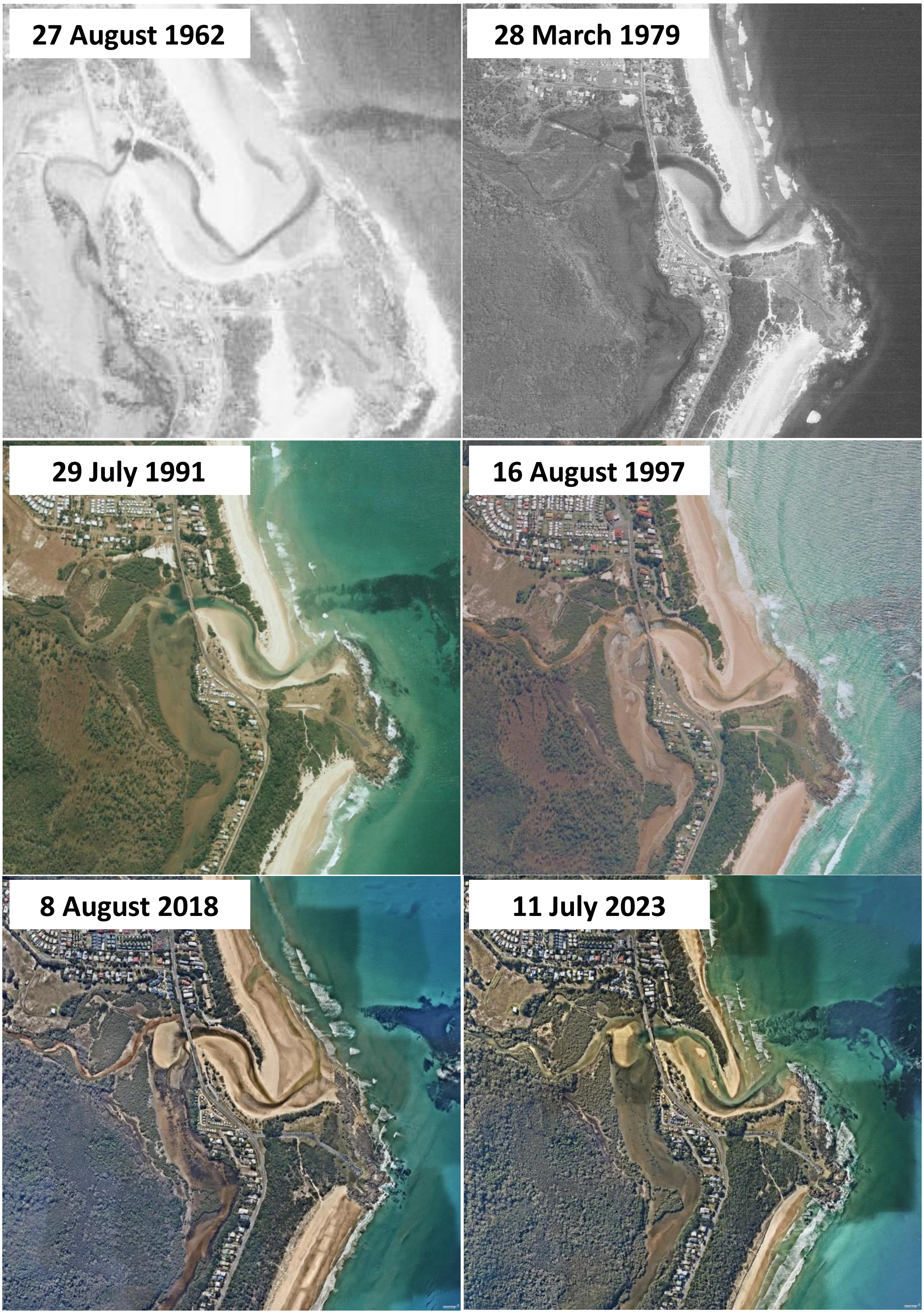


Figure 52: Aerial photographs of Cudgera Creek entrance between 1962 and 2023.

7.2.3 Cudgen Creek

An overview of the modern geomorphic setting and geology of the Cudgen Creek entrance at Kingscliff is presented in Figure 53. Alongshore elevation profiles from the latest topographic/ bathymetric surveys of the entrance (1993, 2011 and 2018) are shown in Figure 54 and Figure 55. A series of aerial photographs of Cudgen Creek entrance is provided in Figure 56.

Based on the available evidence, the following observations on the entrance behaviour were made:

- The entrance area has remained in the same alongshore position since the training walls were completed in 1967.
- The entrance is predominantly in an open state. Infilling of the creek entrance associated with periods of wave-driven onshore sand transport and headland bypassing events around Cudgen Headland (see Section 4.5.2) associated with natural climate variability can cause the entrance channel to narrow at times (e.g., 1997 and 2018 aerial images in Figure 56). Dredging of the creek entrance has been conducted previously for the purpose of sand nourishment to Kingscliff Beach as well as for navigation purposes (e.g., 2011 and 2016 as described in Table 1). Similar to Mooball Creek entrance, Cudgen Creek entrance was generally shallower in 2018 than in the 1993 survey (Figure 54 and Figure 55) associated with largely accreted beach states at adjacent beaches (Figure 56) and increased sand supply related to headland bypassing around Cudgen Headland (see Section 4.5.2). Variable sand supply is likely to continue to influence the creek entrance morphology with periods of short-term oversupply of sand from headland bypassing events the main contributor to shallower entrance conditions. However, natural processes such as increased rainfall (see Section 3.9) and periods of low sand supply help to maintain a predominantly open entrance (e.g., 2023 in Figure 56).
- The sand budget completed herein (Section 4) has confirmed that this section of the coast is relatively stable to the south of the creek entrance, however, Kingscliff Beach to the north is experiencing long-term recession (i.e., net sand loss). Also, the sand volumes in this area can vary significantly on a short to medium timescale associated with headland bypassing events (see Section 4.5.2). This potential for low sand volumes may lead to an unstable entrance in the future, with the training walls (particularly on the northern side of the entrance) potentially susceptible to being undermined.
- A section of South Kingscliff Beach to the south of the current entrance position near the Cudgen Creek Bridge has the potential for entrance breakthrough in the future (Figure 57). To the south of the entrance, for a section of approximately 120m, the width of the vegetated area between the eastern bank of Cudgen Creek and South Kingscliff Beach is only 80 to 100m and the present day dune crest is 6.5 to 7.0m AHD. The land behind the dune crest remains elevated over 6.0m AHD, however, there is a steep creek bank where erosion of the foreshore is a known issue (see Section 7.4). Present day coastal inundation results (Section 6.3) suggest that overwash does not present an immediate breakthrough hazard, however, erosion and recession hazard modelling (Section 5.4) highlight a potential future breakthrough hazard by 2120, albeit at a low exceedance probability (less than 5%). The creek position is also fixed by the bridge and associated rock revetments in this location which may restrict the dune in this position from being able to rollover with sea level rise. Together with the bank erosion, this leads to there being a potential future entrance breakthrough hazard in this area.

The Cudgen Creek trained entrance is currently stable and does not present a present day hazard. However, there are entrance hazards that require consideration for future planning periods with the potential for significant changes in the entrance behaviour associated with sea level rise, long-term recession and erosion. Specifically, by 2120 there is a potential of entrance breakthrough to the south and with long-term recession of Kingscliff Beach, the training walls may become undermined during reduced sand supply periods.

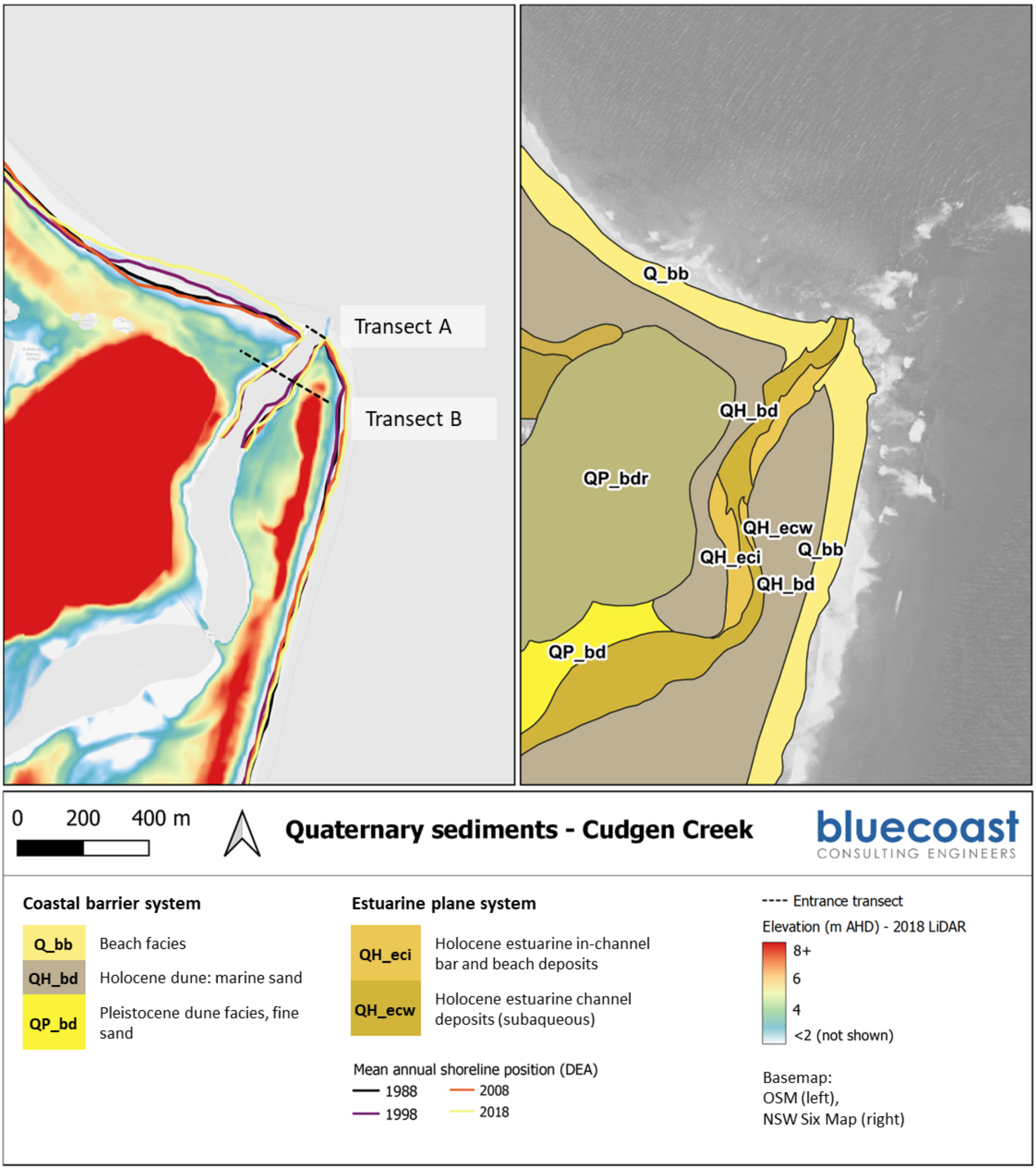


Figure 53: Geomorphic overview and Quaternary geology and sediments surrounding Cudgen Creek entrance.

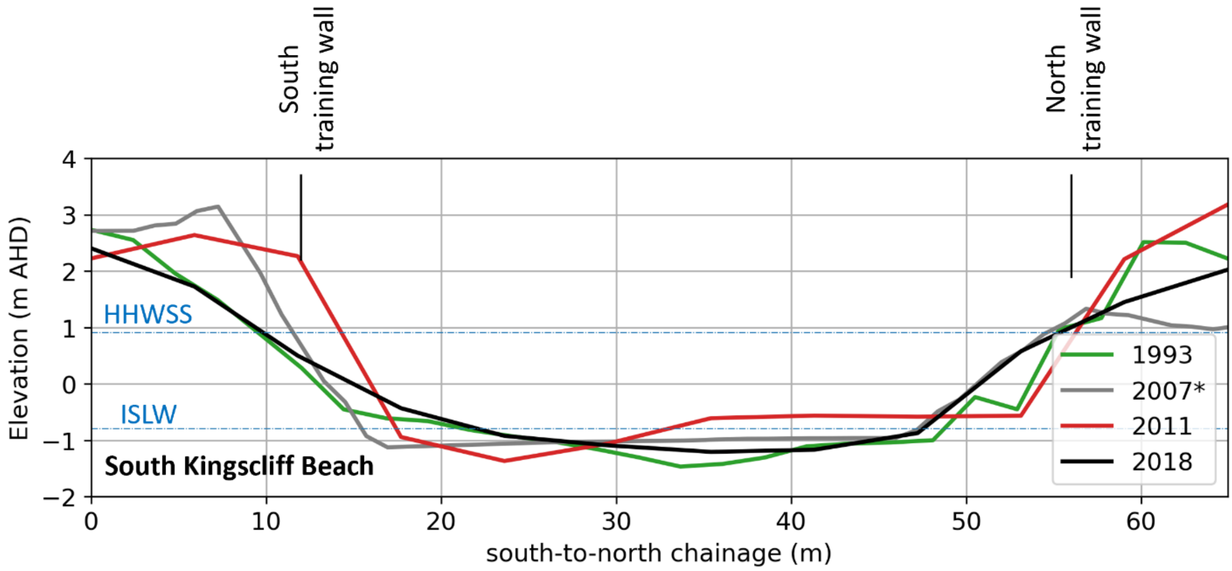


Figure 54: Alongshore elevation profile across Cudgen Creek entrance (between training walls).

Note: *extracted from numerical model DEM based on 2007 survey data described in BMT WBM (2009). Transect location shown in Figure 53 as Transect A.

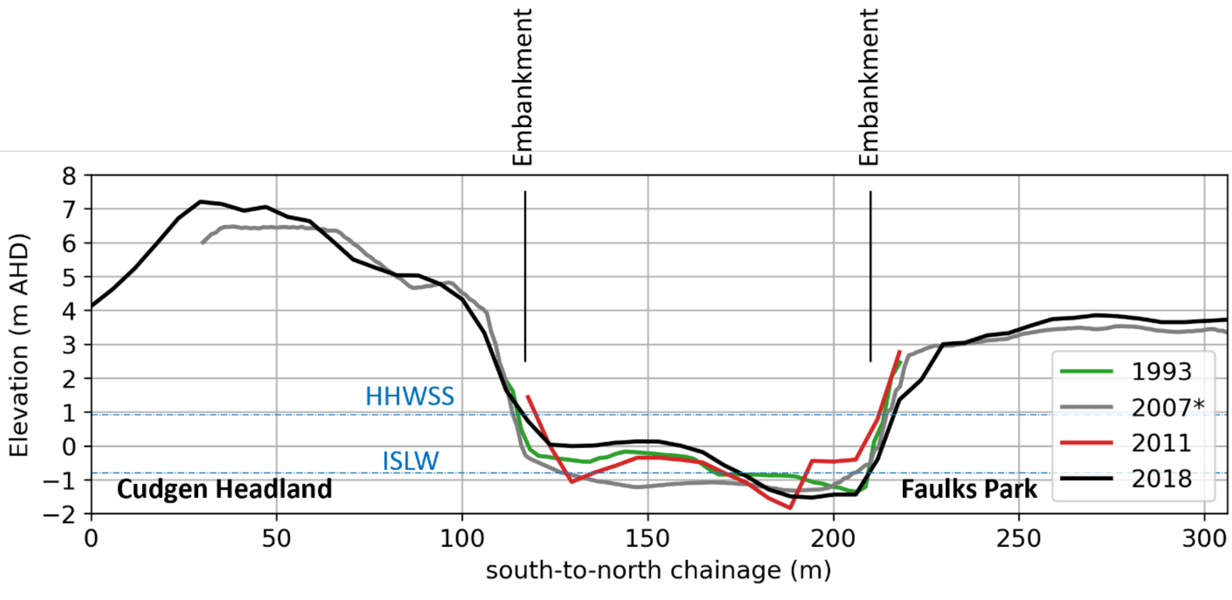


Figure 55: Alongshore elevation profile across Cudgen Creek (inside training walls).

Note: *extracted from numerical model DEM based on 2007 survey data described in BMT WBM (2009). Transect location shown in Figure 53 as Transect B.

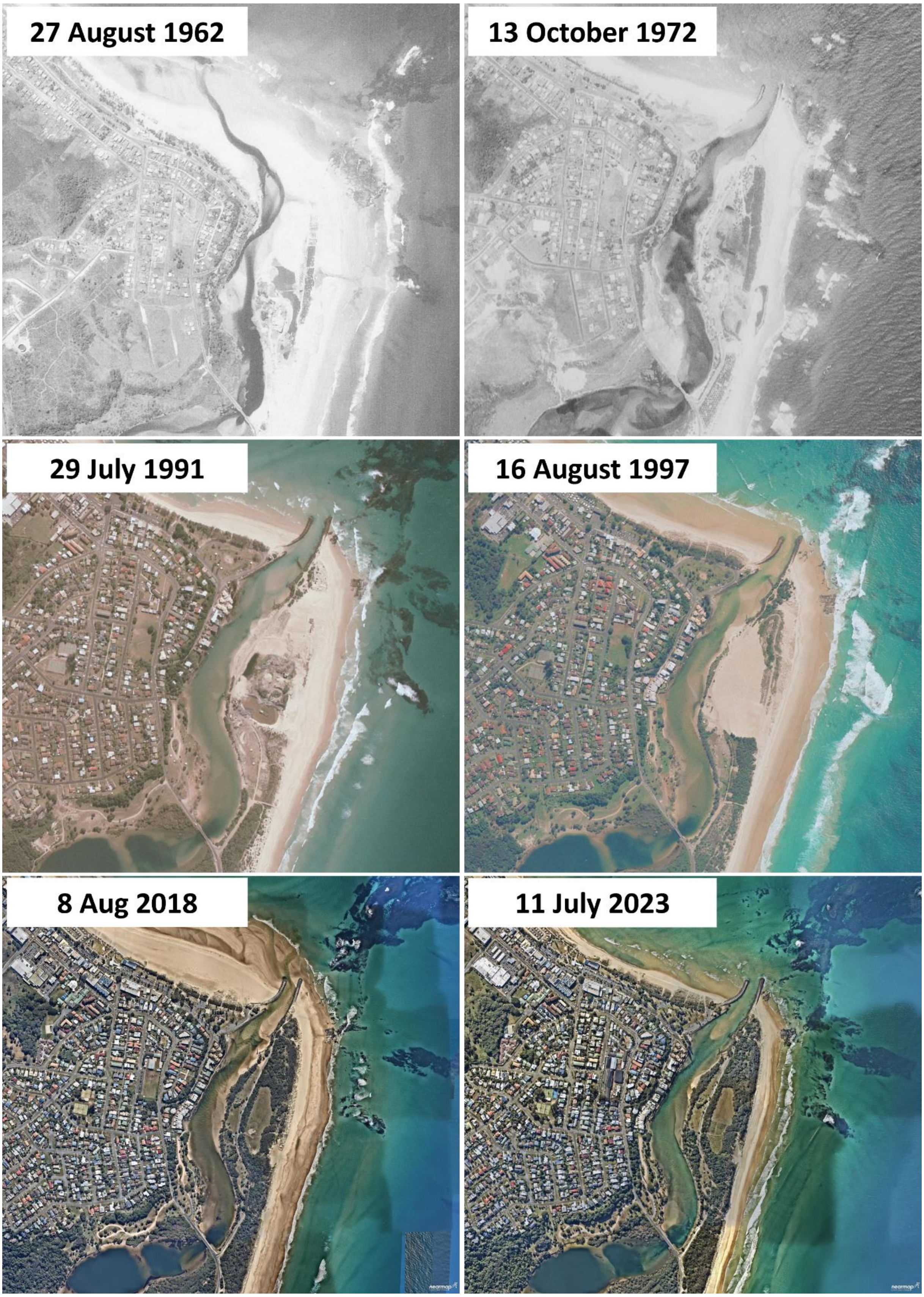


Figure 56: Aerial photographs of Cudgen Creek entrance between 1962 and 2023.

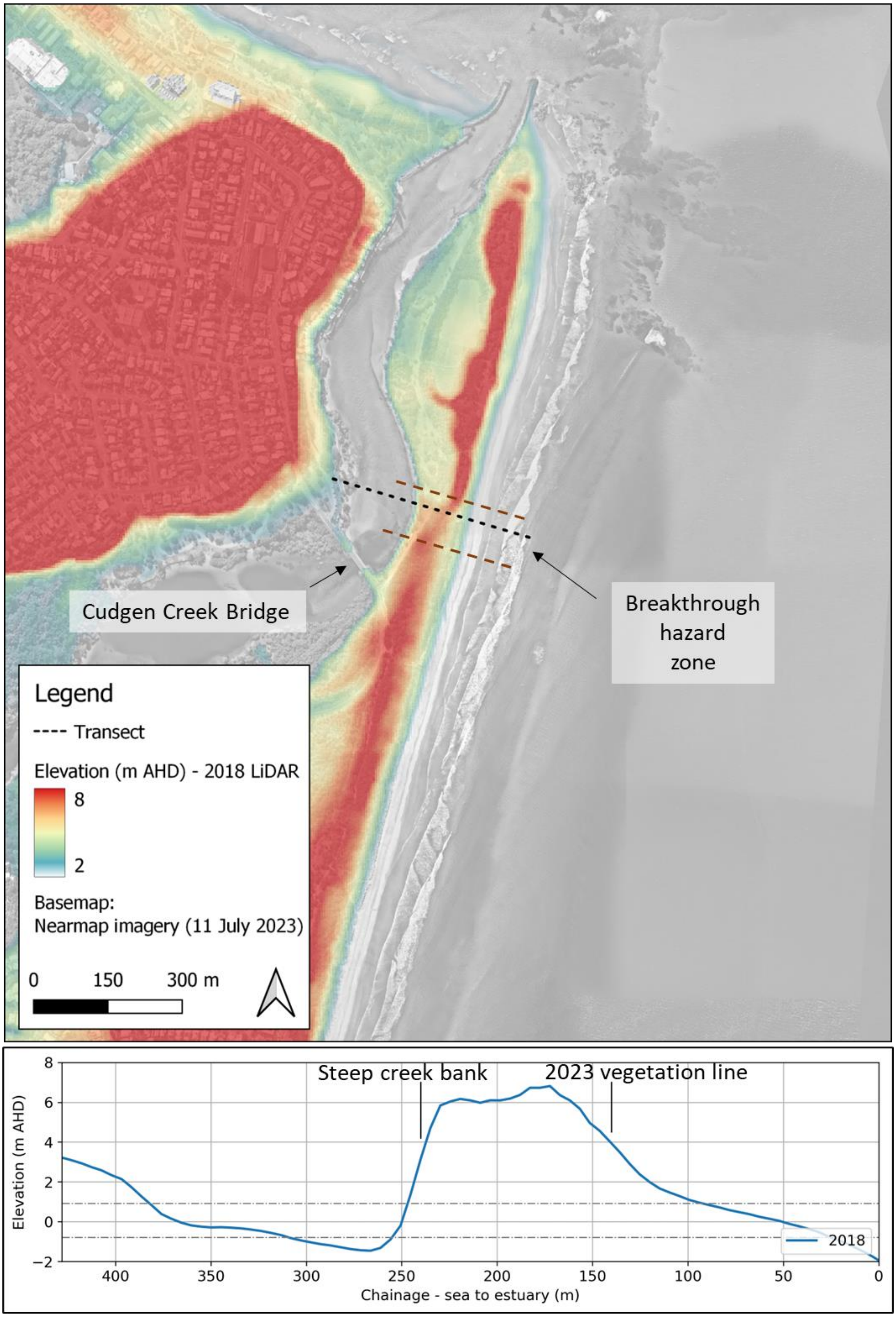


Figure 57: Overview of Cudgen Creek breakthrough hazard zone.

7.3 Tidal inundation hazard assessment

7.3.1 General

A tidal inundation assessment has been undertaken for Mooball Creek, Cudgera Creek and Cudgen Creek. The propagation of ocean tidal conditions into the three coastal estuaries up to their tidal limit for present and future planning periods during average meteorological conditions was simulated with the use of the numerical models.

The methodology, calibration, validation and results of the assessment are provided in **Appendix C**. A summary of the assessment approach and results is provided below. A series of maps showing the peak tidal inundation extent and depth for each planning period are presented in the map compendium in Section 9.

7.3.2 Approach

A detailed numerical modelling approach to assess tidal inundation across the three coastal creeks was adopted. The two-dimensional hydrodynamic model, Delft3D Flexible Mesh D-Flow (D-FLOW FM), was used to allow for a detailed assessment of the tidal inundation hazard. Two models were developed for the purpose of this assessment, including:

- Mooball and Cudgera Creek coastal estuaries – these were modelled together as one region for the purposes of the tidal inundation assessment due to their potential interaction during large tidal events
- Cudgen Creek – a standalone model was developed for this coastal estuary.

A detailed description of the numerical models, calibration and validation is provided in **Appendix C**.

7.3.3 Scenarios

The assessment included simulation of water depth and flood extents for four tidal scenarios which capture present (Immediate) and future (2040, 2070 and 2120) planning periods during average meteorological conditions.

For the present-day scenario, the Highest High Water Spring Tide (HHWSS) at Brunswick Head was adopted as the peak water level. The maximum HHWSS, determined through harmonic analysis over 19 years (2001 to 2020), reached 1.14m AHD in 2010 (MHL, 2023). This is considered a proxy for a ‘king tide’ which is commonly used for tidal inundation assessments in NSW (OEH, 2018b).

For future planning periods of 2040, 2070 and 2120 a sea level rise allowance was added to the ocean tidal signal. The adopted sea level rise values (0.21m, 0.56m and 1.46m) are in accordance with Section 3.6 and are representative of the SSP8.5 (83rd percentile) values. These sea level rise values are well above the 50th percentile (median) sea level rise scenarios and therefore, represent a conservative approach to tidal inundation for future scenarios. The adopted values may differ from previous tidal inundation studies in the local area (e.g., Tweed River CMP) and are based on the most up-to-date information.

Water level time series as input to the models were developed for four planning horizons, noted below with the peak tidal level as:

- Immediate: 1.14m AHD
- 2040: 1.35m AHD
- 2070: 1.70m AHD
- 2120: 2.60m AHD.

Figure 10 contextualises the selected tidal inundation scenarios with sea level rise projections and less or more frequent tidal events, including storm tides (i.e., combination of storm surge and astronomical tide). Although other peak ocean water levels were not simulated in this assessment, the results presented herein may help understand inundation hazards in different scenarios. For example, the simulated tidal inundation extent and depth for 2120 may also reflect a present-day 100-year ARI storm tide level with an allowance for 1.14m of sea level rise, which aligns with the 50th percentile projection in IPCC's high-emission scenario (SSP8.5) for 2120.

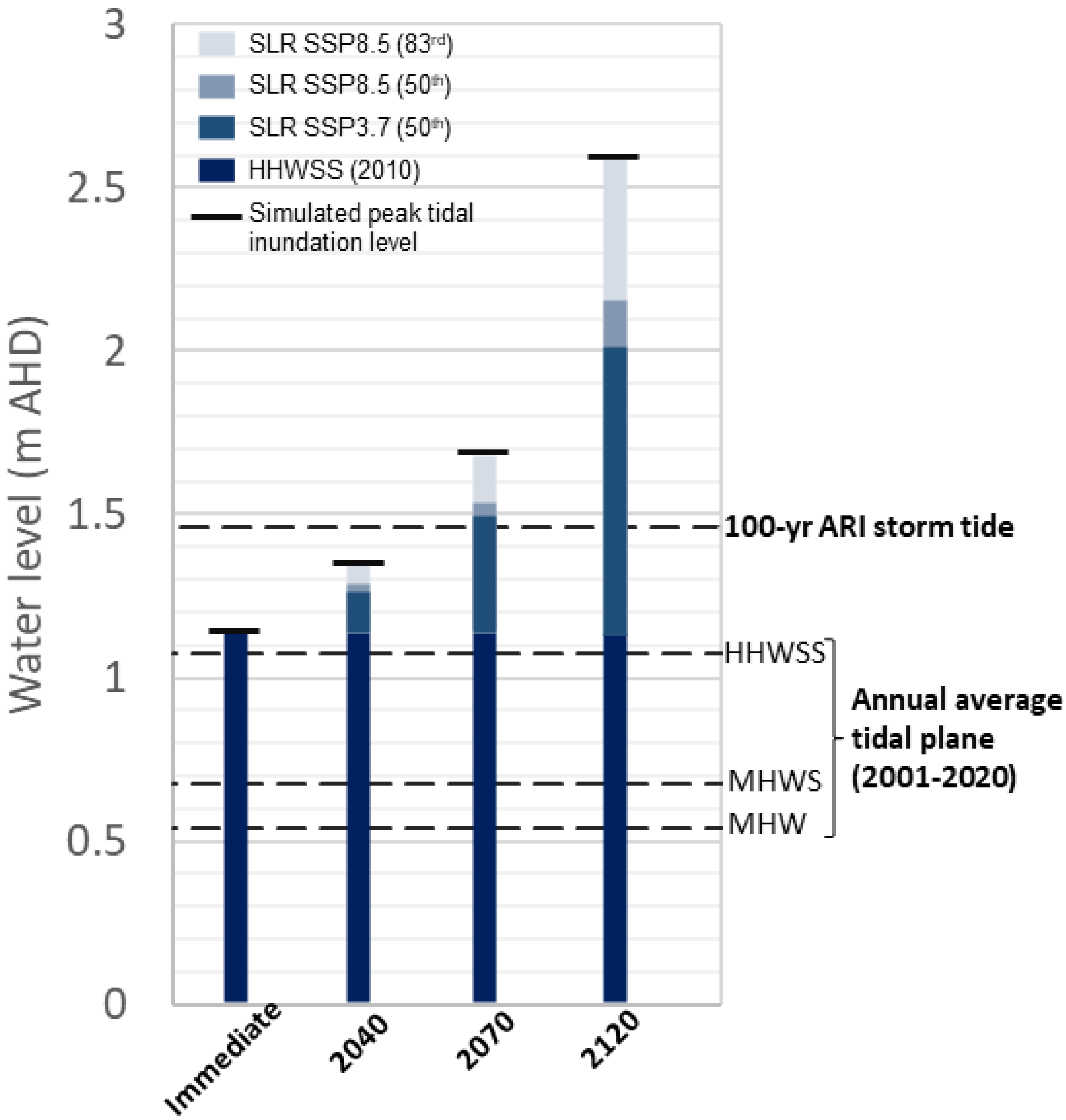


Figure 58: Comparison of tidal inundation scenarios with sea level rise projections, present-day tidal planes and storm tide level.

Note: Tidal planes are derived from Brunswick Head tide gauge (MHL, 2023). Storm tide levels presented in Section 3.5.

7.3.4 Results

The peak tidal extents and inundation depths are shown in the map compendium in Section 9. A description of the tidal inundation results for each of the three estuaries modelled is provided in the following sections.

Mooball Creek

- Under present day conditions, tidal waters are typically contained within the estuary banks with some inundation of vegetated areas in upstream reaches.
- There is little change in the 2040 scenario, with some lateral expansion of the tidal extent, particularly between the southern end of the township and Sheens Creek.
- In 2070, tidal flows break out of the western bank into adjacent vegetated areas, and the tidal extent pushes further upstream into the narrower reaches of Mooball Creek.
- In the 2120 scenario, the tidal inundation extents expand significantly further west and south compared to the existing scenario, reaching as far as Pottsville Road at Wooyung.

Cudgera Creek

- Similar to Mooball Creek, tidal waters are typically contained within the estuary banks with some inundation of vegetated areas in upstream reaches at Pottsville and adjacent to Christies Creek under present day conditions.
- There is little change in the 2040 scenario, with some lateral expansion of the tidal extent, particularly near the Pottsville Beach Football Club sports field.
- In 2070, tidal flows break out of banks either side of the creek into adjacent vegetated areas, and the tidal extent expands approximately 1.5km westward at Christies Creek.
- In the 2120 scenario, the tidal inundation extents expand significantly further west and south compared to present day, inundating properties as far south as along Coronation Avenue, Pottsville.

Cudgen Creek

- Under present day conditions, tidal waters are typically contained within the estuary banks, with exception for some adjacent vegetated areas along Salt and Casuarina.
- Contrary to Mooball and Cudgera Creek, there is significant lateral expansion of the tidal inundation extents in the 2040 scenario along most areas upstream of Salt. Tidal inundation extents are predicted to reach Kings Forest and as far as the M1 motorway west of Cudgen Lake.
- There was minimal change in the 2070 scenario compared to 2040.
- In the 2120 scenario, some further lateral expansion of the tidal inundation extents is observed, mainly between Sutherland Street bridge and Salt as well as along Blacks Creek. A section of Casuarina Way just south of Sutherland Street bridge is predicted to be inundated.

7.4 Erosion and inundation of foreshores

Estuary foreshores and surrounding lands typically comprise unconsolidated material deposited during the evolution of the estuary. Unlike open coast beaches and dunes, they may not recover after erosion, leading to continuous bank recession. Bank erosion can degrade adjacent vegetation and ecosystems or impact on public and private assets. Factors causing bank erosion and inundation of foreshores include changing water levels (including sea level rise), wind-formed waves, boat-induced wash, tidal currents, and catchment floods, along with unrestricted access. Human activities like entrance modifications, dredging, and management approaches can also affect erosion and inundation processes by altering tides, introducing ocean waves, and impacting current speeds and sediment movement.

The hazards related to estuary bank erosion and foreshore inundation due to the combination of coastal and estuarine processes have been reviewed for Mooball Creek, Cudgera Creek and Cudgen Creek estuaries. The purpose of the assessment is to identify sites that may require further detailed assessment and/or be considered for potential on-ground works during subsequent CMP stages. This desktop assessment included:

- A review of available aerial imagery between 1958 and 2023.
- A review of survey data and elevation changes in the riparian area, including:
  - 1993 hydrographic survey (Cudgen Creek)
  - 2007 hydrographic surveys (Mooball and Cudgera Creeks)
  - 2018 coastal LiDAR data (all estuaries)
- Review of previous literature and tidal inundation modelling results (refer Section 7.3).

The desktop assessment is based on the available information with no site-based verification of the findings completed. There may be exceptions to the findings presented herein with localised erosion or stable areas not being identified in the available data due to reasons such as data quality, data resolution and/or the assessment approach. Furthermore, presented numerical modelling results do not consider potential changes to estuary entrance conditions (refer Section 7.2) which may affect predicted tidal flows for future scenarios.

7.4.1 Summary of previous bank erosion study

A comprehensive bank erosion study for all three coastal estuaries in the study area (Hydrosphere, 2012) has been previously completed as part of the *CZMP for the Tweed Coast Estuaries* (Hydrosphere, 2013). This previous study mapped erosion hotspots using high tide survey data from September and/or October 2011 for all three estuaries. The survey data was used to classify each section of bank as stable, controlled or experiencing minor, moderate or severe erosion. A summary of the findings from this study is shown in Table 30. Natural erosion processes, together with anthropogenic impacts, were the main cause of erosion in the estuaries. Specifically, higher flow velocities at outer banks of bends in the creeks was a common cause of bank erosion and in the lower estuary, natural tidal processes together with boat wash and uncontrolled pedestrian access was another common cause of bank erosion. Specific results from this previous study are further discussed for each individual estuary in the following sections.

Table 30: Results summary from previous bank erosion study (Hydrosphere, 2012).

Creek	Survey length (km)	Stable (%)	Controlled (%)	Minor erosion (%)	Moderate erosion (%)	Severe erosion (%)
Mooball	14.8	58	12	22	5	3
Cudgera	14.7	81	3	15	0	1
Cudgen	15.5	52	11	25	6	6

7.4.2 Mooball Creek

Bank erosion is a known issue at Mooball Creek, as documented in the review of Tweed Coast estuaries management plan (Australian Wetlands, 2004). The Tweed Coast Estuaries CZMP (Hydrosphere, 2013) identifies high and medium risk areas of bank erosion at uncontrolled access points in the lower and mid-estuary, where public roads are close to the erosion scarps on both sides of the creek. This includes the foreshore upstream of the Tweed Coast Road bridge on the northern/ western bank and the eastern bank along Tweed Coast Road further upstream.

Modelled tidal currents for the immediate and 2120 planning periods are presented in Figure 59. The model results show that:

- Modelled peak tidal currents are relatively low throughout the lower estuary, suggesting that other factors, such as catchment floods, runoff or uncontrolled access, are contributing to bank erosion in the abovementioned areas.
- By 2120, peak tidal currents in the immediate entrance area are predicted to increase significantly with sea level rise. This would likely influence the morphology and bank conditions in this area. In this future scenario, peak tidal currents are also predicted to increase throughout the lower estuary. Some localised areas with peak tidal currents above 1m/s are predicted adjacent to the Tweed Coast Road bridge, potentially adding pressures to existing sites where bank erosion is already observed.

Figure 59: Modelled peak tidal currents in Mooball Creek lower estuary for present day and 2120 scenarios.

7.4.3 Cudgera Creek

Sections along lower Cudgera Creek downstream of the Tweed Coast Road bridge (northern side) have previously been identified at risk of erosion, according to Hydrosphere (2013). A review of available survey data from 2007 hydrographic survey elevation and 2018 suggests that bank erosion continues to be an issue in this area. Further upstream, near Cudgera Avenue bridge, other sites experiencing bank erosion have been reported by Australian Wetlands (2004).

Modelled tidal currents for the immediate and 2120 planning periods are presented in Figure 60. The model results show that:

- The distribution of simulated peak tidal currents for the immediate scenario aligns well with the abovementioned areas with existing bank erosion issues.
- By 2120, peak tidal current speeds are predicted to increase throughout the lower estuary with sea level rise. Specific areas with significant increases in peak tidal current speeds include the immediate entrance area downstream of the Tweed Coast Road bridge, sections within Christies Creek and adjacent to Cudgera Avenue bridge, adding further pressures to existing sites experiencing bank erosion.

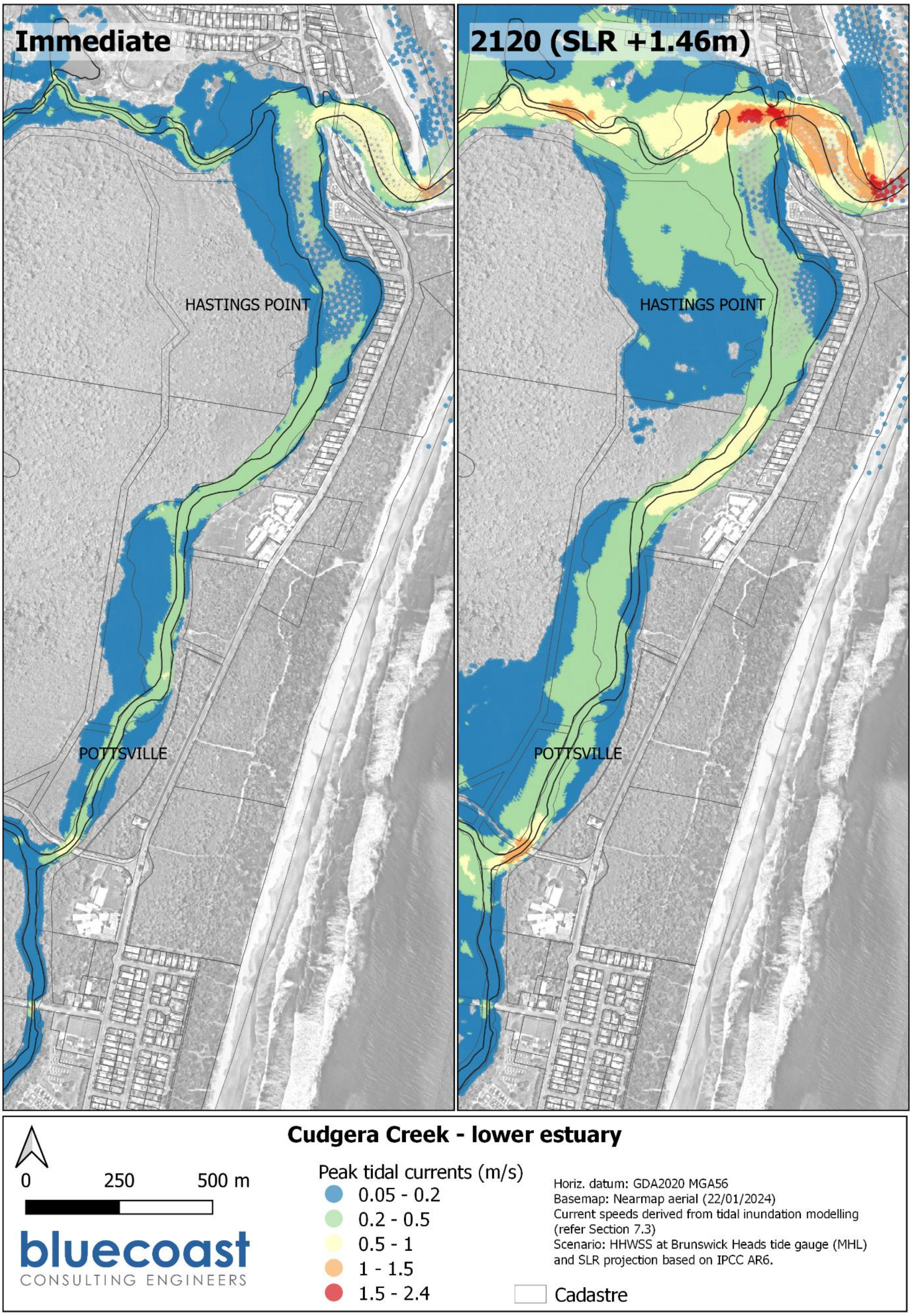


Figure 60: Modelled peak tidal currents in Cudgera Creek lower estuary for present day and 2120 scenario.

7.4.4 Cudgen Creek

Known bank erosion sites are located on the eastern side of Cudgen Creek downstream of the Sutherland Street bridge, where uncontrolled pedestrian access occurs on a steep embankment. Hydrosphere (2013) also notes potential risk of bank erosion near the Salt development area and that protection structures have been installed at Cudgen Foreshore Park, Ed Parker Park and Robert Dixon Park over the last 10 years to establish bank stabilisation.

Modelled tidal currents for the immediate and 2120 planning periods are presented in Figure 61. The model results show that:

- With exception for the immediate entrance area, simulated peak tidal currents are relatively low throughout the estuary, suggesting that other factors such as catchment floods, runoff or uncontrolled access contribute to bank erosion at the abovementioned upstream sites.
- By 2120, predicted peak tidal current speeds increase throughout the estuary with sea level rise. Specific sections of the estuary that show significant increases in peak tidal current speeds include, within creek bends along Salt and at either side of the Tweed Coast Road bridge at Casuarina.

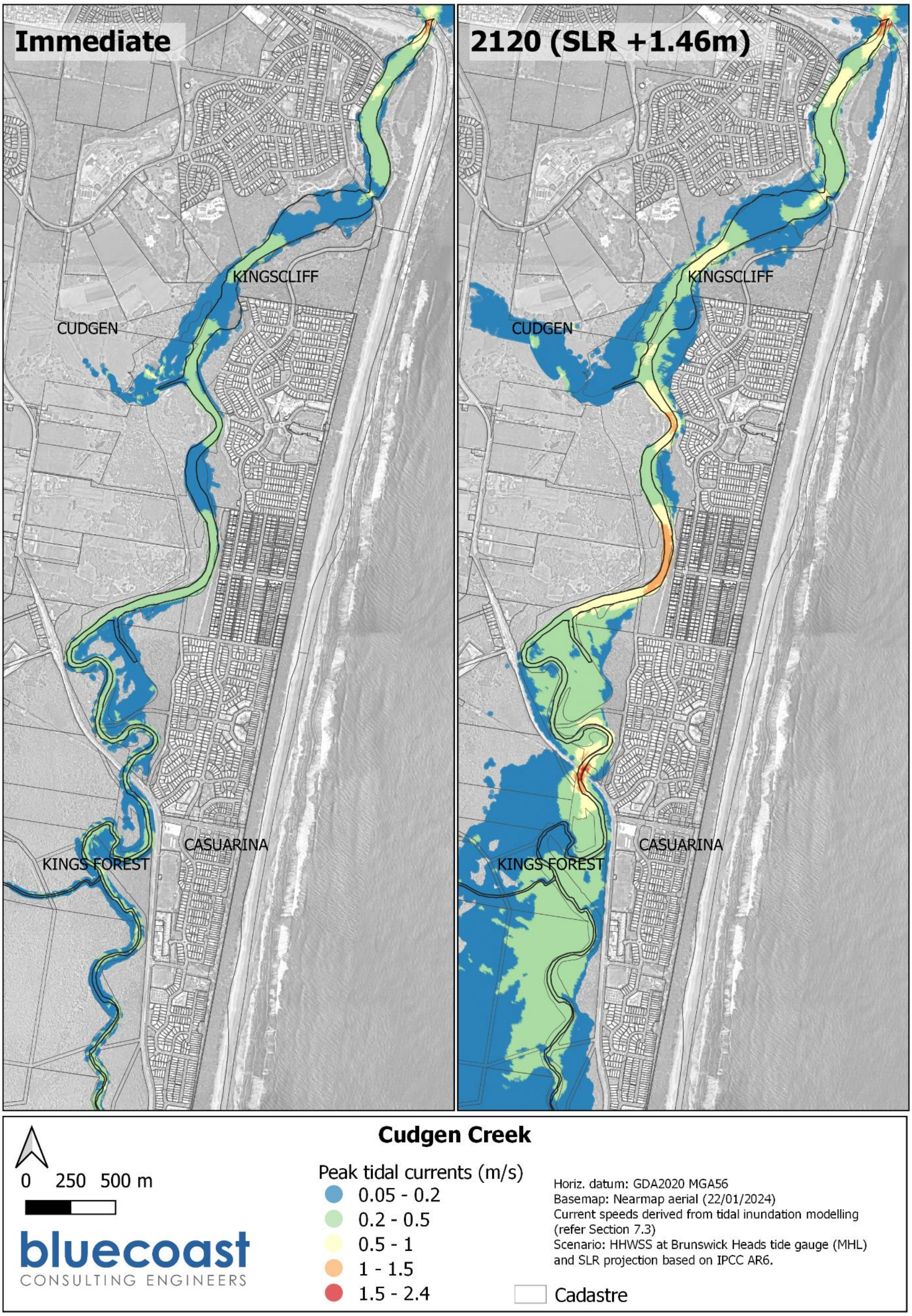


Figure 61: Modelled peak tidal currents in Cudgen Creek for present day and 2120 scenario.

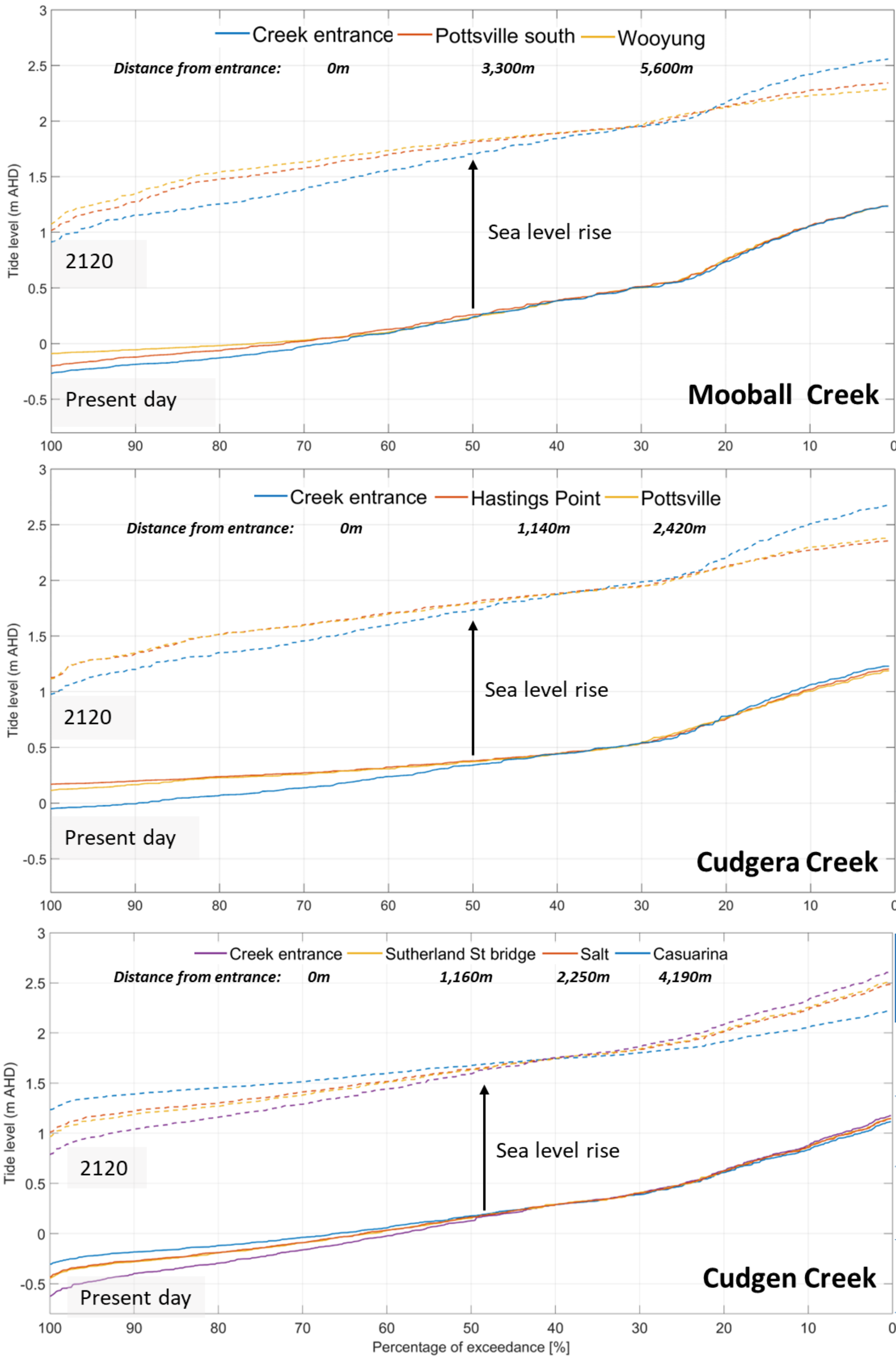
7.5 Potential impacts on ecology and groundwater

The Marine Estate Management Authority's (MEMA) state-wide Threat and Risk Assessment (TARA) identified climate change effects, including sea level rise, as a priority threat to environmental assets in estuaries in NSW (BMT WBM, 2017). Other priority threats include dredging and entrance management activities. Impacted environmental assets include saltmarshes, mangroves, seagrasses and other species protected under the *NSW Fisheries Management Act 1994* and *NSW Biodiversity Conservation Act 2016*.

Predicted changes in the tidal propagation and amplitudes with sea level rise were analysed based on the numerical modelling simulations undertaken as part of the tidal inundation assessment for the three coastal estuaries in the study area (refer Section 7.3). Typical tide level exceedance curves derived from a representative HHWSS tidal cycle and projected sea level rise for present day and a future scenario (2120) are presented in Figure 62. This data was used to consider the potential implications for estuarine ecology and groundwater resources, as described in the following sections.

The following key observations on the predicted changes in the tidal propagation in each estuary are made based on the simulation of a HHWSS tidal cycle at present and for the 2120 planning timeframe:

- Mooball Creek – An increase in tidal range (approximately +15cm) is observed in the lower entrance area while a slight decrease of around 10cm is predicted further upstream. This is largely explained by a higher increase in high tide levels at the entrance compared to locations further upstream. Mean tidal water levels at the assessed estuary sites are increased approximately by the projected sea level rise in the ocean (i.e., 1.46m by 2120).
- Cudgera Creek – A more significant increase in tidal range is predicted for both lower entrance and upstream sites, ranging from around +30cm (entrance) to around +20cm (2.4km upstream). As for the other estuaries, increase in mean tidal water levels are proportional to projected sea level rise.
- Cudgen Creek – No significant increase in tidal range is observed within the lower entrance area. With distance from the entrance, a progressive decrease in tidal range is observed for upstream sites. At the most upstream site, at 4.1km from the entrance, a reduction by around 40cm is predicted. Mean tidal water levels are also predicted to increase proportionally with sea level rise.



Distance from entrance		Tide level (m AHD) Min	Max	Range (m)
0m	Present:	-0.27	1.23	1.50
	2120:	0.92	2.56	1.64
3,300m	Present:	-0.20	1.24	1.44
	2120:	1.02	2.34	1.33
5,600m	Present:	-0.09	1.24	1.33
	2120:	1.07	2.29	1.21

Distance from entrance		Tide level (m AHD) Min	Max	Range (m)
0m	Present:	-0.05	1.23	1.28
	2120:	0.98	2.67	1.70
1,140m	Present:	0.11	1.19	1.07
	2120:	1.12	2.38	1.27
2,420m	Present:	0.17	1.21	1.04
	2120:	1.13	2.36	1.23

Distance from entrance		Tide level (m AHD) Min	Max	Range (m)
0m	Present:	-0.62	1.18	1.80
	2120:	0.79	2.61	1.82
1,160m	Present:	-0.44	1.15	1.60
	2120:	0.97	2.51	1.54
2,250m	Present:	-0.43	1.15	1.58
	2120:	1.01	2.49	1.48
4,190m	Present:	-0.30	1.12	1.42
	2120:	1.24	2.22	0.99

Figure 62: Simulated tide levels along three coastal estuaries for HHWSS tidal cycle and sea level rise (2120 scenario).

Note: Refer to tide level extraction locations shown on maps below.

7.5.1 Potential impacts on ecology

Potential ecology impacts were assessed by mapping known habitat features and predicted changes in tide levels based on tidal inundation modelling presented in Section 7.3, see Figure 63 to Figure 65. The DPI – Fisheries estuarine macrophyte mapping data was used to locate the vegetation communities along each estuary. To visualise the predicted tide levels and present day macrophyte distribution, a representative cross-section within the lower estuary at Cudgen Creek is presented in Figure 69 (see location of transect in Figure 65).

Generally, changes in tidal levels have consequences for the distribution patterns of:

- Seagrasses, which are typically found below the tide and whose distribution is determined by site-specific depth constraints that depend on light reaching through the water (the photic depth)
- Mangroves, which grow in areas ranging from mean sea level to mean high water
- Saltmarshes, which are found from mean high water to the highest astronomical tide.

Daily fluctuations in estuary water levels, potentially altering the size of the intertidal zone, could have significant repercussions for fish habitat. Increased water depths lowering light penetration may affect seagrass photosynthesis, diminishing productivity or resulting in die-offs. Higher tide levels could cause mangroves to encroach landward, potentially displacing saltmarshes. Shifts in the extent and condition of intertidal habitats could also impact shorebirds, particularly concerning sand and mudflats as well as saltmarshes, especially species thriving in lower vegetation. The impact on different estuary sections could be beneficial or detrimental.

As such, shifts in the frequency and duration of flooding could modify these ecosystems' distribution. Moreover, variances in species composition within mangrove and saltmarsh populations might occur as specific species react differently to the varying conditions of submersion. Even minor variations in tidal elevations can significantly influence the intertidal zone depending on the area's topography. That is, a gentle slope will cause more pronounced increases in both duration and range of flooding compared to a steeper terrain. The estuary bathymetry and intertidal sand or mudflats are inherently dynamic due to tidal actions and flooding, and this variability is expected to persist with rising sea levels. Consequently, anticipating precise adjustments in estuarine water levels and their effects on estuarine vegetation is challenging.

Greater tidal reach upstream may prompt the spread of seagrasses, mangroves, freshwater macrophytes, and associated lifeforms. This in turn, could alter the migratory behaviours and spawning sites of fish.

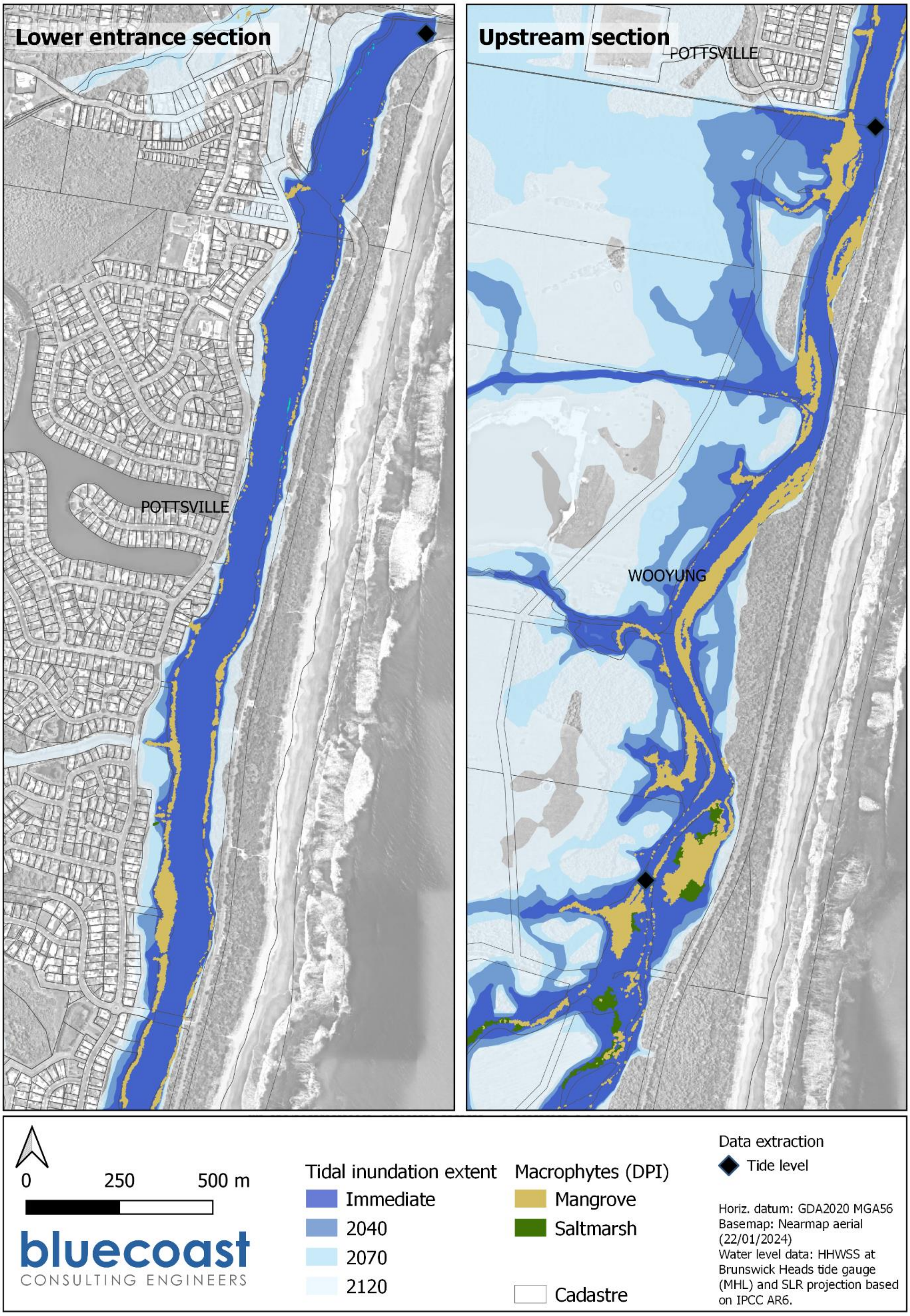


Figure 63: Predicted tidal inundation extent and DPI macrophyte mapping for sections along Mooball Creek.

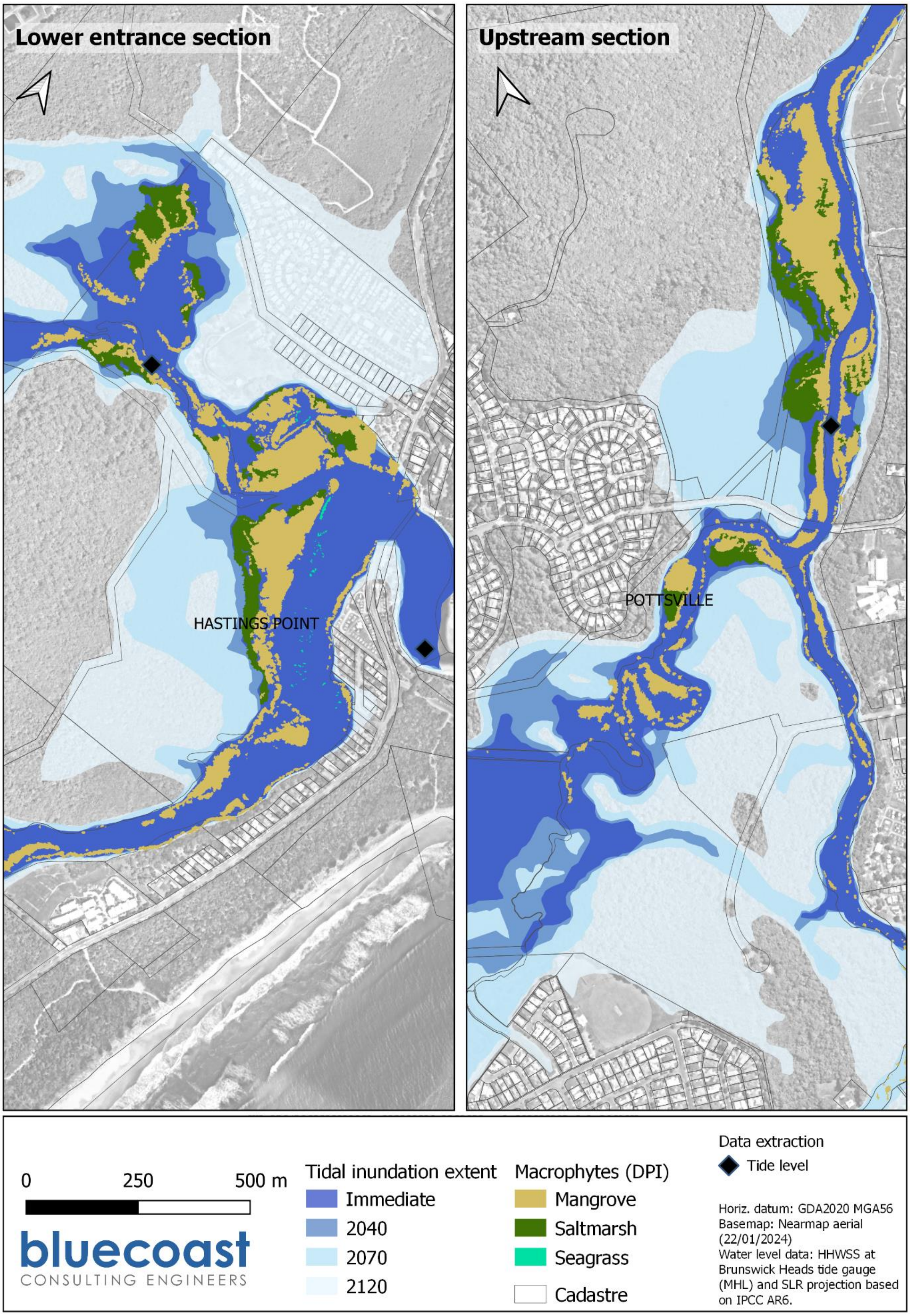


Figure 64: Predicted tidal inundation extent and DPI macrophyte mapping for sections along Cudgera Creek.

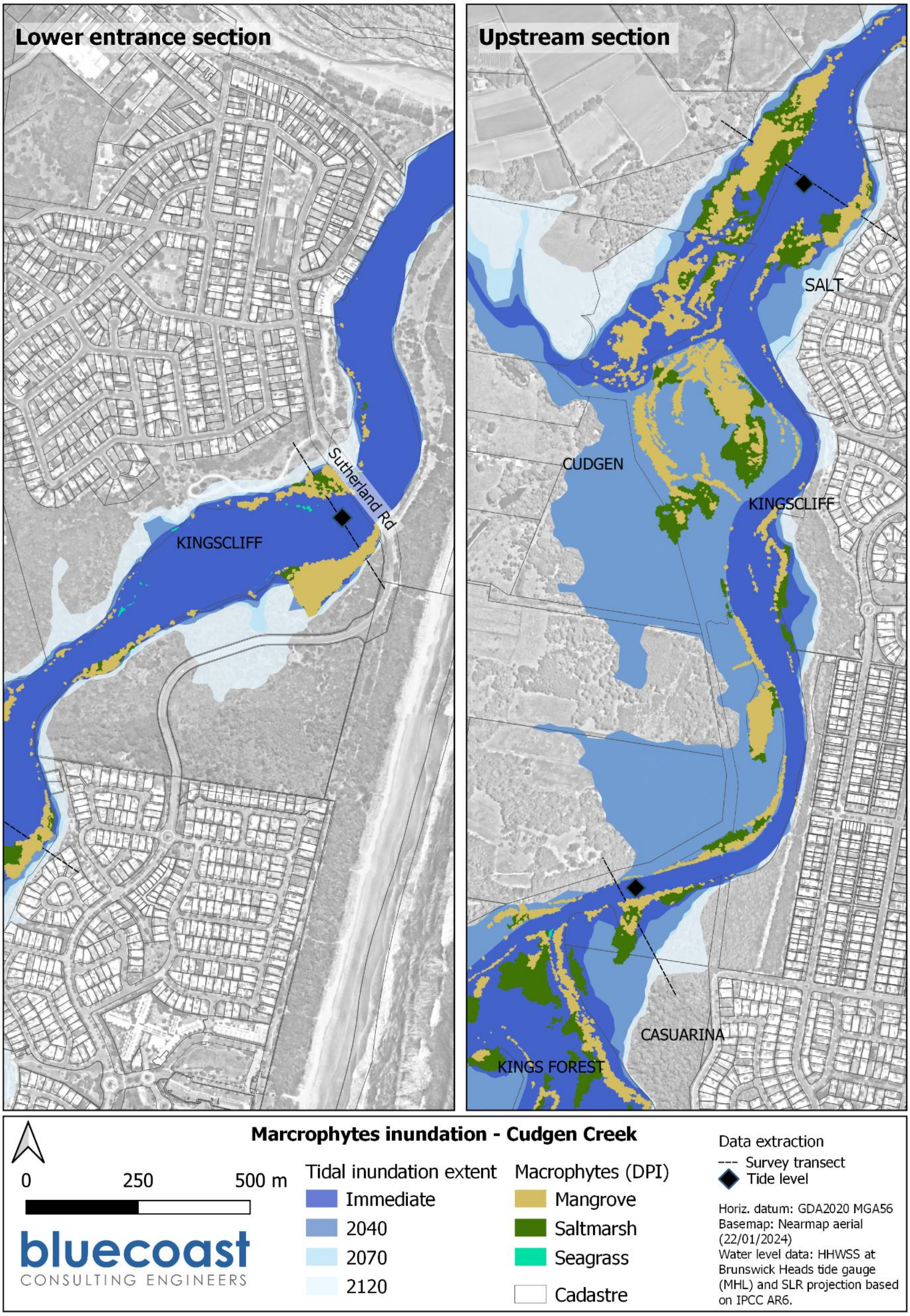


Figure 65: Predicted tidal inundation extent and DPI macrophyte mapping for sections along Cudgen Creek.

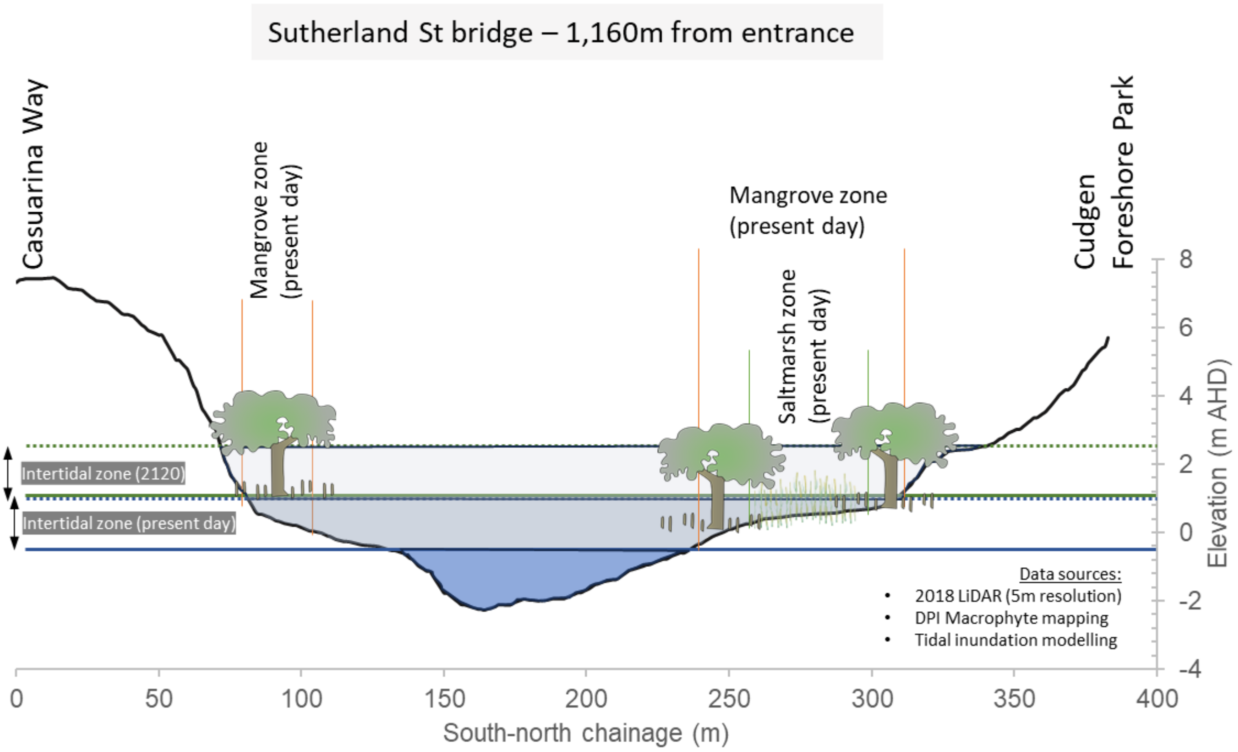


Figure 66: Conceptual model of predicted tidal inundation during a high spring tide and current macrophyte distribution for a transect across Cudgen Creek (upstream of Sutherland Street bridge).

Note: Refer to maps above for transect location.

7.5.2 Potential impacts on groundwater

Sea level rise may contribute to saline intrusion and inundation of coastal freshwater resources along low-lying coastal areas, particularly surrounding estuaries (Timms et al., 2008). This includes sub-surface impacts such as inland migration of the freshwater-saltwater interface and surface inundation of low-lying areas, including changes to the frequency and duration of inundation. Changes in the tidal extent as well as frequency and duration for the three coastal estuaries are shown in earlier sections (refer Figure 68 and tidal inundation maps in Section 9).

When freshwater resources are mixed with as little as 5% seawater, they become unsuitable for many valuable uses (Timms et al., 2008). This includes providing drinking water, irrigating agricultural fields, maintaining parks, gardens, golf courses, and supporting ecosystems that rely on groundwater. Such impacts are likely compounded by changes in climate seasonality such as longer droughts and elevated groundwater levels from more frequent extreme rainfall and inundation (Anderson, 2017).

Site-specific data on groundwater resources was not available for this study. Hence, no detailed assessment of the predicted tidal inundation extents and associated impacts on groundwater resources was completed.

8. Coastal asset risk assessment

A coastal risk assessment of coastal erosion/ recession and tidal inundation in the Tweed Shire was undertaken. The assessment identifies, and evaluates, risks to coastal assets (natural and built) across five planning periods (immediate, 2040, 2050, 2070, and 2120). The assessment approach and results are provided in Appendix D.

9. Map compendium

10. Glossary of terms

Accretion – the build-up of sediments to form land or shoaling in coastal waters or waterways.

Alongshore or Longshore – parallel to and near the shoreline.

Annual Exceedance Probability (AEP) – the probability as a percentage at which a given event is likely to occur in one year.

Australian Height Datum (AHD) – the official national vertical datum for Australia.

Average Recurrence Interval (ARI) – the average or expected value of the periods between exceedances of a given intensity event over a given duration.

Bathymetric data – measurements of the shape of the bed or the depth of a body of water.

Beach profile (or coastal profile) – a cross-section taken perpendicular to a given beach contour; the profile may include the face of a dune or seawall, extend over the backshore, across the foreshore, and seaward underwater into the nearshore zone.

Beach scraping – also referred to as 'nature assisted beach enhancement' (NABE) is a mechanical intervention to speed up the natural processes of berm and foredune recovery after a storm event.

Beach slope – the gradient at which the beach slopes seaward.

Bedrock – a general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material.

Berm – on a beach, a nearly horizontal plateau on the beach face or backshore, formed by the deposition of beach material by wave action or by means of a mechanical plant as part of a beach renourishment scheme. Some natural beaches have no berm, others have several.

Built assets – built infrastructure.

Bypassing, sand – hydraulic or mechanical movement of sand from the accreting up–drift side to the eroding down-drift side of an inlet or harbour entrance. The hydraulic movement may include natural movement as well as movement caused by humans.

Closure depth – generally considered the seaward limit of littoral transport (collected over several years).

Coastal barrier – a barrier between the sea and other land or landforms or river/lake/lagoon (generically used herein for natural dunes or man-made structures).

Coastal inundation – coastal inundation occurs when a combination of marine and atmospheric processes raises the water level at the coast above normal elevations, causing land that is usually 'dry' to become inundated by sea water. Alternatively, the elevated water level may result in wave runup and overtopping of natural or built shoreline structures (e.g., dunes, seawalls).

Coastal lake or lagoon – a coastal water body that is generally closed off from the sea by a sandy barrier. Water levels and water quality may be quite different to the nearby ocean.

Coastal management program (CMP) – a long-term strategy for the coordinated management of land within the coastal zone, prepared and adopted under Part 3 of the CM Act.

Coastal sediment compartment – an area of the coast defined by its sediment flows and landforms. Coastal sediment compartments may be mapped at primary, secondary or tertiary (local) scales. Boundaries are generally defined by structural features related to the geologic frameworks that define the planform of the coast.

Damage (to seawalls) – defined as any displacement or dislodgment of armour units.

Digital elevation model (DEM) – gridded elevation data to represent terrain.

DCCEEW – Department of Climate Change, Energy, the Environment and Water.

Dune ridge – shore-parallel sand ridge that forms part of a dune system.

East Coast Low – an intense low-pressure system that occurs off the east coast of Australia, bringing storms, high waves and heavy rain. East coast lows generally occur in autumn and winter off NSW, southern Queensland and eastern Victoria.

Elevated still water levels – ocean water level raised due to a storm surge.

El Niño southern oscillation (ENSO) – a year to year fluctuation in atmospheric pressure, ocean temperatures and rainfall associated with El Niño (warming of the oceans in the equatorial eastern and central Pacific). El Niño tends to bring below average rainfall.

Erosion – the wearing away of land by the action of natural forces. On a beach, the carrying away of beach material by wave action, tidal currents, littoral currents, or by deflation.

Estuary – CM Act defines as any part of a river, lake, lagoon, or coastal creek whose level is periodically or intermittently affected by coastal tides, up to the highest astronomical tide.

Geomorphology – that branch of physical geography which deals with the form of the earth, the general configuration of its surface, the distribution of the land, water, etc.; or the investigation of the history of geologic changes through the interpretation of topographic forms.

Geotextile – a synthetic fabric which may be woven or non–woven and used as a filter.

High High Water Solstice Springs (HHWSS) – highest tidal level that tides reach during the spring tides at the solstices. It is consistent with predicted levels for higher (king) tides but is slightly lower than highest astronomical tide (HAT).

Highest Astronomical Tide (HAT) – the highest tidal level which can be predicted to occur under average meteorological conditions.

Holocene – an epoch of the Quaternary period, from the end of the Pleistocene, about 8,000 years ago, to the present time.

Hydrodynamic – relates to the specific scientific principles that deal with the motion of fluids and the forces acting on solid bodies immersed in fluids, and in motion relative to them.

Incipient dune – the most seaward and immature dune of the dune system. Vegetation characterised by grasses such as spinifex. On an accreting coastline, the incipient dune will develop into a foredune.

Infiltration – the process at which water is absorbed into the ground.

Intermittently closed and open lakes and lagoons (ICOLL) – coastal lakes and lagoons where the entrance may be closed to the sea from time to time and for varying periods, by accretion of a berm.

Inundation – flooding of land area.

IPCC – Intergovernmental Panel on Climate Change.

Interdecadal Pacific Oscillation (IPO) – an irregular interdecadal sea surface temperature in the Pacific Ocean that modulates the strength and frequency of the El Niño Southern Oscillation.

Joint probability – the probability of two events occurring at the same time.

King tides – any high water level that is well above the average, commonly applied to two spring tides that are the highest for the year, one during summer and one in winter.

LiDAR – Light Detection and Ranging, is a remote sensing method that uses light in the form of a pulsed laser to measure ranges.

Littoral – of or pertaining to a shore, especially of the sea. Often used as a general term for the coastal zone influenced by wave action, or, more specifically, the shore zone between the high and low water marks.

Lowest Astronomical Tide (LAT) – the lowest levels which can be predicted to occur under average meteorological conditions.

Mean High Water Neaps (MHWN) – the height of mean high water neaps is the average throughout a year of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least.

Mean High Water Springs (MHWS) – the height of mean high water springs is the average throughout a year of the heights of two successive high waters during those periods of

24 hours (approximately once a fortnight) when the range of the tide is greatest.

Mean Low Water Neaps (MLWN) - the height of mean low water neaps is the average throughout a year of the heights of two successive low waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is least.

Mean Low Water Springs (MLWS) – the height of mean low water springs is the average throughout a year of the heights of two successive low waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest.

Mean Sea Level (MSL) – the average level of the sea over longer periods of time.

Morphological response – change in beach shape/slope due to an event.

Multivariate copula analysis - used to describe the dependence between random variables.

Natural assets – the natural beach, dunes, and vegetation.

Numerical modelling – computer software modelling used to simulate coastal processes.

OEH – NSW Office of Environment and Heritage (now DCCEEW).

Overtopping – the process of water passing over a hard coastal structure such as seawall.

Overwash – the process of water passing over a dune.

Pleistocene – the geological epoch that lasted from c. 2.58 million to 11,700 years ago, spanning the Earth's most recent period of repeated glaciations. First epoch of the Quaternary period, between the Pliocene and Holocene epochs.

Quaternary – current and most recent of the three periods of the Cenozoic Era in the geologic time scale of the International Commission on Stratigraphy. It follows the Neogene Period and spans from 2.58 million years ago to the present.

Recession – a continuing landward movement of the shoreline; or a net landward movement of the shoreline over a specified time.

Refraction – the process by which the direction of a wave moving in shallow water at an angle to the contours is changed. The part of the wave advancing in shallower water moves more slowly than that part still advancing in deeper water, causing the wave crest to bend toward alignment with the underwater contours; or the bending of wave crests by currents.

Revetment or seawall – a type of coastal protection work which protects assets from coastal erosion by armouring the shore with erosion–resistant material. Large rocks/boulders, concrete or other materials (such as geotextile sand containers) are used, depending on the specific design requirements.

RCP – Representative Concentration Pathway is a greenhouse gas concentration trajectory adopted by the IPCC.

Rip – a narrow, strong shore normal current in the nearshore area of most wave-dominated beaches (i.e. most beaches along the open coast of NSW). They are fed by along shore feeder currents initiated by the deflection of waves at the shoreline. There are diverse types of rip on NSW beaches and they affect beach safety.

Riparian – pertaining to the banks of a body of water, such as an estuary.

Sand budget – quantitative analysis of the movement and distribution of sediment (or sand) within a coastal region. Accounts for the sources of sand, such as erosion from coastal cliffs, discharge from rivers or onshore sand supply, and the processes that transport it, such as wave action or longshore sand movements. The coastal sand budget also includes the sinks or locations where sand is deposited, such as on the beach or in a coastal lagoon.

Scour – loss of beach/sediment at the toe of a hard structure or dune.

Sediment transport – the process whereby sediment is moved offshore, onshore or along shore by wave, current or wind action.

Semi-diurnal tide – two high and two low tides a day.

Significant wave height – the average height of the largest 1/3rd of waves in a given period.

Southern Oscillation Index – the normalised mean atmospheric pressure difference between Tahiti and Darwin, measured at sea level. The SOI is negative during El Niño and positive during La Niña.

Storm surge – the abnormal rise in sea level during a storm, measured as the height of the water above the normal predicted astronomical tide.

Swell waves – ocean waves that travel beyond the area where they are generated.

Tidal delta – where an inlet of a barrier estuary or open coastal lake is dominated by tidal processes, a flood tide delta develops inside the entrance, as tidal currents transport marine sand into the estuary. Ebb tide deltas may also occur, outside the mouth of an estuary.

Tidal plane – a plane of reference for elevations, determined from the rise and fall of the tides.

Tidal limit – the maximum upstream location on a watercourse at which a tidal variation in water level is observed.

Toe – the 'bottom' or 'front' of a hard structure.

Training walls – walls constructed at the entrances of estuaries and rivers to improve navigability.

Tropical cyclone – intense low-pressure system in which winds of at least 63km/hour whirl in a clockwise direction, in the southern hemisphere around a region of calm air.

Wave climate – the seasonal and annual distribution of wave height, period and direction.

Wave runup - the maximum vertical extent of wave uprush on a beach or structure above the still water level (SWL).

Wave setup - occurs as waves approach the coast and transform over the nearshore beach profile where radiation stresses and ultimately wave breaking force elevated water levels at the shoreline.

Wind waves (or sea) – ocean waves resulting from the action of the wind on the surface of the water.

WRB – Waverider Buoy used to measure ocean wave conditions.

XBeach – numerical model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms.

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Appendix A: Beach compartment context and analysis results

Overview

Supporting information for the survey analysis is provided as follows:

- An overview of all sediment cells used in the survey analysis is provided in Table 31.
- A summary of the survey analysis results for each beach within the study area is provided in Table 31.

The remainder of this appendix provides a detailed assessment relevant to the coastal hazards separately for each beach compartment, including:

- An overview of each compartment and its individual beaches.
- Long-term beach volume and shoreline change data to inform the coastal sand budget and hazard assessments.
- Beach erosion storm demand estimates to inform the probabilistic erosion and recession hazard assessment. These were based on the observed range of storm demand volumes in the available photogrammetry data, i.e., maximum volume change between successive survey/imagery dates.

Table 31: Sediment cells adopted for survey analysis.

Beach compartment	Beach	Cell ID	Cell area	Alongshore length - m (along 0m AHD contour)	Alongshore length - m (along -4m AHD contour)
Wooyung to Pottsville	Wooyung Beach	WY-1-1	439,552	4,728	
		WY-1-2	2,722,162		4,710
		WY-1-LS	2,568,631		
	Mooball Beach	WY-2-1	133,830	1,509	
		WY-2-2	818,186		1,528
		WY-2-LS	772,603		
Pottsville to Hastings Point	Pottsville Beach (south)	PV-1-1	250,708	2,561	
		PV-1-2	1,396,179		2,543
		PV-1-LS	1,021,145		
		PV-2-1	125,380	1,408	

Beach compartment	Beach	Cell ID	Cell area	Alongshore length - m (along 0m AHD contour)	Alongshore length - m (along -4m AHD contour)
	Pottsville Beach (north)	PV-2-2	701,709		1,389
		PV-2-LS	503,405		
	Cudgera Beach	HP-1-1	160,529	1,516	
		HP-1-2	672,306		1,510
		HP-1-LS	609,037		
Hastings Point to Norries Headland	Hastings Point headland	HP-BYPASS-IN	361,355		604
		HP-BYPASS-OUT	290,056		
	Maggies Beach (south)	HP-2-1	101,170	1,089	
		HP-2-2	695,964		1,016
		HP-2-LS	404,716		
	Maggies Beach (north)	CB-1-1	144,435	1,455	
		CB-1-2	798,460		1,425
		CB-1-LS	803,577		
Norries Headland to Cudgen Headland	Norries Headland	CB-BYPASS-IN	98,271		224
		CB-BYPASS-OUT	200,690		
	Cabarita Beach	CB-2a-1	11,127	149	
		CB-2-1	90,055	1,136	
		CB-2-2	996,564		1,374
		CB-2-LS	729,719		
	Casuarina Beach	CS-1-1	251,821	2,978	
		CS-1-2	1,915,250		2,951
		CS-1-LS	1,733,405		

Beach compartment	Beach	Cell ID	Cell area	Alongshore length - m (along 0m AHD contour)	Alongshore length - m (along -4m AHD contour)
	South Kingscliff Beach (south)	CS-2-1	233,815	2,962	
		CS-2-2	1,590,372		2,929
		CS-2-LS	1,206,137		
	South Kingscliff Beach (north)	CS-3-1	149,200	1,649	
		CS-3-2	868,754		1,765
		CS-3-LS	693,445		
Cudgen Headland to Fingal Head	Cudgen Headland	KC-BYPASS-IN	441,851		282
	Kingscliff Beach (south)	KC-1-1	197,634	1,874	
		KC-1-2	1,210,186		1,761
	Kingscliff Beach (north)	KC-2-1	110,866	1,372	
		KC-2-2	579,891		1,343
	Dreamtime Beach (south)	DT-1-1	153,615	1,911	
		DT-1-2	784,335		1,893
	Dreamtime Beach (north)	DT-2-1	162,419	1,730	
		DT-2-2	746,359		1,688
Fingal Head to Point Danger	Fingal Head	FH-BYPASS-IN	346,209		482
		FH-BYPASS-OUT	128,848		
	Fingal Head Beach	LB-1-2	873,538	1,159	1,129
		LB-1-LS	281,576		
	Letitia Beach (south)	LB-2-2	1,032,700	1,182	1,157
		LB-2-LS	496,938		
		LB-3-2	981,421	1,162	1,073

Beach compartment	Beach	Cell ID	Cell area	Alongshore length - m (along 0m AHD contour)	Alongshore length - m (along -4m AHD contour)
	Letitia Beach (north)	LB-3-LS	329,894		
		TE-S	15,606		
	Tweed River Entrance	TE-OUT	496,264		348
	Tweed River Entrance	TE-IN	92,978		
	Duranbah Beach	DB-1-2	536,950	408	566

Table 32: Observed volume change in each analysis cell within the study area.

Compartment	Beach (cell ID)	Zone	Volume change relative to 2018 baseline (m^3)	
			2011	2018
Wooyung to Pottsville	Wooyung Beach (WY-1)	Subaerial beach	No data	0
		Upper shoreface	941,059	0
		Lower shoreface	1,343,668	0
	Mooball Beach (WY-2)	Subaerial beach	63,845	0
		Upper shoreface	224,261	0
		Lower shoreface	432,957	0
Pottsville to Hastings Point	Pottsville Beach (south) (PV-1)	Subaerial beach	No data	0
		Upper shoreface	426,853	0
		Lower shoreface	471,045	0
	Pottsville Beach (north)	Subaerial beach	50,466	0
		Upper shoreface	83,633	0

Compartment	Beach (cell ID)	Zone	Volume change relative to 2018 baseline (m^3) 2011	2018
	(PV-2)	Lower shoreface	129,998	0
	Cudgera Beach (HP-1)	Subaerial beach	134,579	0
		Upper shoreface	324,293	0
		Lower shoreface	258,828	0
Hastings Point to Norries Headland	Maggies Beach (south) (HP-2)	Subaerial beach	47,329	0
		Upper shoreface	448,659	0
		Lower shoreface	167,336	0
	Maggies Beach (north) (CB-1)	Subaerial beach	-25,437	0
		Upper shoreface	-122,370	0
		Lower shoreface	381,247	0
Norries Headland to Cudgen Headland	Cabarita Beach (CB-2)	Subaerial beach	9,170	0
			No data	0
		Upper shoreface	518,032	0
		Lower shoreface	177,723	0
	Casuarina Beach (CS-1)	Subaerial beach	59,620	0
		Upper shoreface	-95,597	0
		Lower shoreface	214,036	0
	South Kingscliff Beach (south) (CS-2)	Subaerial beach	118,246	0
		Upper shoreface	234,624	0
		Lower shoreface	225,401	0
	South Kingscliff Beach (north)	Subaerial beach	122,693	0
		Upper shoreface	257,870	0

Compartment	Beach (cell ID)	Zone	Volume change relative to 2018 baseline (m^3) 2011	2018
	(CS-3)	Lower shoreface	225,194	0
Cudgen Headland to Fingal Head	Kingscliff Beach (south) (KC-1)	Subaerial beach	328,131	0
		Upper shoreface	946,955	0
	Kingscliff Beach (north) (KC-2)	Subaerial beach	-20,234	0
		Upper shoreface	7,237	0
	Dreamtime Beach (south) (DT-1)	Subaerial beach	61,763	0
		Upper shoreface	-261,447	0
	Dreamtime Beach (north) (DT-2)	Subaerial beach	224,554	0
		Upper shoreface	32,674	0
Fingal Head to Point Danger	Fingal Head Beach (LB-1)	Subaerial beach & upper shoreface	960,284	0
		Lower shoreface	179,777	0
	Letitia Beach (south (LB-2))	Subaerial beach & upper shoreface	342,243	0
		Lower shoreface	338,575	0
	Letitia Beach (north) (LB-3)	Subaerial beach & upper shoreface	-63,952	0
		Lower shoreface	230,817	0
	Duranbah Beach (DB-1)	Subaerial beach & upper shoreface	283,038	0

Wooyung to Pottsville

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Wooyung to Pottsville compartment is a 10km beach that lies between South Golden Beach and Mooball Creek entrance (Figure 67). Table 33 provides the main characteristics of this compartment.

Table 33: Main characteristics of Wooyung to Pottsville compartment.

Parameter	Wooyung Beach	Mooball Beach	Pottsville Beach (south)
Beach type	Open beach	Open beach	Open beach
Sandy beach length	3,500m	4,000m	2,500m
Orientation	East-south-east	East-south-east	East-south-east
Relative wave exposure (NSW Nearshore Wave Tool)	Medium to high	Low to medium	Low
Coastal land-use / Resilience SEPP mapping	Billinudgel Nature Reserve at the southern end SEPP coastal wetland and littoral rainforest along the compartment	Extensive natural coastal area SEPP coastal wetland along the compartment SEPP littoral rainforest along the southern section	Suburban areas (Pottsville) along the northern bank of Mooball Creek at the northern end of the compartment SEPP coastal wetland along the southern section
Key morphological features	Nil	Black Rocks at the northern end	Black Rocks at the southern end Mooball Creek entrance and Potts Point at the northern end

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

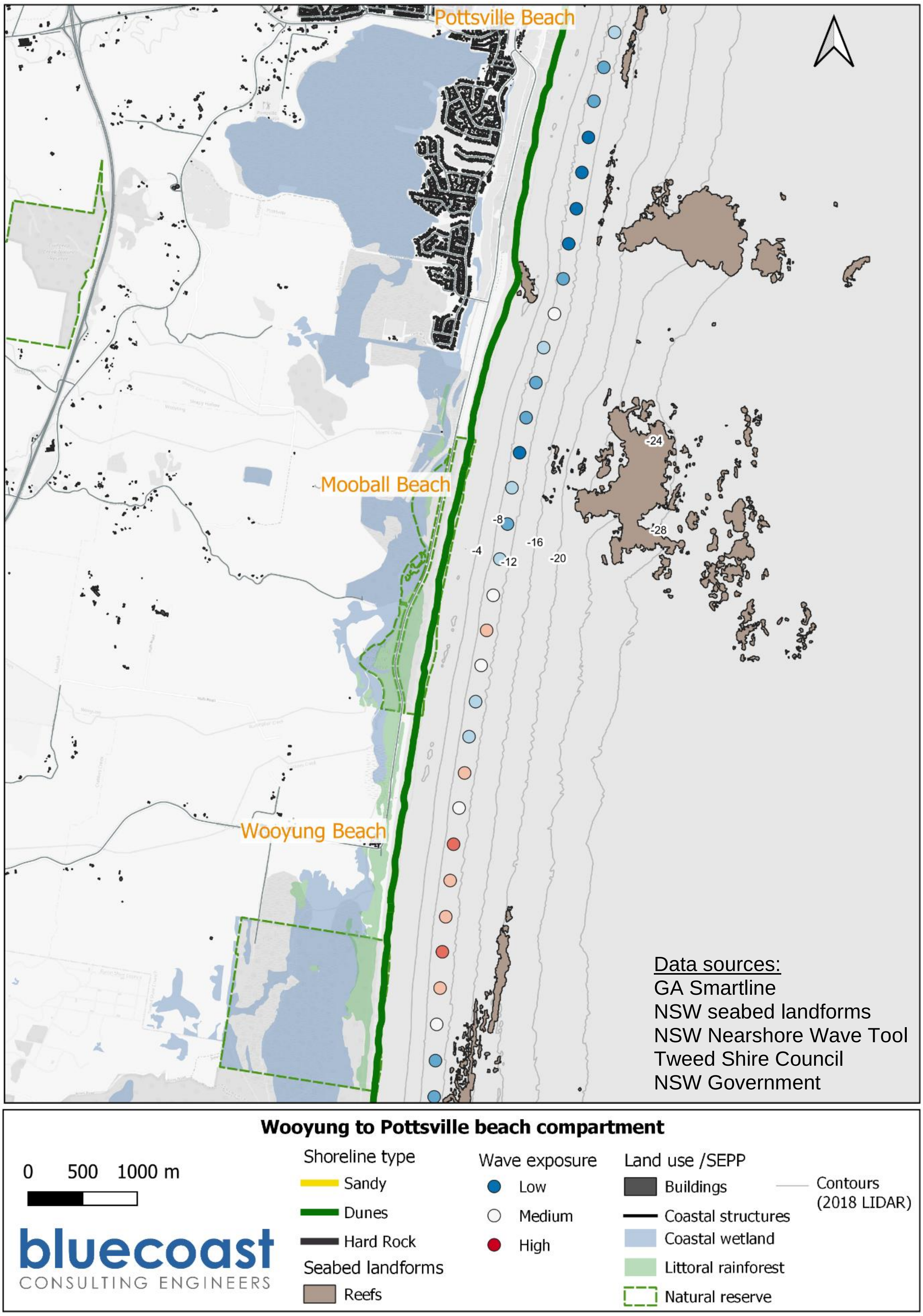


Figure 67: Overview of Wooyung to Pottsville compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Wooyung to Pottsville compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Wooyung to Pottsville compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 68.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 69.

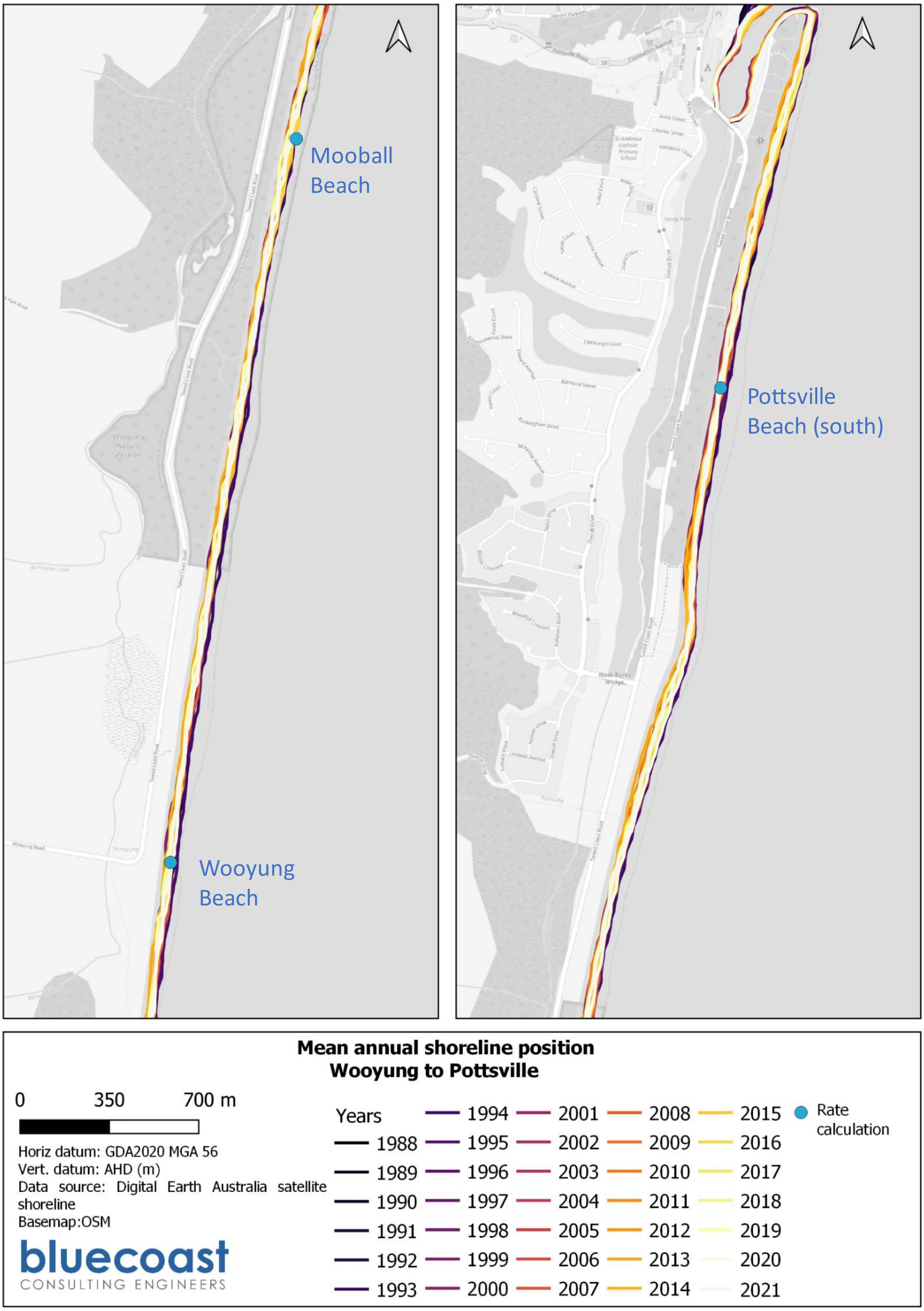


Figure 68: Mean annual shorelines within the Wooyung to Pottsville compartment from 1988 to 2021.

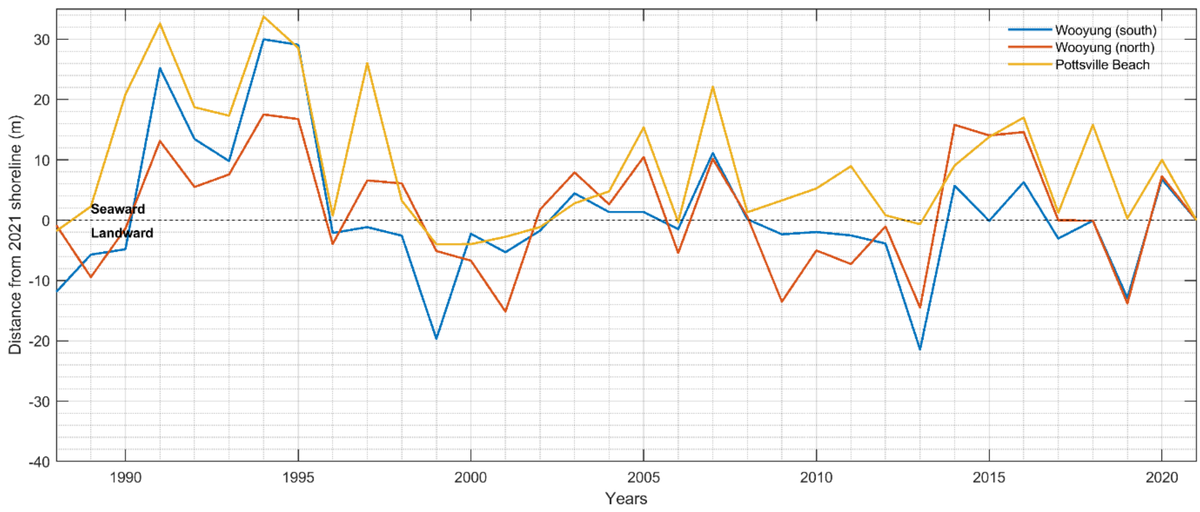


Figure 69: Mean annual shoreline position relative to 2021 shoreline for key areas within Wooyung to Pottsville compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. Block 1 here represents Wooyung Beach and block 2 represents Mooball Beach and Pottsville Beach (south). A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 70 for three different periods.
- Table 34 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

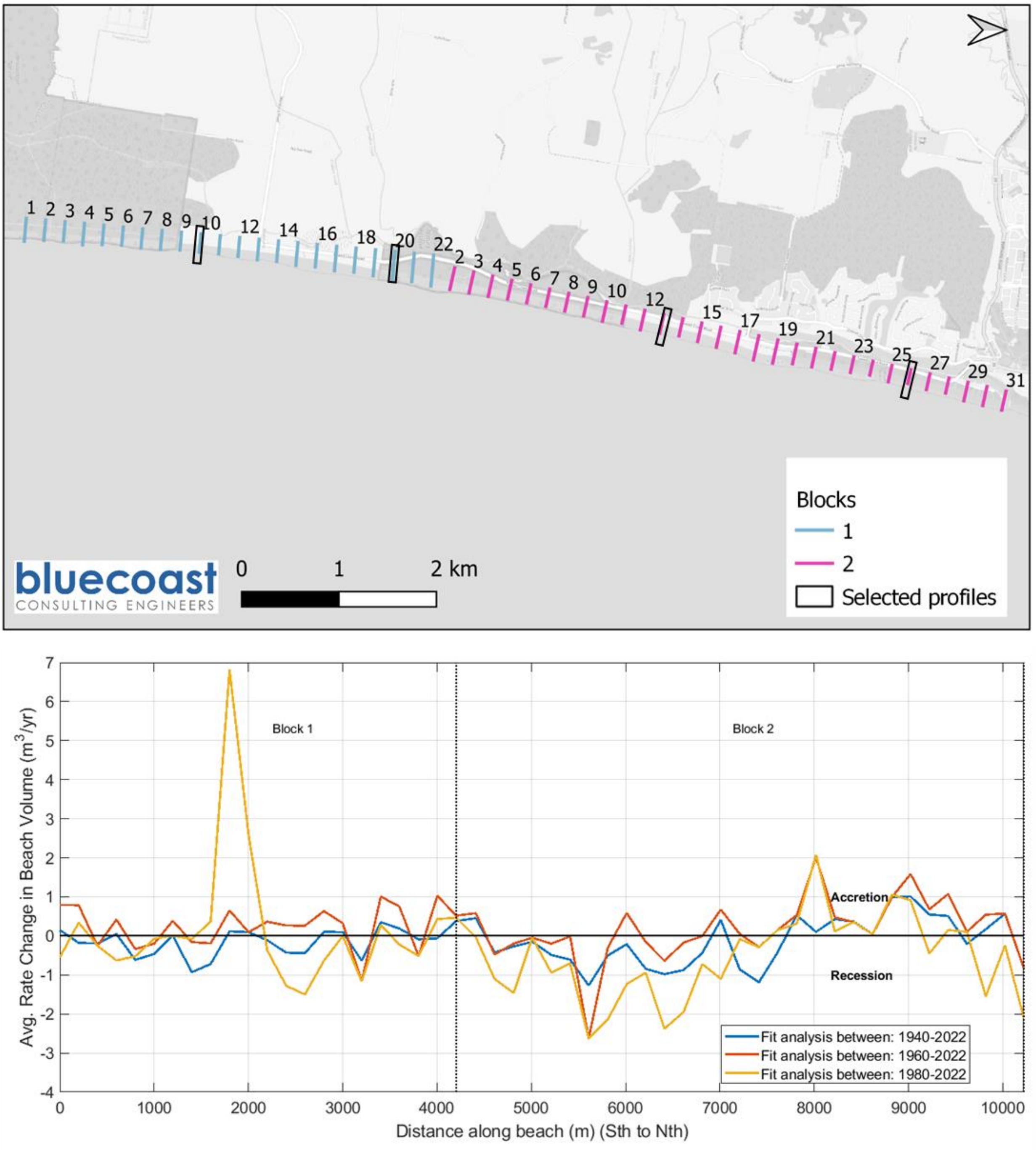


Figure 70: Profile locations and rate of change of subaerial beach volume along Wooyung to Pottsville compartment for short, medium and long-term analysis periods.

Table 34: Overview of photogrammetry profile analysis for Wooyung to Pottsville compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max] 1940-2022	1960-2022	1980-2022
Wooyung (1)	4,224m (22)	1947 – 2022 (75)	12 (varies)	-0.92, -0.15, 0.38	-1.16, 0.25, 1.02	-1.49, 0.16, 6.80
Mooball to Pottsville Beach (2)	6,000m (30)			-1.26, -0.14, 1.01	-2.62, 0.17, 2.00	-2.62, -0.56, 2.07

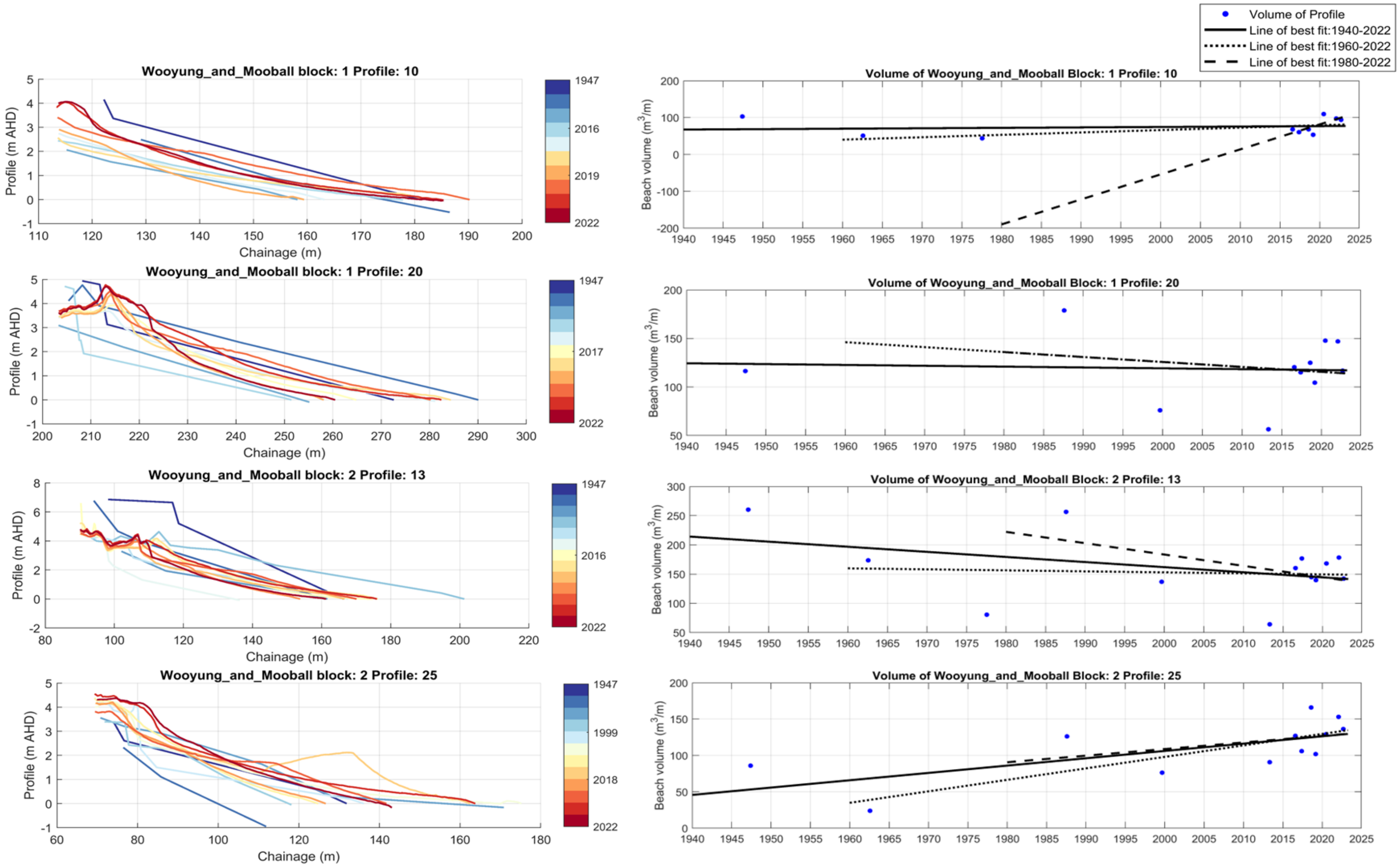


Figure 71: Photogrammetry beach profiles (right) and associated beach volume change over time (left).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 72. Individual beach profiles for Wooyung Beach, Mooball Beach and Pottsville Beach (south) are shown in Figure 73, Figure 74 and Figure 75.

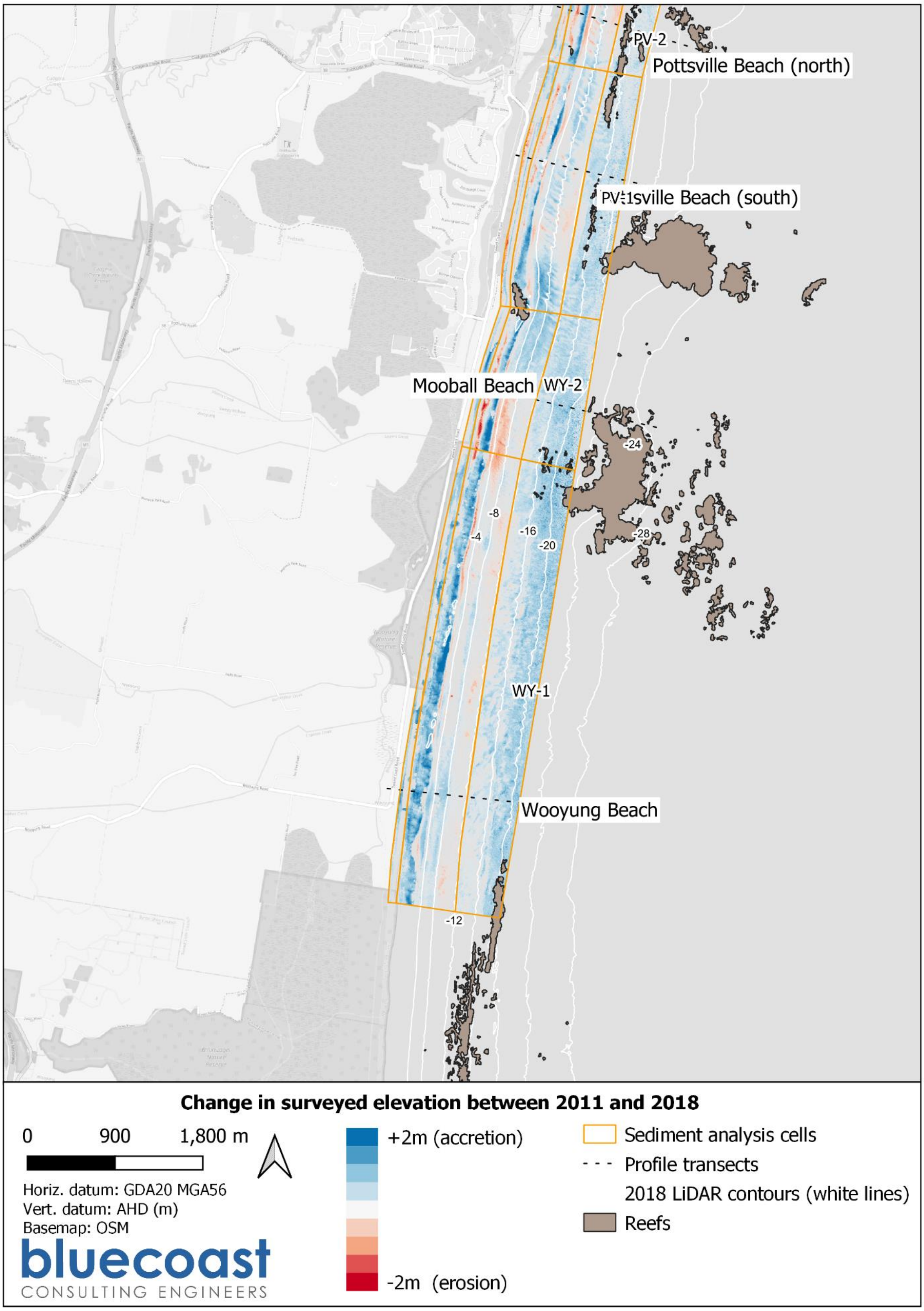


Figure 72: Surveyed elevation change along Wooyung to Pottsville compartment between 2011 and 2018.

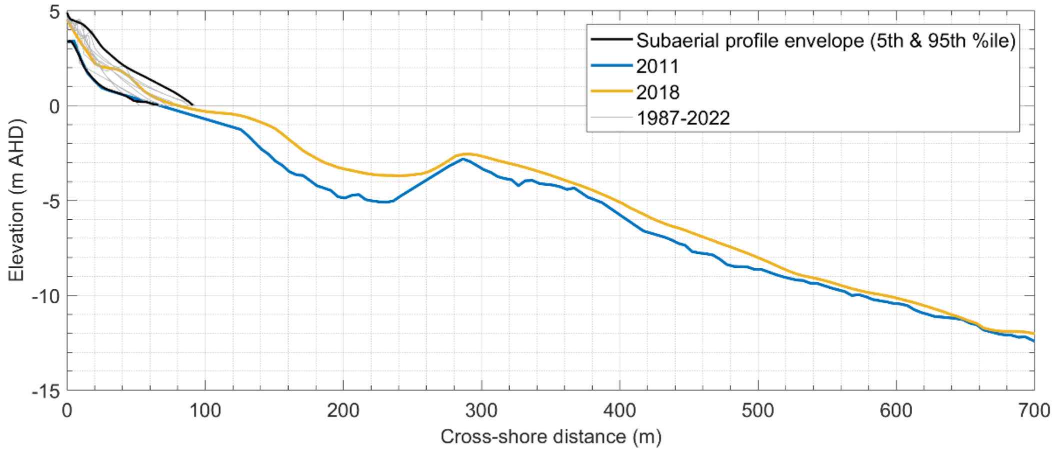


Figure 73: Profile evolution for Wooyung Beach transect.

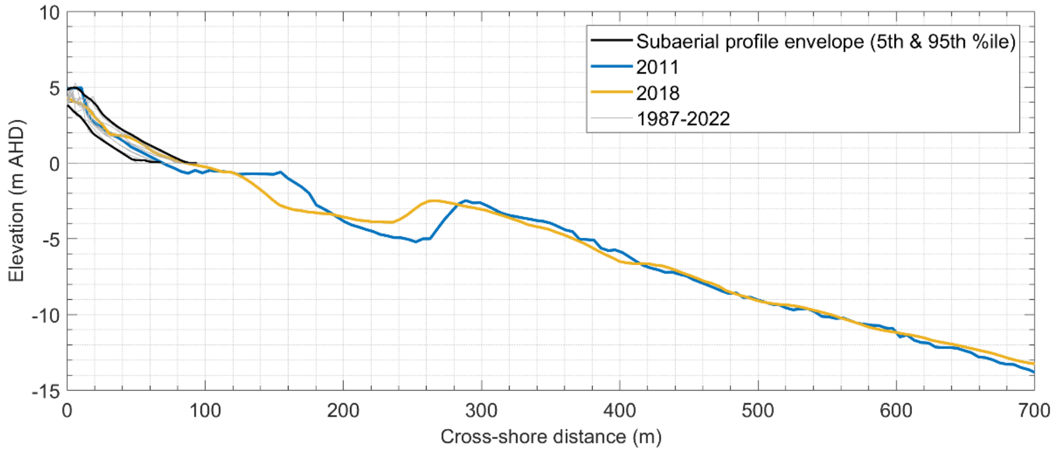


Figure 74: Profile evolution for Mooball Beach transect.

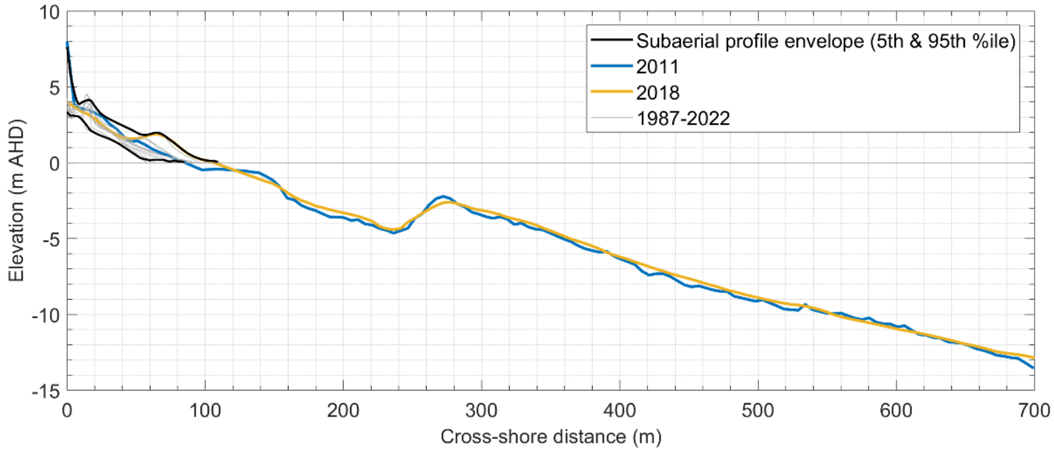


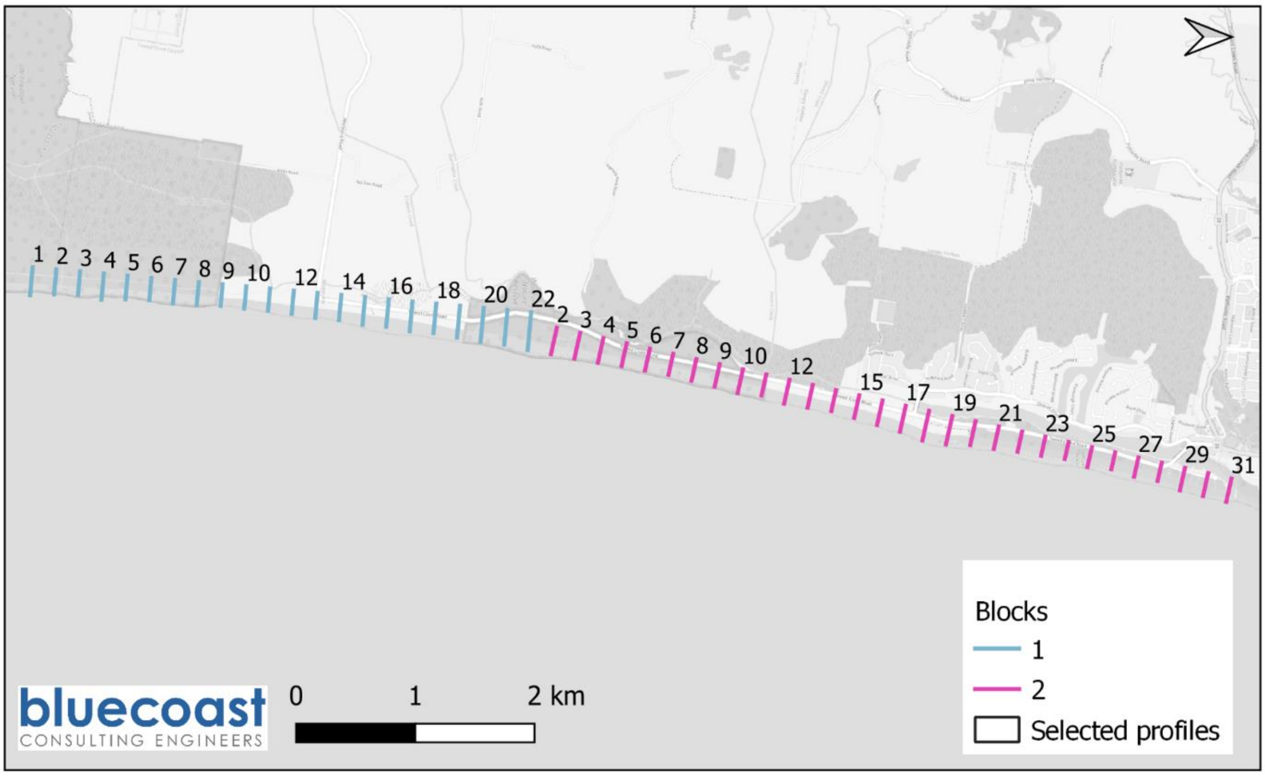
Figure 75: Profile evolution for Pottsville Beach (south) transect.

Beach erosion

Figure 76 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 1954 tropical cyclone, 1974 tropical cyclones and the 1999 East Coast Lows. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed. The pattern, from south to north, is described as:

- No observed alongshore trend in storm demand consistent with the open beach type. The storm demand volume is shown to be approximately 150m^3/m for all beaches in this compartment.
- For the 1974 storm, accretion is observed in the far north whereas erosion is observed along the rest of the beach. This may be associated with the Mooball Creek entrance being built during this same period (1967).



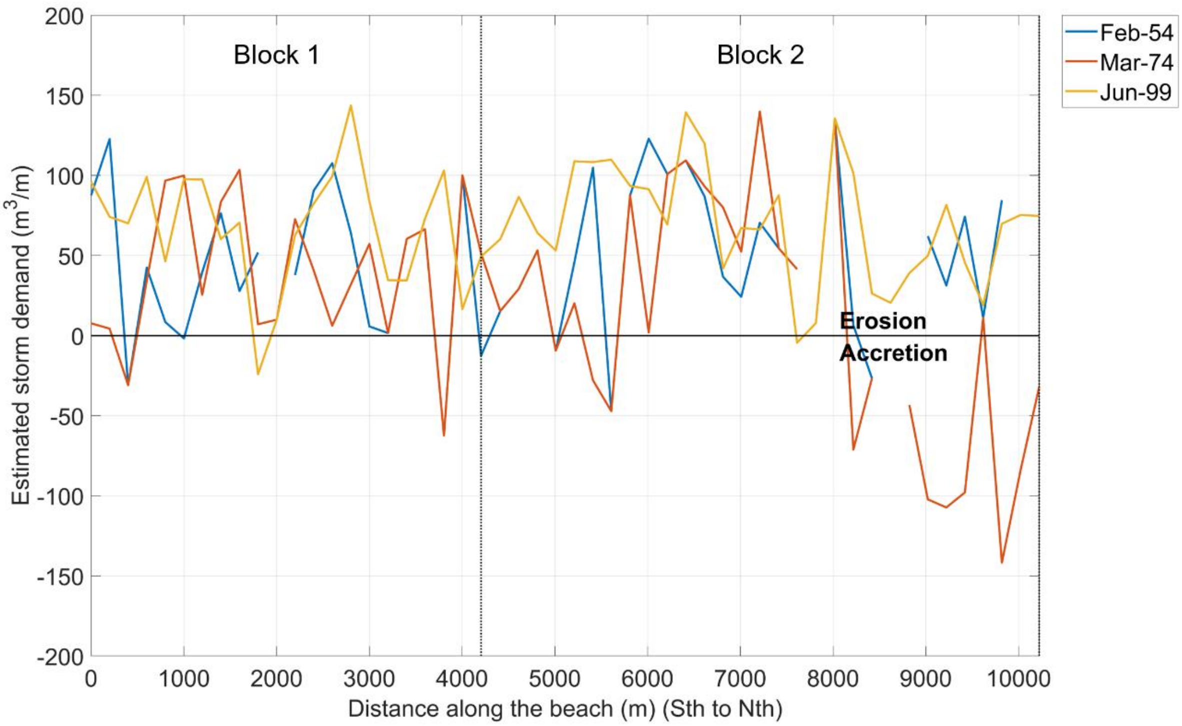


Figure 76: Alongshore storm demand estimates derived from photogrammetry for storms in 1954, 1974 and 1999.

Pottsville to Hastings Point

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Pottsville to Hastings Point beach compartment is 3,000m long and starts Mooball Creek entrance and extends to Hastings Point headland to the north (Figure 77). Table **35** provides the main characteristics of this compartment.

Table 35: Main characteristics of Pottsville to Hastings Point compartment.

Parameter	Pottsville Beach (north)	Cudgera Beach
Beach type	Open beach	Semi- embayment beach (headland control to the north)
Sandy beach length	1,500m	1,500m
Orientation	East-south-east	South-east
Relative wave exposure (NSW Nearshore Wave Tool)	Low	Low
Coastal land-use / Resilience SEPP mapping	Suburban area (Pottsville).	Extensive natural coastal area with suburban area (Hastings Point) to the northern end. SEPP littoral rainforest at the northern end.
Key morphological features	Mooball Creek entrance to the south	Hastings Point Headland to the north

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

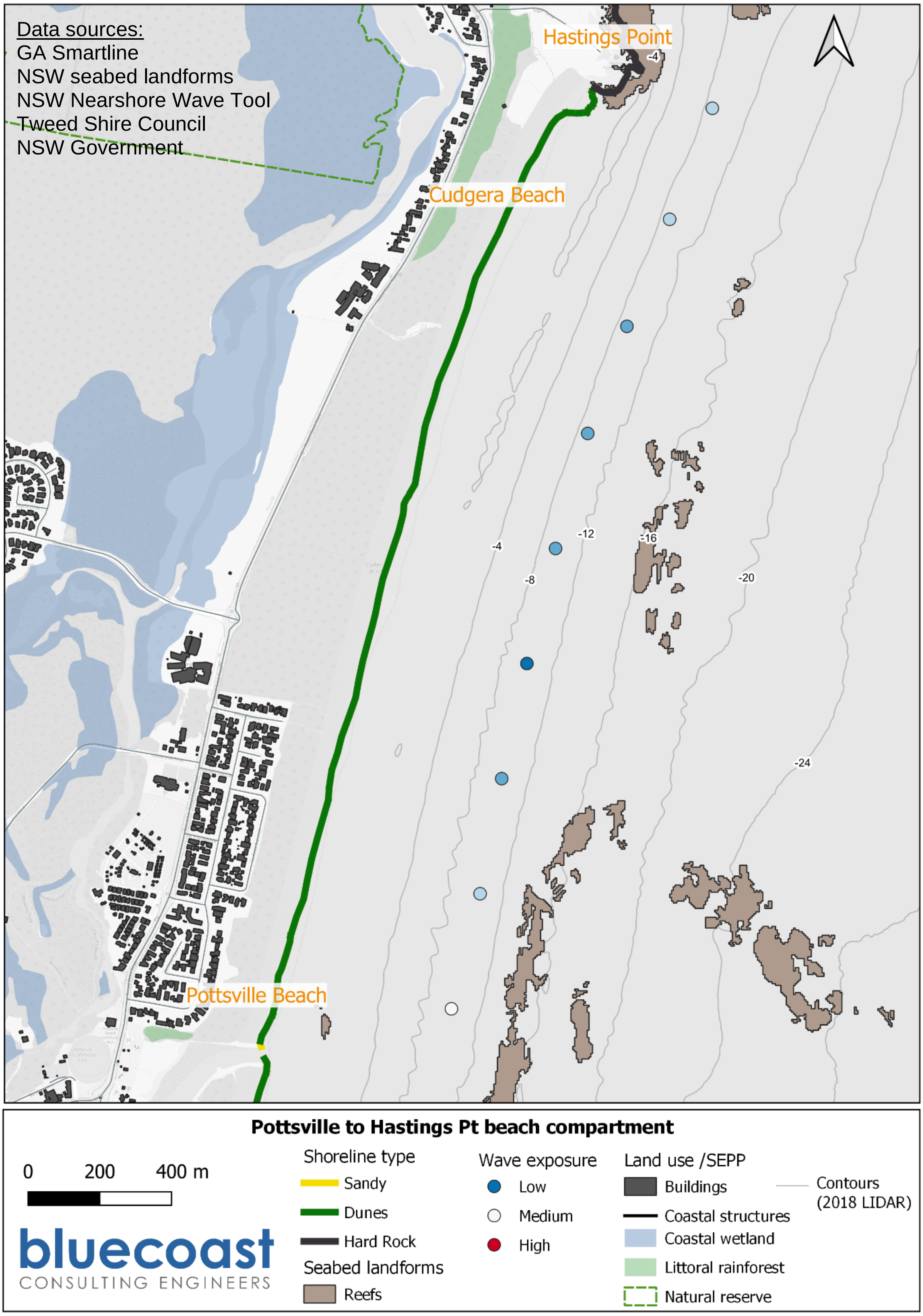


Figure 77: Overview of Pottsville to Hastings Point compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Pottsville to Hastings Point compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Pottsville to Hastings Point compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 78.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 69.

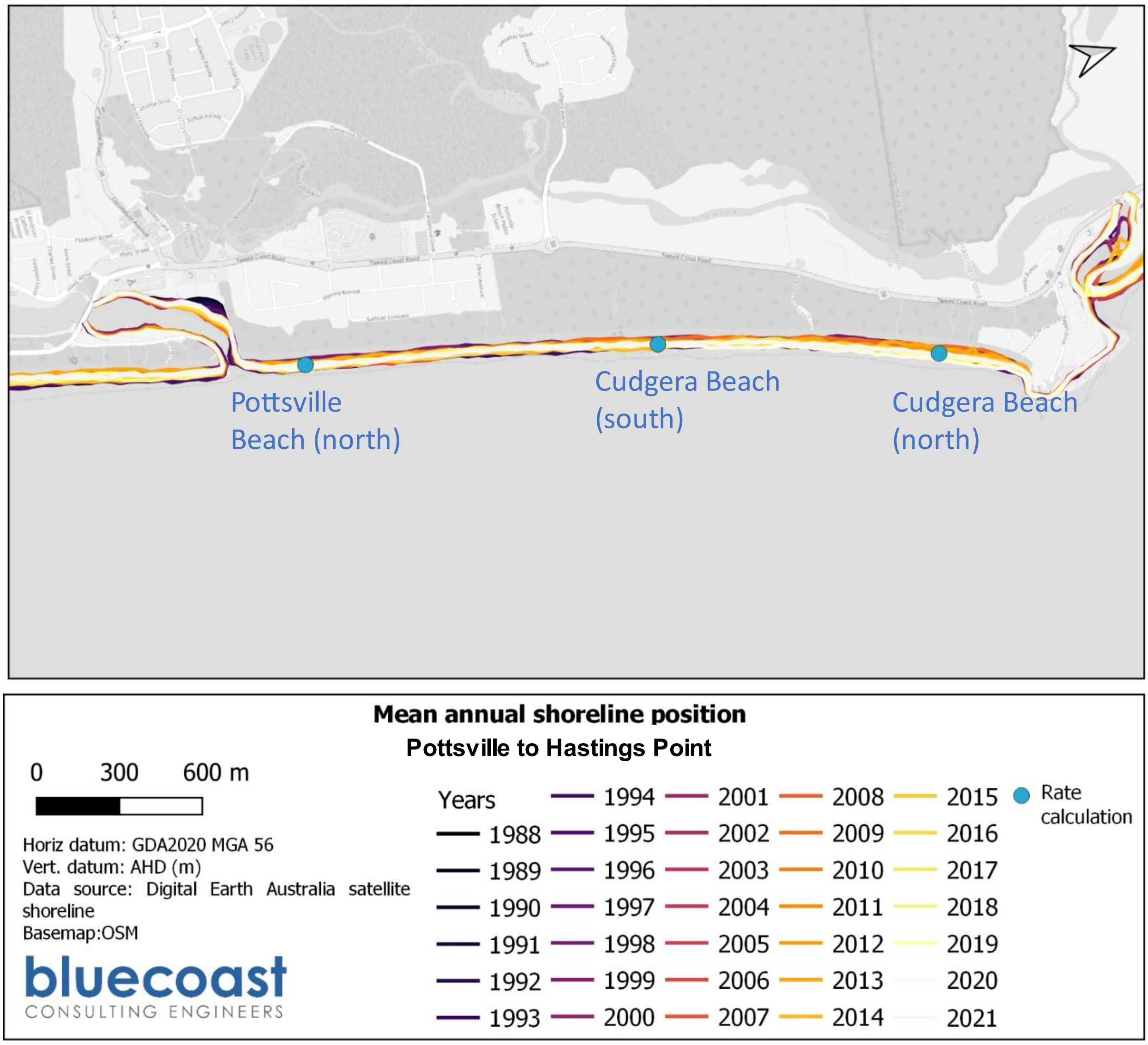


Figure 78: Mean annual shorelines within the Pottsville to Hastings Point compartment from 1988 to 2021.

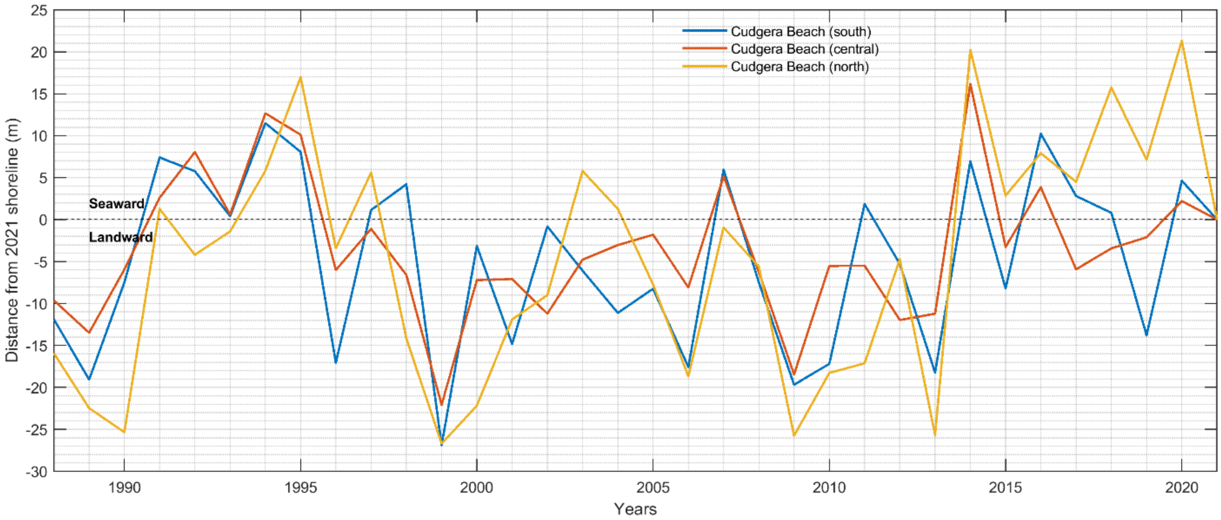


Figure 79: Mean annual shoreline position relative to 2021 shoreline for key areas within Pottsville to Hastings Point compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 80 for three different periods.
- Table 36 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

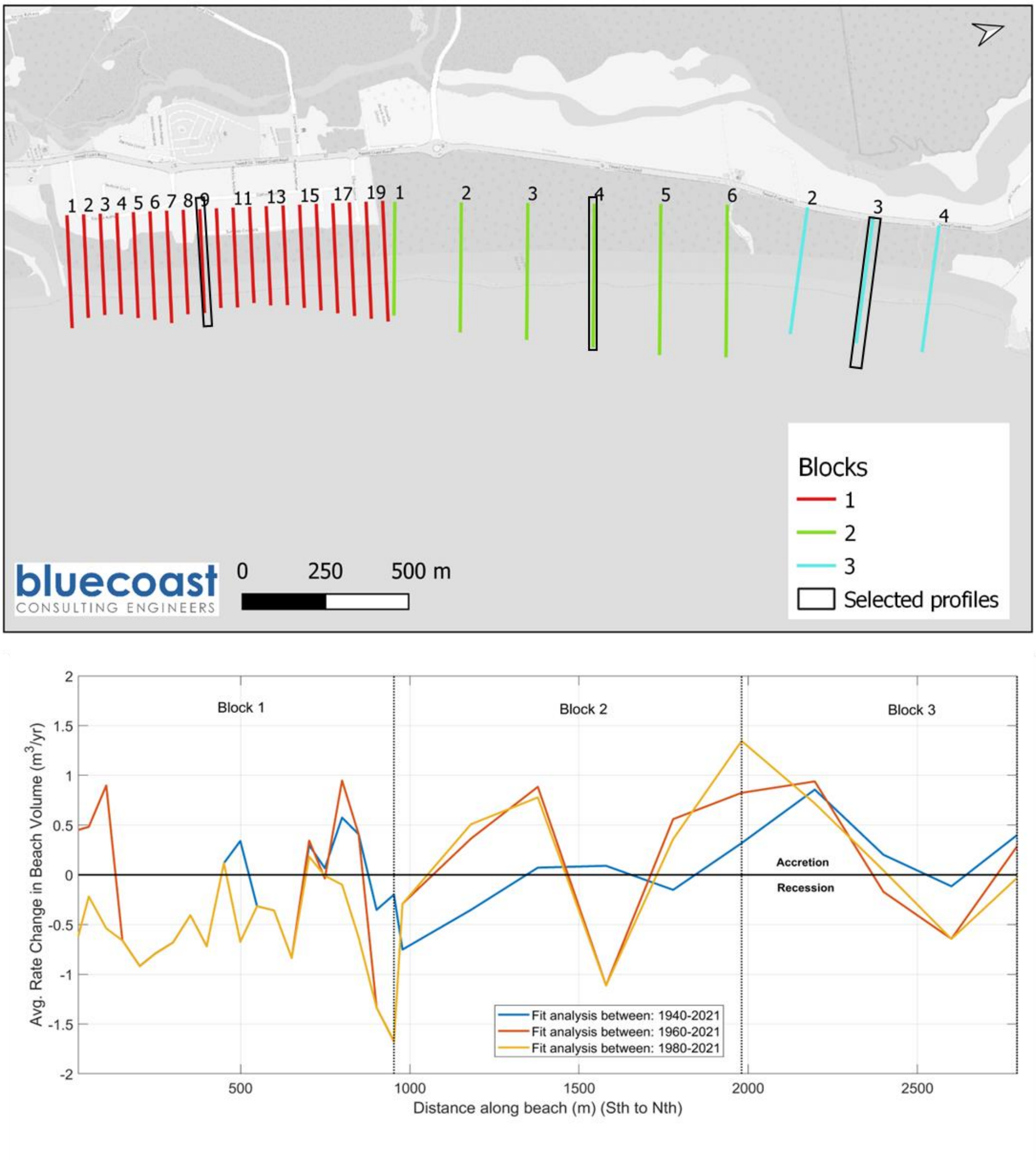


Figure 80: Profile locations and rate of change of subaerial beach volume along Pottsville to hastings Point compartment for short, medium and long-term analysis periods.

Table 36: Overview of photogrammetry profile analysis for Pottsville to Hastings Point compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max]		
				1940-2022	1960-2022	1980-2022
Pottsville Beach (south) (1)	950m (19)	1947 – 2022 (75)	16 (varies)	-0.91, -0.13, 0.9	-1.67, -0.29, 0.94	-1.67, -0.56, 0.18
Cudgera Beach (south) (2)	1096m (6)			-0.75, -0.13, 0.32	-1.11, 0.2, 0.88	-1.11, 0.26, 1.34
Cudgera Beach (north) (3)	616m (3)			-0.11, 0.33, 0.85	-0.64, 0.1, 0.94	-0.64, 0.02, 0.72

Note: BMT WBM (2013) adopted a recession rate of 0.05m/year.

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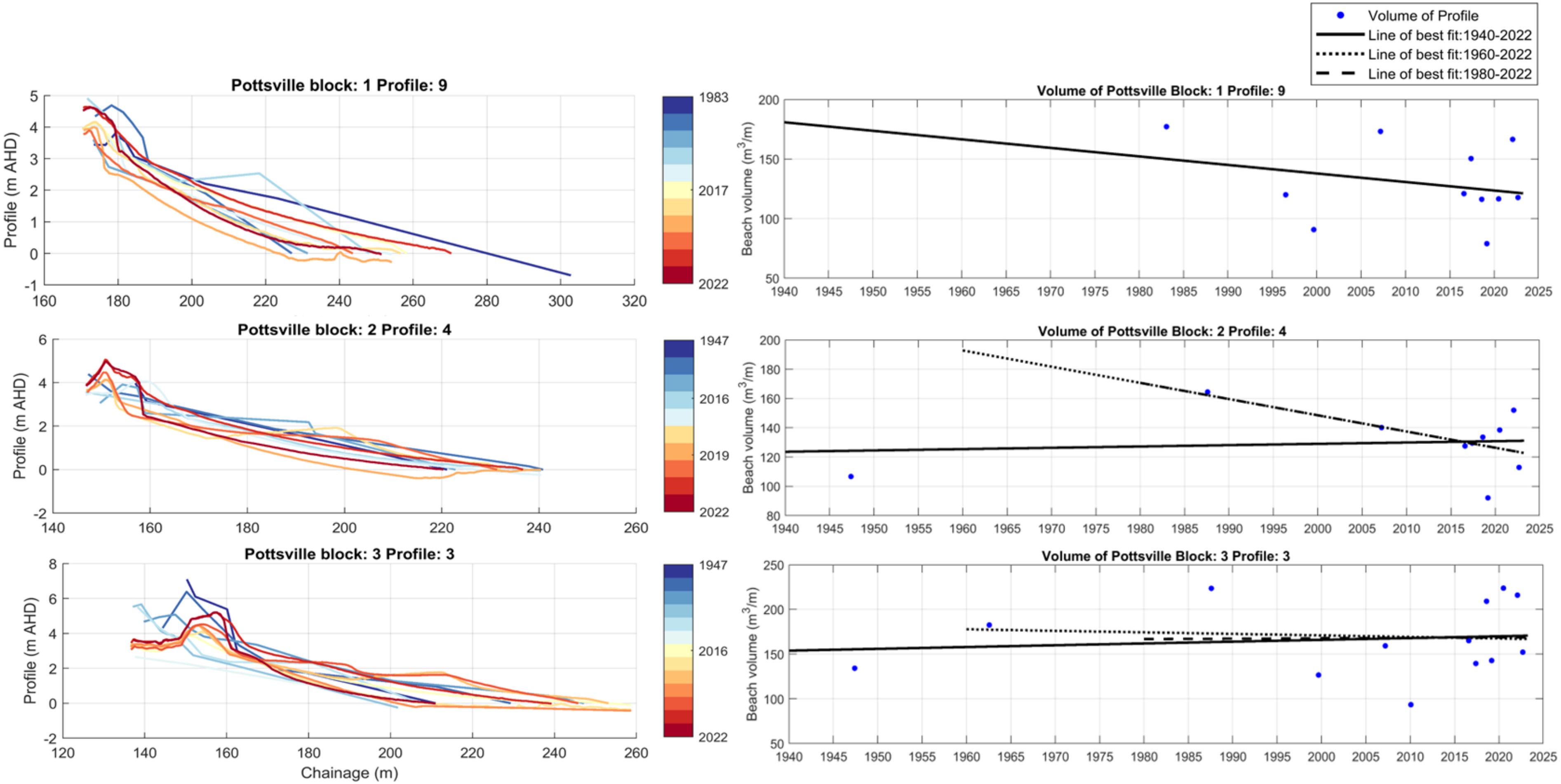

Figure 81: Photogrammetry beach profiles (right) and associated beach volume change over time (left).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 82. Individual beach profiles for Pottsville Beach (north) and Cudgera Beach are shown in Figure 83 and Figure 84.

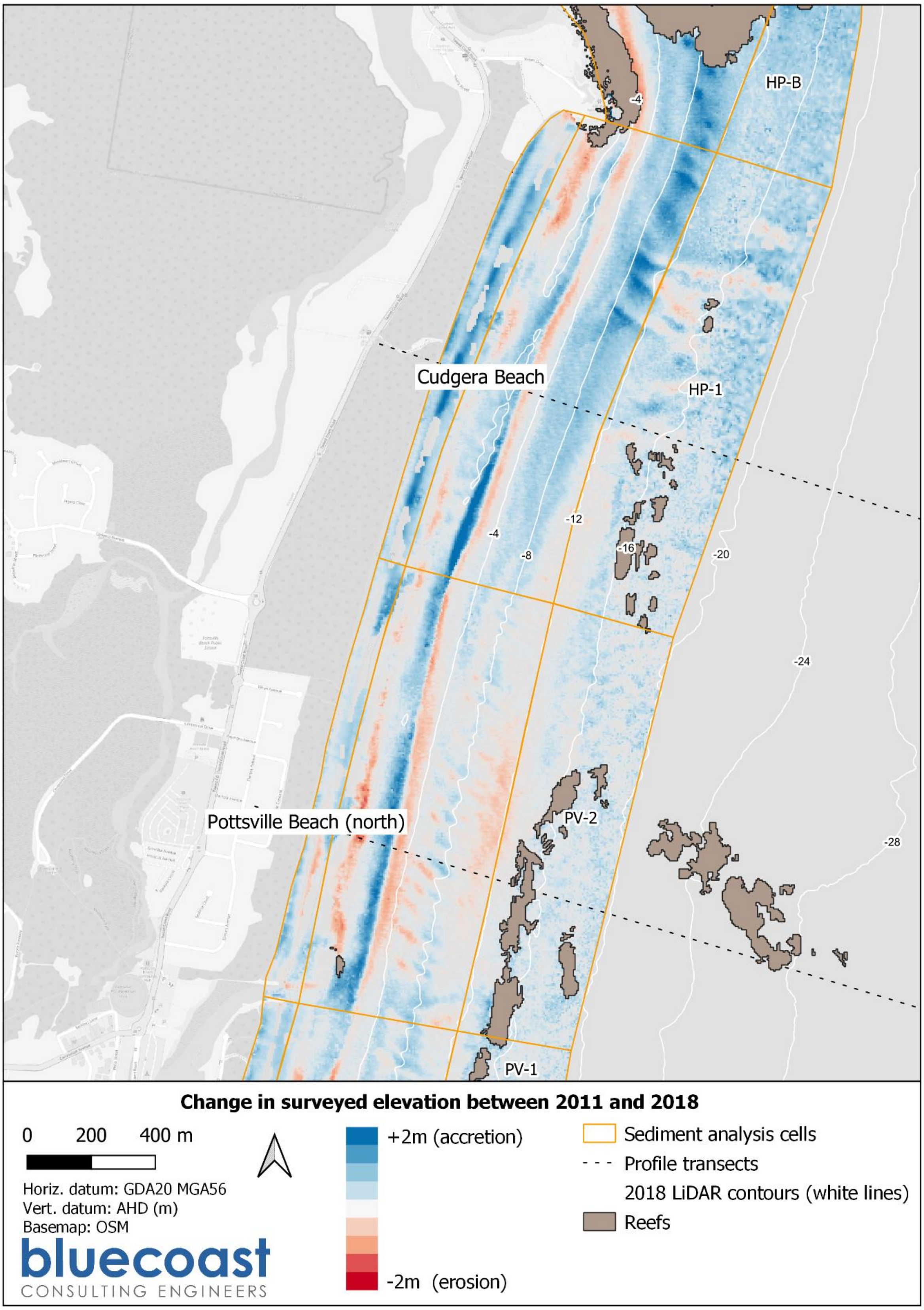

Figure 82: Surveyed elevation change along Pottsville to Hastings Point compartment between 2011 and 2018.

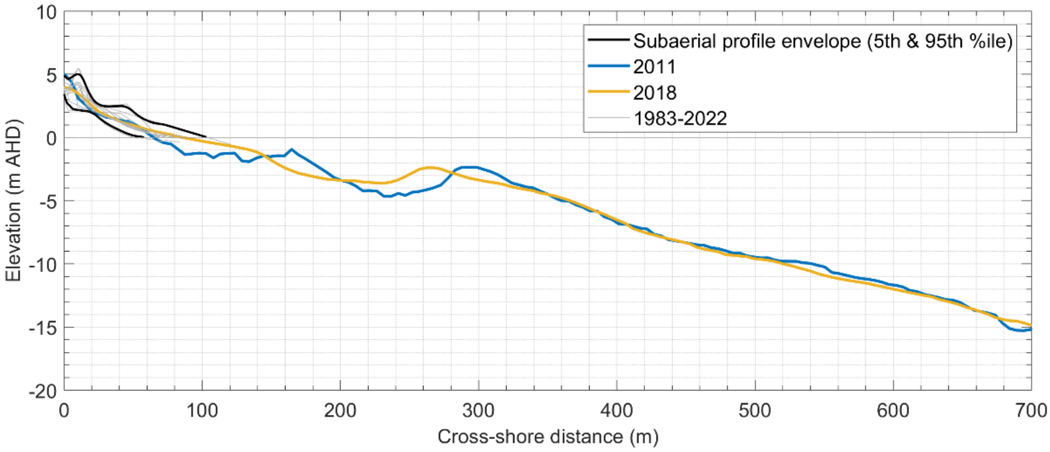

Figure 83: Profile evolution for Pottsville Beach (north).

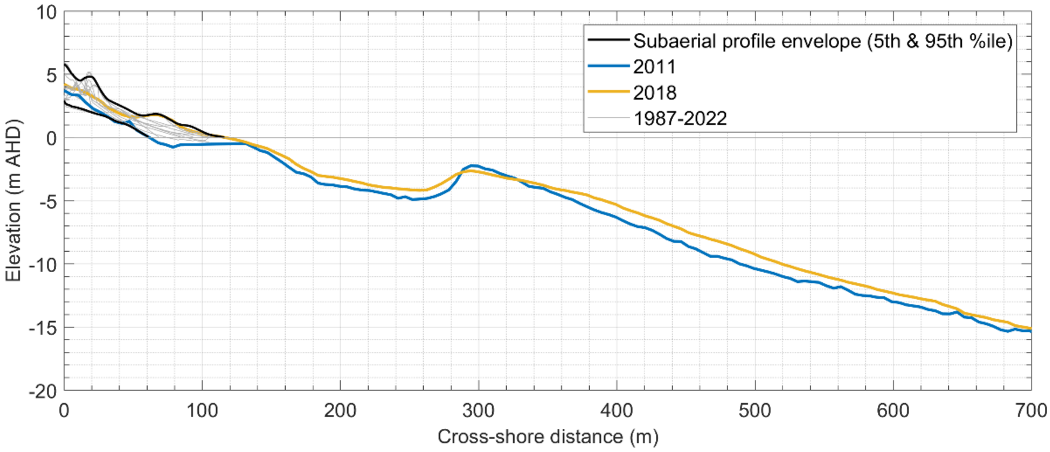

Figure 84: Profile evolution for Cudgera Beach.

Beach erosion

Figure 85 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 1999 East Coast Lows, 2009 East Coast Low and the 2019 tropical cyclone. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed. The pattern, from south to north, is described as:

- The storm demand volume is shown to be approximately 150m^3/m for this beach compartment (Figure 85).
- For the 1999 and 2019 storms, there was lower storm erosion volumes at Pottsville Beach (north) near Mooball Creek entrance and larger storm erosion at the northern end of Cudgera Beach near Hastings Point. However, the 2009 East Coast Low event showed a different trend where storm erosion volumes were highest at Pottsville Beach (north).

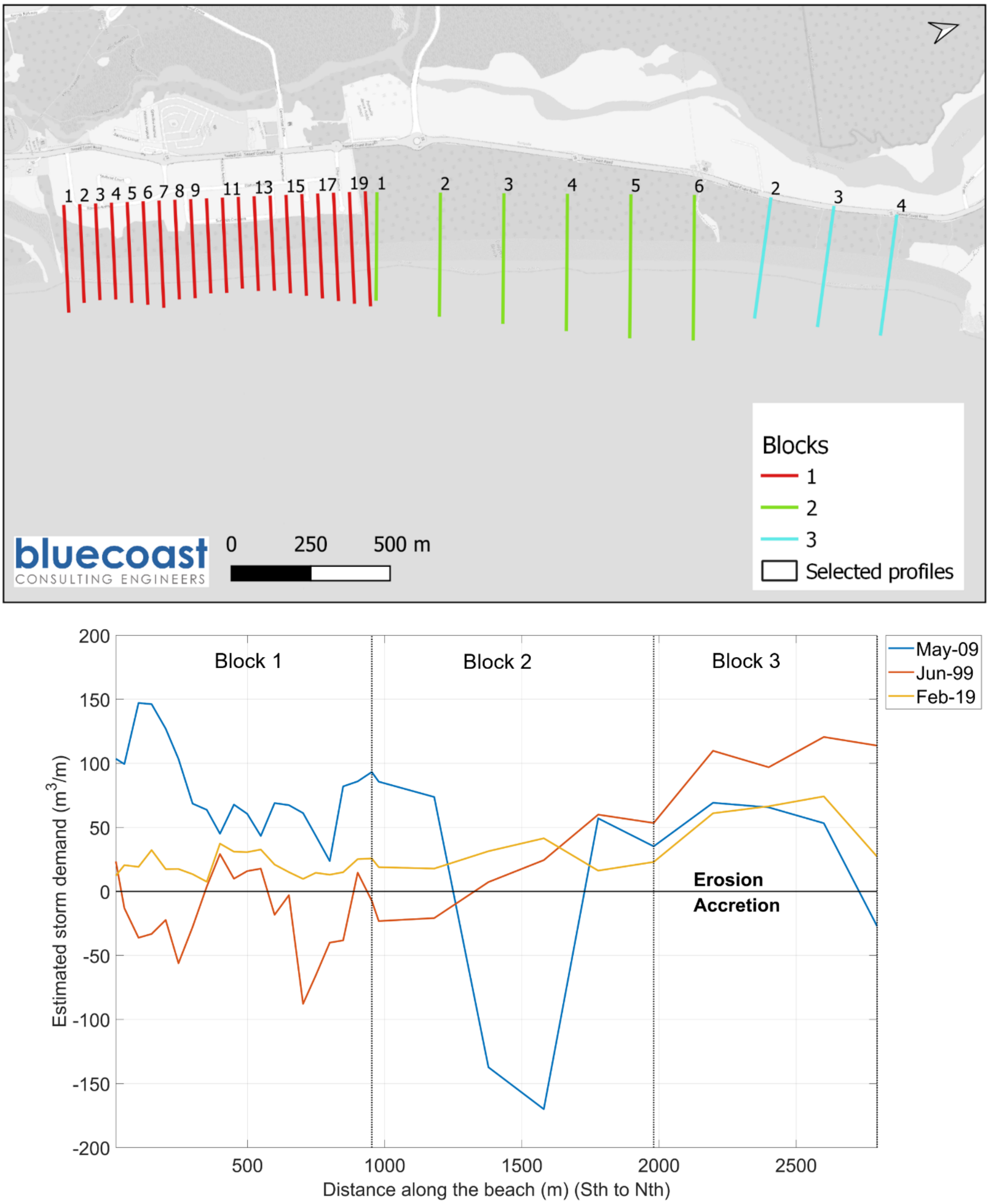

Figure 85: Alongshore storm demand estimates derived from photogrammetry for storms in 1999, 2009 and 2019.

Hastings Point to Norries Headland

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Hastings Point to Norries Headland beach compartment is 3,000m long and start at Hastings Point headland and extends to Norries Headland headland to the north (see Figure 86). Table 37 provides the main characteristics of this compartment.

Table 37: Main characteristics of Hastings Point to Norries Headland compartment.

Parameter	Hastings Point	Maggies Beach
Beach type	Embayment beach	Embayment beach
Sandy beach length	500m	2,500 km
Orientation	East	East
Relative wave exposure (NSW Nearshore Wave Tool)	Medium to high	Low
Coastal land-use / Resilience SEPP mapping	Suburban area (Hastings Point). SEPP coastal wetland located upstream in Cudgera Creek.	Extensive natural coastal area with suburban area to the north (Bogangar).
Key morphological features	Hastings Point Headland to the south Cudgera Creek entrance to the south	Norries Headland to the north

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

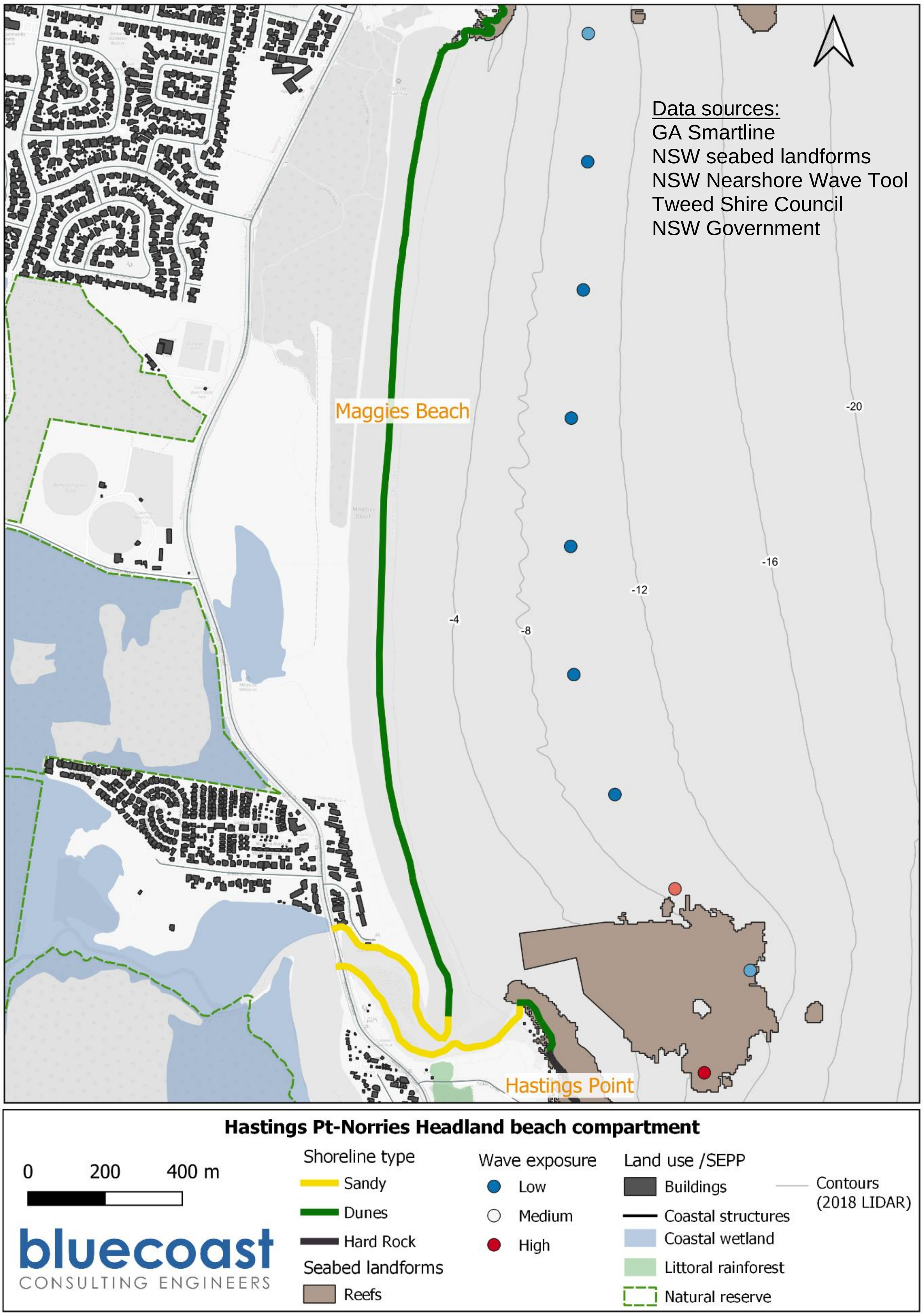

Figure 86: Overview of Hastings Point to Norries Headland compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Hastings Point compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Hastings Point to Norries Headland compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 87.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 88.

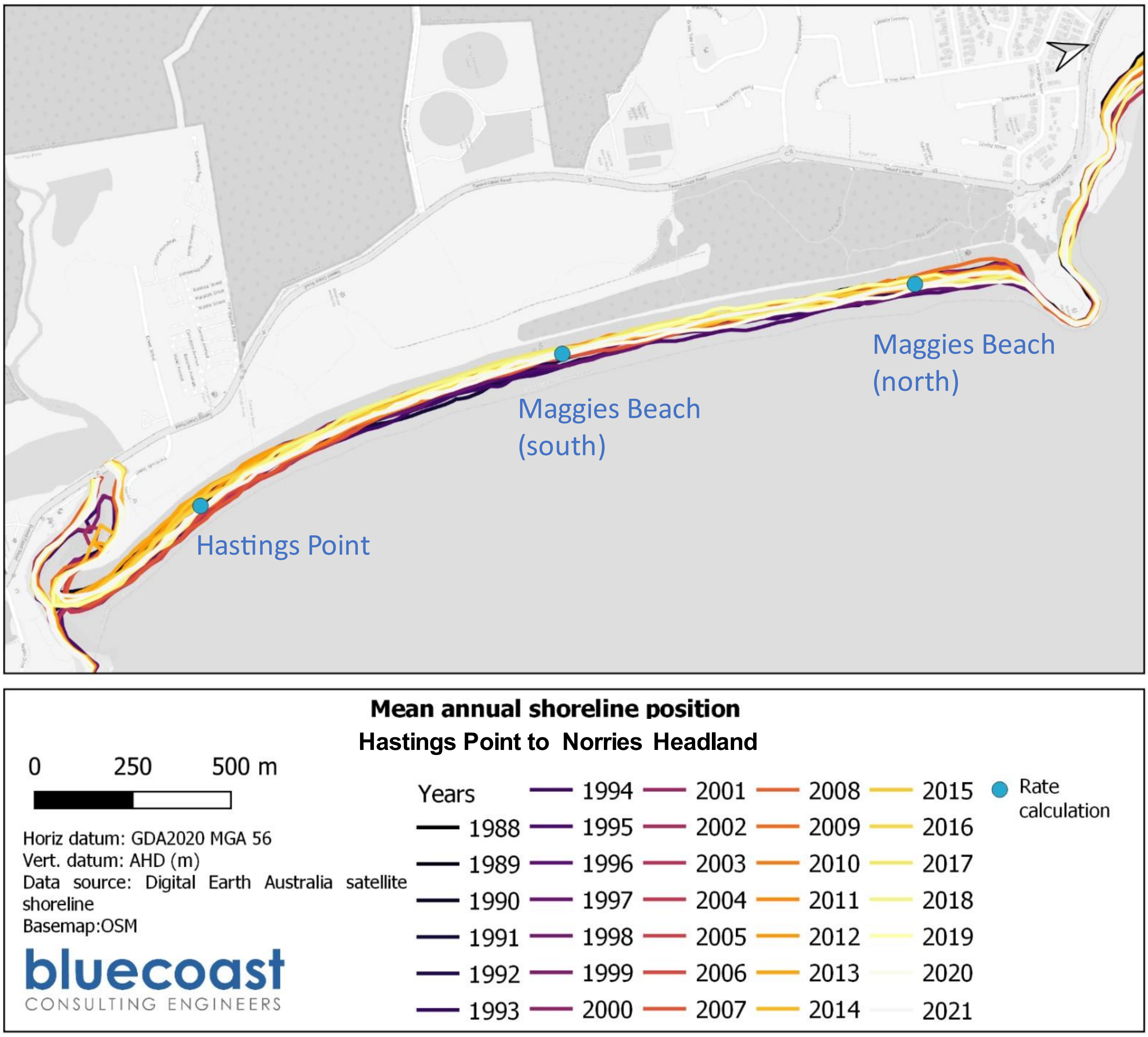

Figure 87: Mean annual shorelines within the Hastings Point to Norries Headland compartment from 1988 to 2021.

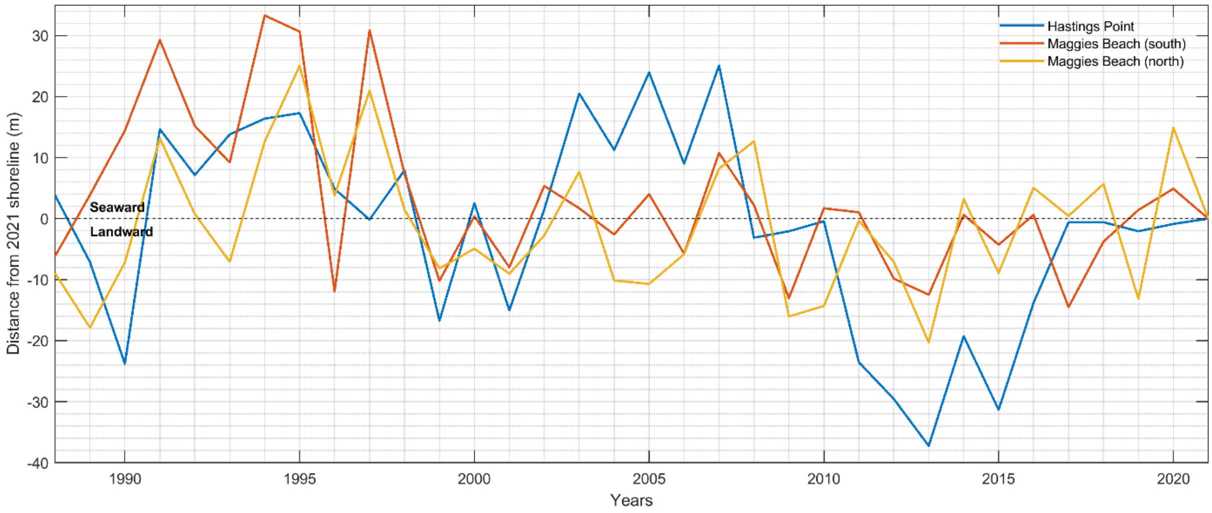

Figure 88: Mean annual shoreline position relative to 2021 shoreline for key areas within Hastings Point to Norries Headland compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 89 for three different periods.
- Table 38 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

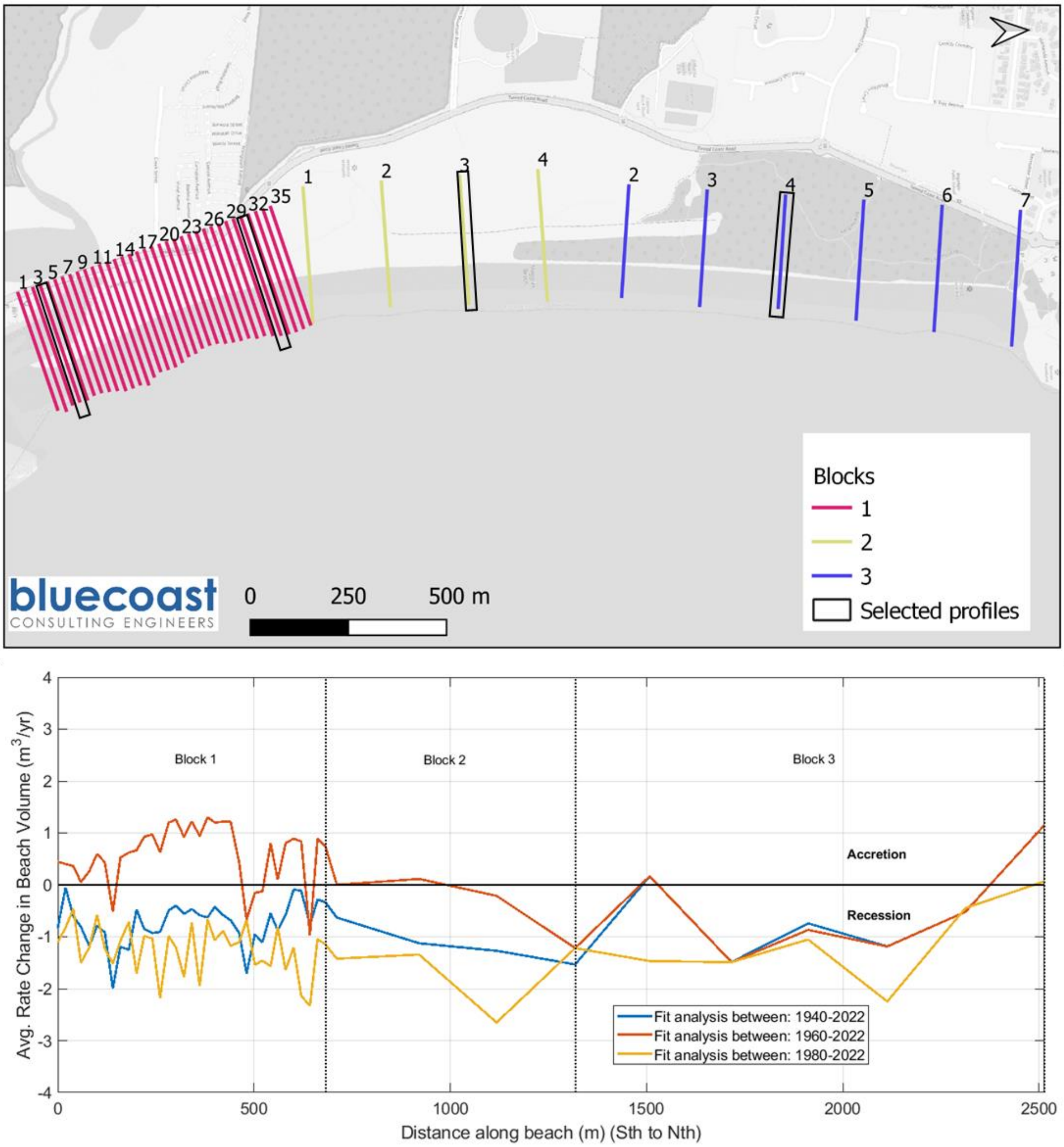

Figure 89: Profile locations and rate of change of subaerial beach volume along the Hastings Point to Norries Headland compartment for short, medium and long-term analysis periods.

Table 38: Overview of photogrammetry profile analysis for Hastings Point to Norries Headland compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max] 1940-2022	1960-2022	1980-2022
Hastings Point (1)	697m (35)	1944 – 2022 (78)	17 (varies)	-1.99, -0.74, -0.05	-0.96, 0.58, 1.3	-2.32, -1.23, -0.46
Maggies Beach (south) (2)	726m (4)	1947 – 2022 (75)	15 (varies)	-1.53, -1.14, -0.63	-1.21, -0.33, 0.11	-2.64, -1.65, -1.21
Maggies Beach (north) (3)	1141m (6)	1947 – 2022 (75)	13 (varies)	-1.49, -0.44, 1.15	-1.48, -0.46, 1.15	-2.24, -1.1, 0.07

Note: BMT WBM (2013) adopted a recession rate of 0.075m/yr for the southern section of the beach unit at Hasting Point, a recession rate of 0.02m/yr just south of Norries Headland.

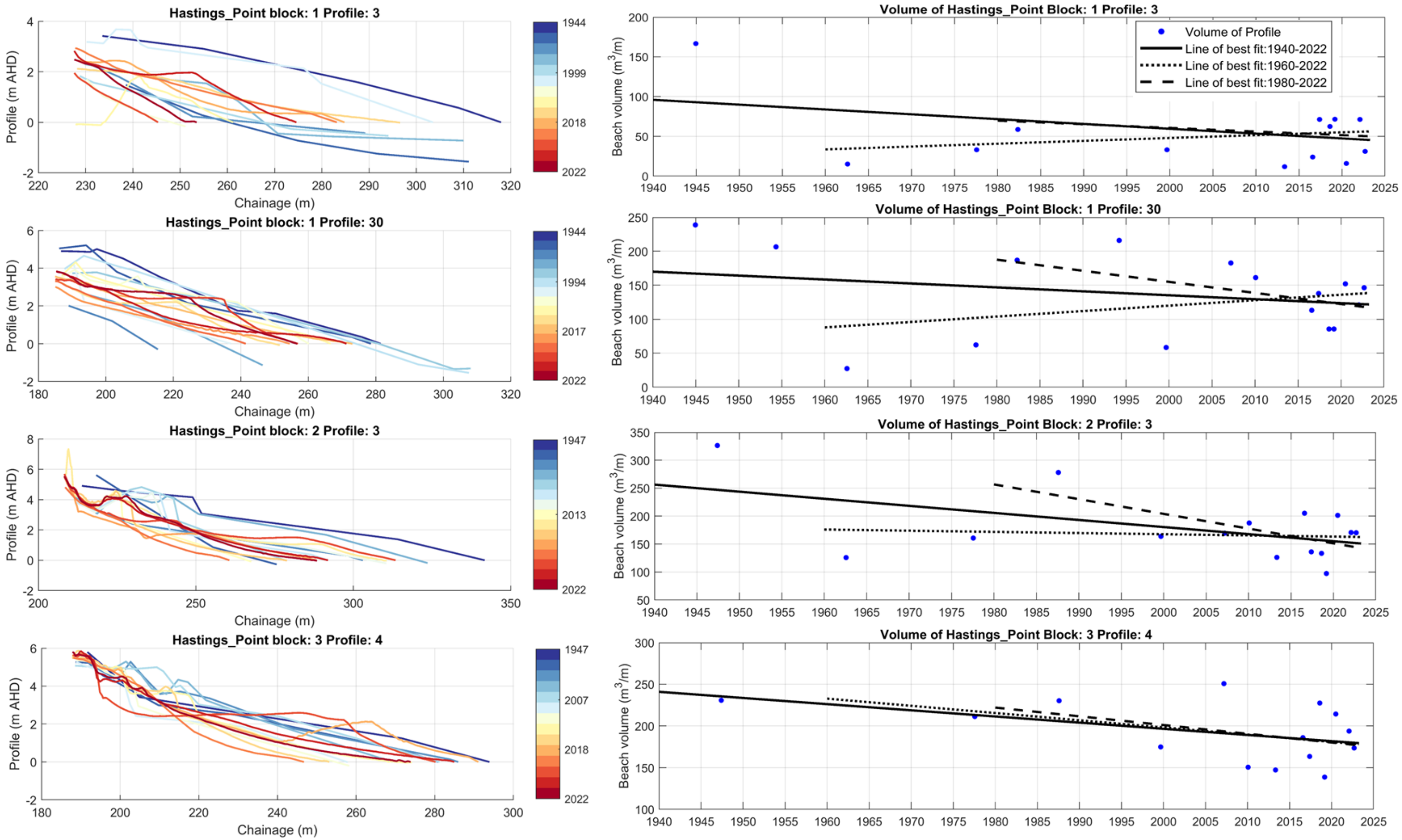

Figure 90: Photogrammetry beach profiles (right) and associated beach volume change over time (left).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 91. Individual beach profiles for Hastings Point and Maggies Beach are shown in Figure 92 and Figure 93.

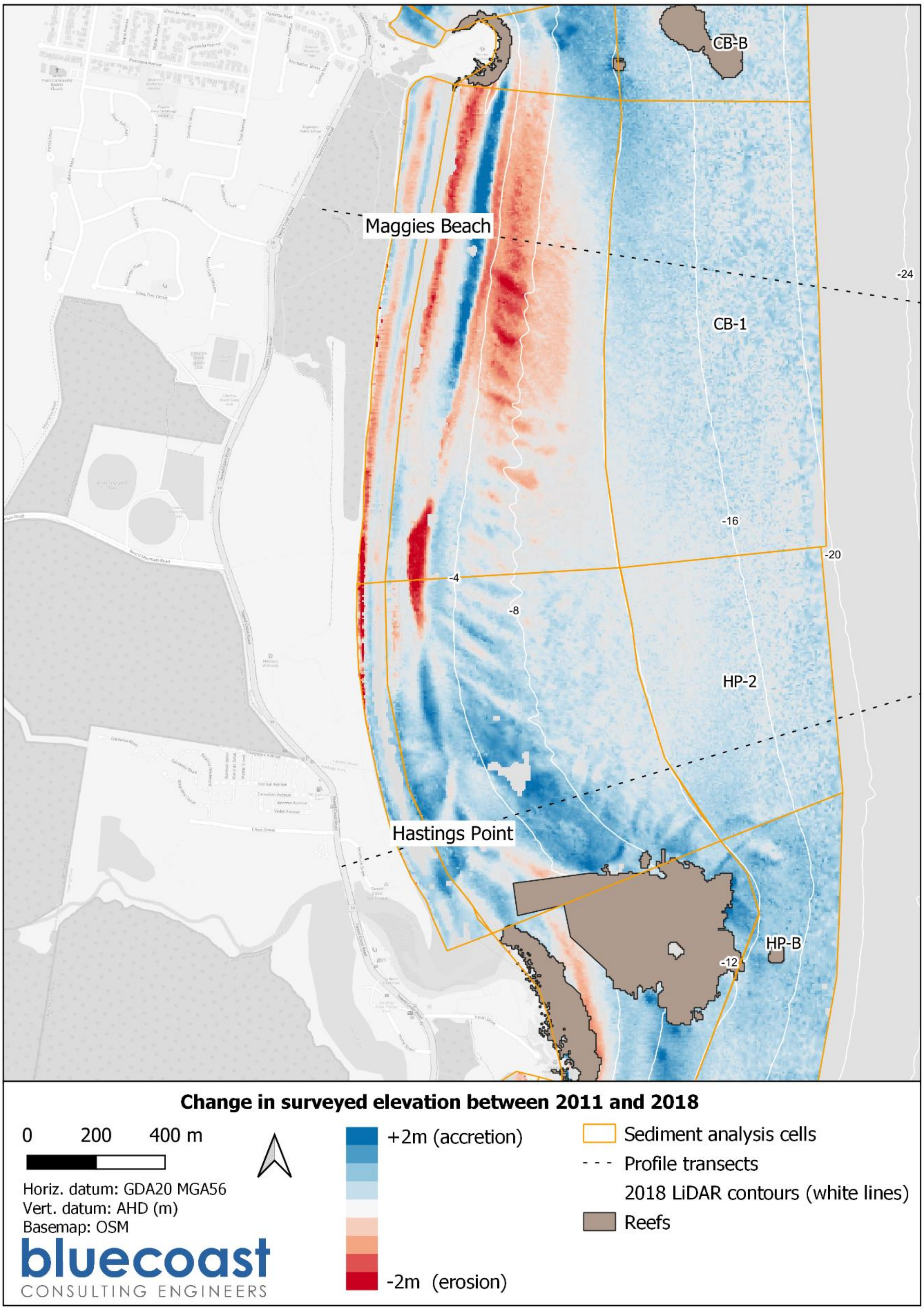

Figure 91: Surveyed elevation change along Hastings Point to Norries Headland compartment between 2011 and 2018.

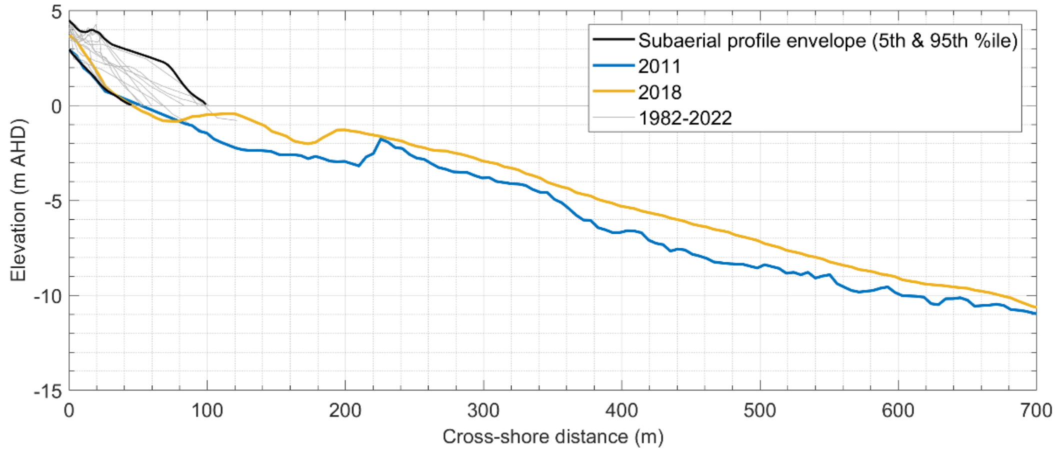

Figure 92: Profile evolution for Hastings Point transect.

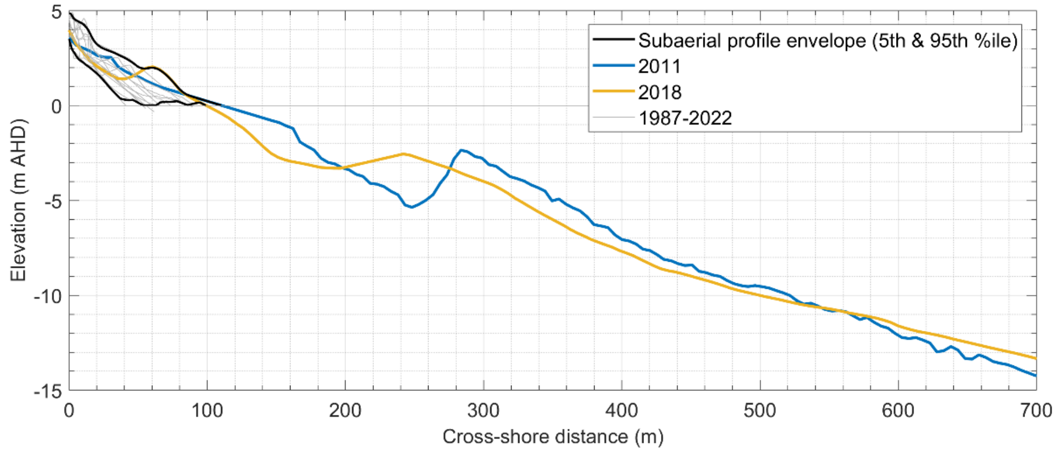

Figure 93: Profile evolution for Maggies Beach transect.

Beach erosion

Figure 94 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 1954 tropical cyclone, 1999 East Coast Lows and the 2019 tropical cyclone. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed with an estimated storm demand volume of approximately 200m^3/m for this beach compartment (Figure 94). Observed erosion volumes at southern beach section likely influenced by creek entrance processes.

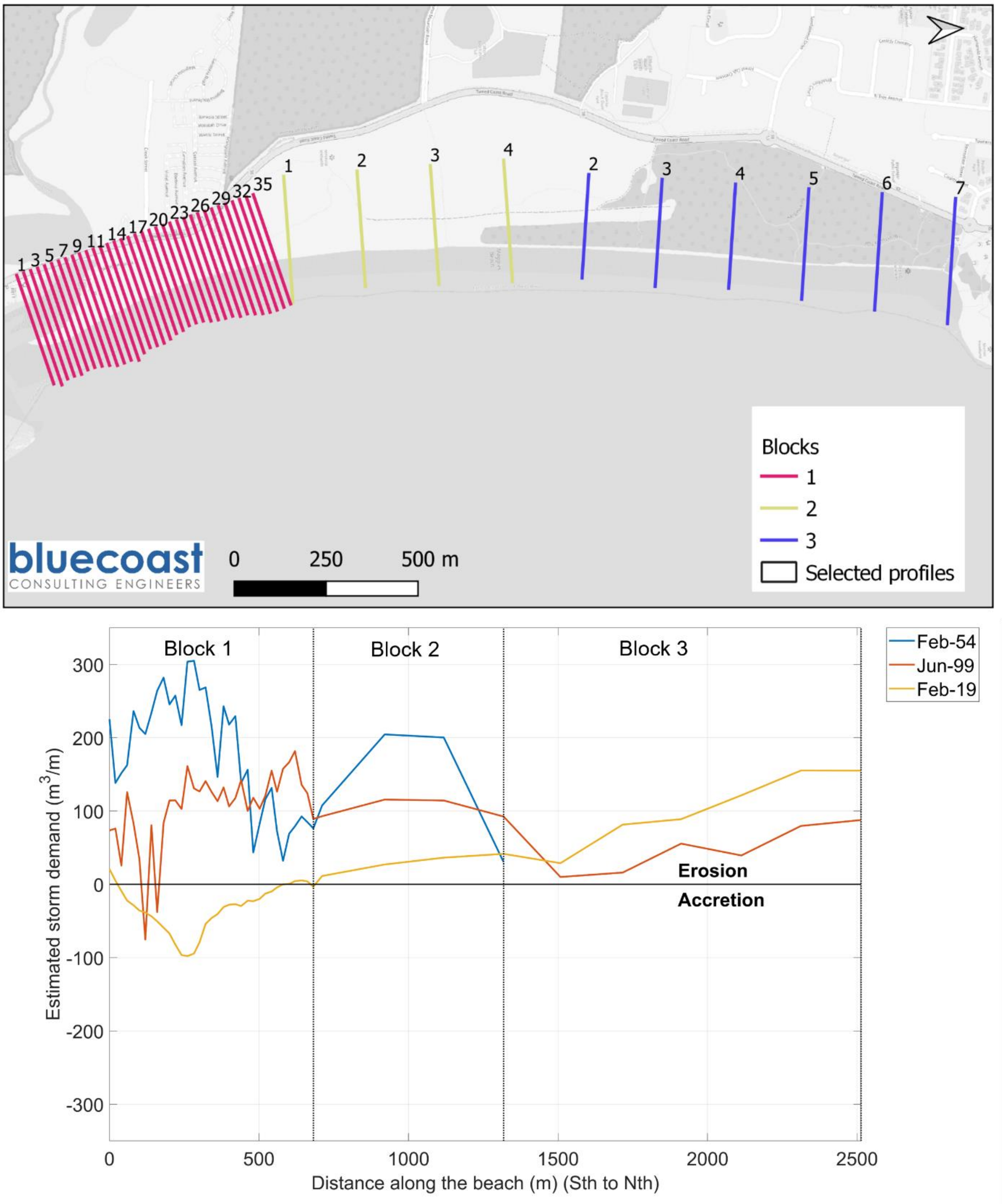

Figure 94: Alongshore storm demand estimates derived from photogrammetry for storms in 1954, 1999 and 2019.

Norries Headland to Cudgen Headland

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Norries Headland to Cudgen Headland beach compartment is 9,000m long and starts at Norries Headland and extends to Cudgen Headland to the north (Figure 95). Table 39 provides the main characteristics of this compartment.

Table 39: Main characteristics of the Norries Headland to Cudgen Headland compartment.

Parameter	Cabarita Beach	Bogangar and Casuarina Beaches	South Kingscliff Beach
Beach type	Semi-embayment (headland control to the south)	Open beach	Open beach
Sandy beach length	1,000m	3,000m	5,000m
Orientation	East-north-east	East-south-east	East-south-east
Relative wave exposure (NSW Nearshore Wave Tool)	Low to medium	Medium to high	Low to medium
Coastal land-use / Resilience SEPP mapping	Suburban area (Cabarita Beach, Bogangar).	Suburban area (Casuarina) with natural coastal area in the south. SEPP coastal wetland located upstream in Cudgen Creek.	Mixed land-use with natural coastal area to the north and suburban area (Salt) to the south. SEPP coastal wetland located upstream in Cudgen Creek.
Key morphological features	Norries Headland to the south	Nil	Cudgen Headland to the north Cudgen Creek entrance to the north

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

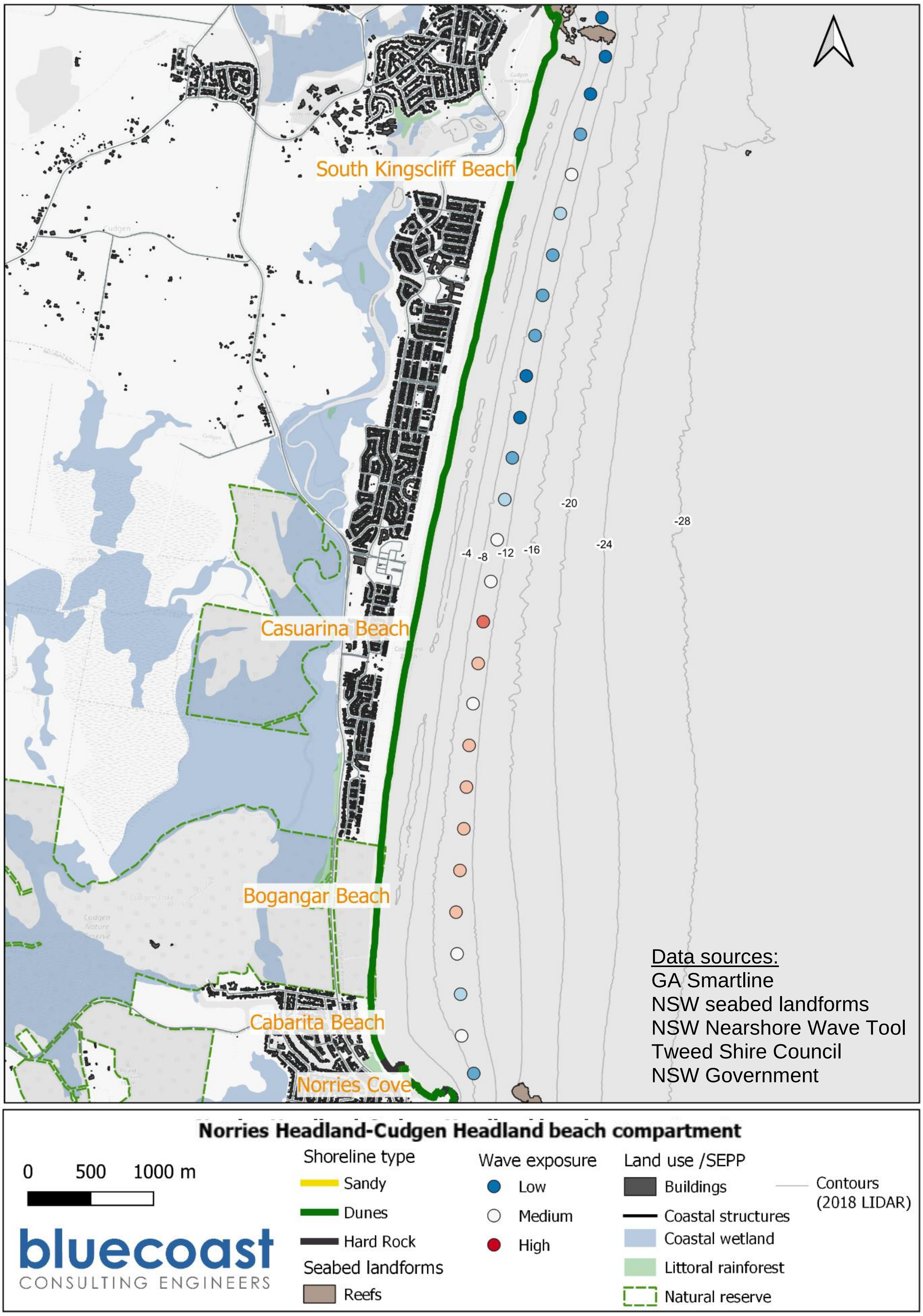

Figure 95: Overview of Norries Headland to Cudgen Headland beach compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Norries Headland to Cudgen Headland compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Norries Headland to Cudgen Headland compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 96.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 97.

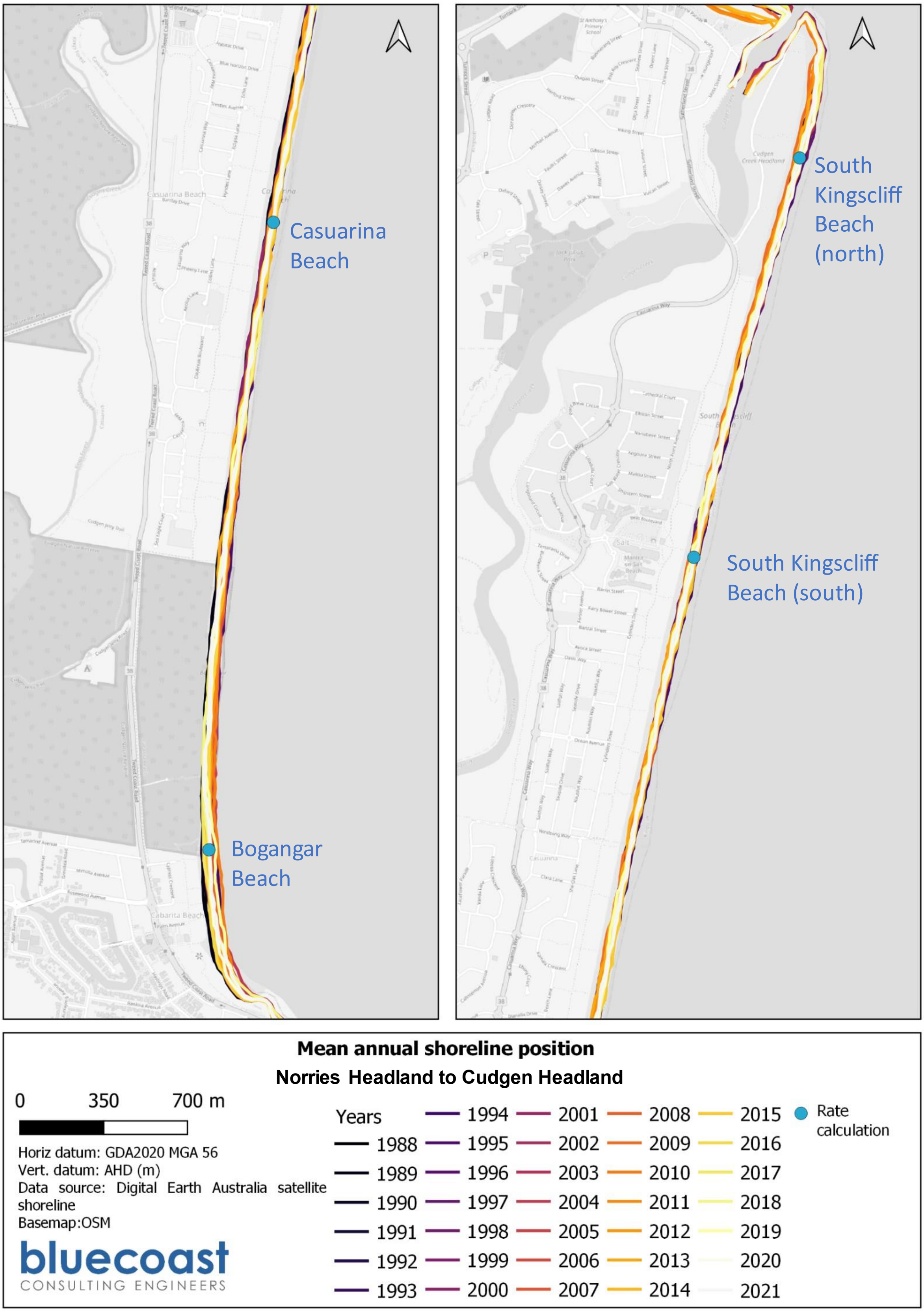

Figure 96: Mean annual shorelines within the Norries Headland to Cudgen Headland compartment from 1988 to 2021.

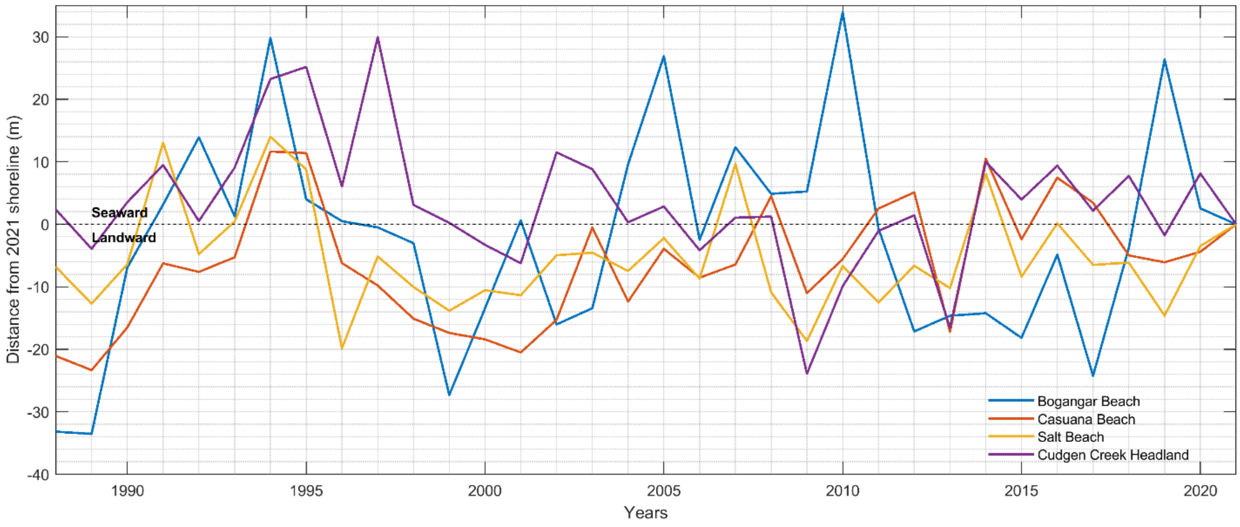

Figure 97: Mean annual shoreline position relative to 2021 shoreline for key areas within Norries Headland to Cudgen Headland compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 98 for three different periods.
- Table 40 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

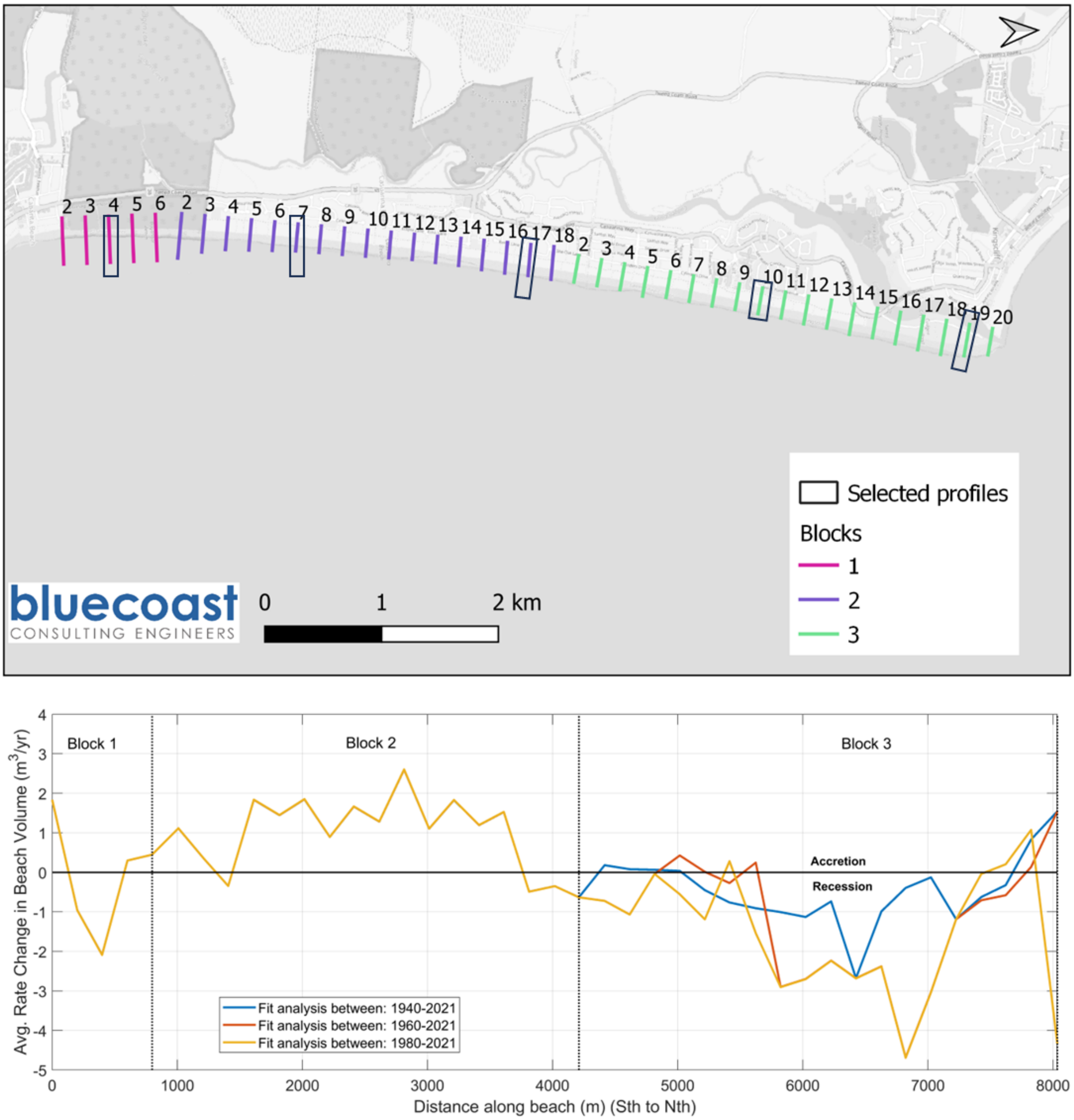

Figure 98: Profile locations and rate of change of subaerial beach volume along Norries Headland to Cudgen Headland compartment for short, medium and long-term analysis periods.

Table 40: Overview of photogrammetry profile analysis for Norries Headland to Cudgen Headland compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max] 1940-2022	1960-2022	1980-2022
Bogangar Beach (1)	937m (5)	1987 – 2022 (35)	13 (varies)	N/A	N/A	-2.08, -0.09, 1.83
Casuarina Beach (2)	3397m (17)	1987 – 2022 (35)	13 (varies)	N/A	N/A	-0.63, 0.99, 2.59
South Kingscliff Beach (3)	3700m (19)	1947 - 2022 (75)	14 (varies)	-2.67, -0.45, 1.54	-4.67, -1.2, 1.54	-4.67, -1.56, 1.07

Note: BMT WBM (2013) adopted a recession rate of 0.15m/yr at Cabarita Beach, 0.125m/yr at Casuarina South (Bogangar) and 0.1m/yr at Casuarina North.

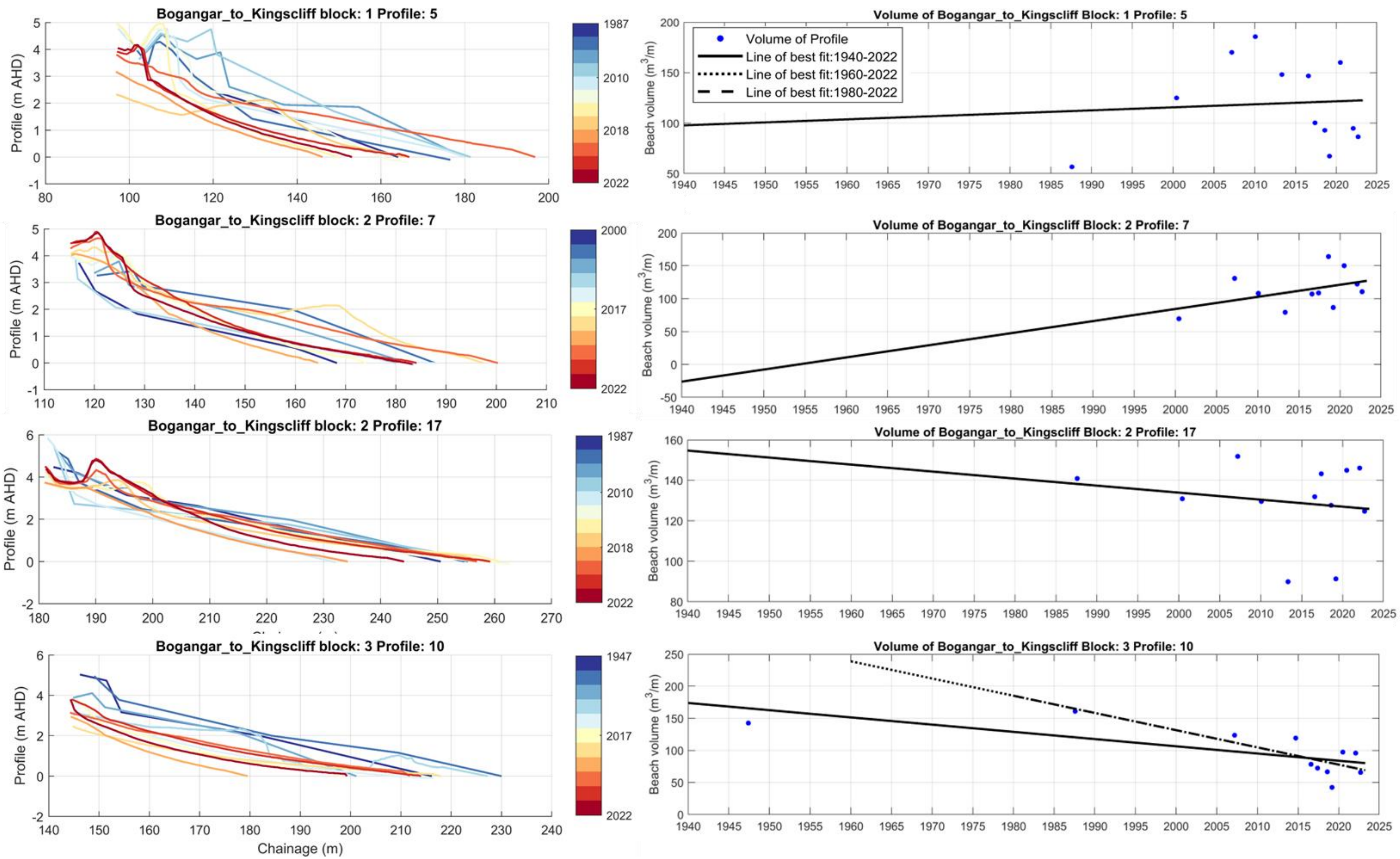

Figure 99: Photogrammetry beach profiles (left) and associated beach volume change over time (right).

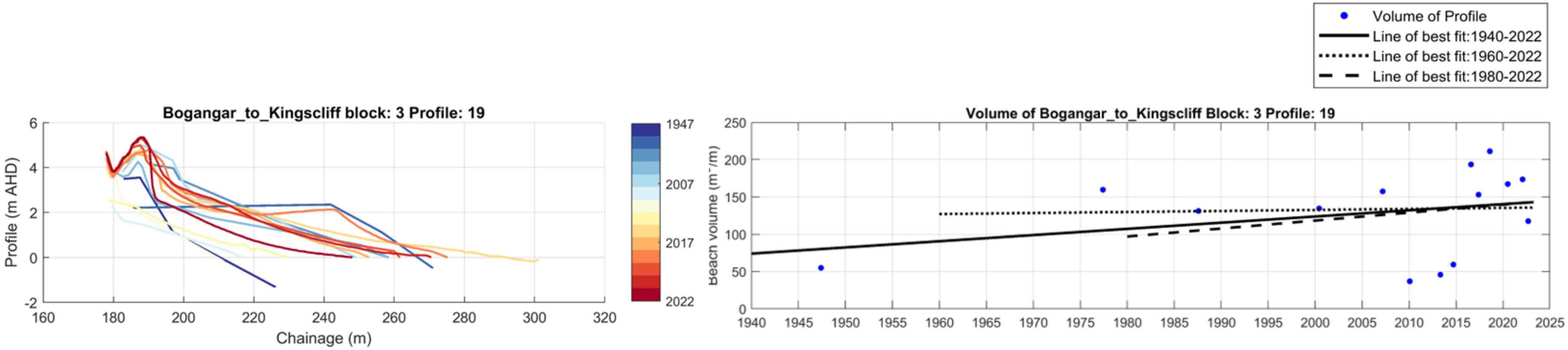

Figure 100: Photogrammetry beach profiles (left) and associated beach volume change over time (right).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 101. Individual beach profiles for Bogangar Beach, Casuarina Beach and South Kingscliff Beach are shown in Figure 102, Figure 103 and Figure 104.

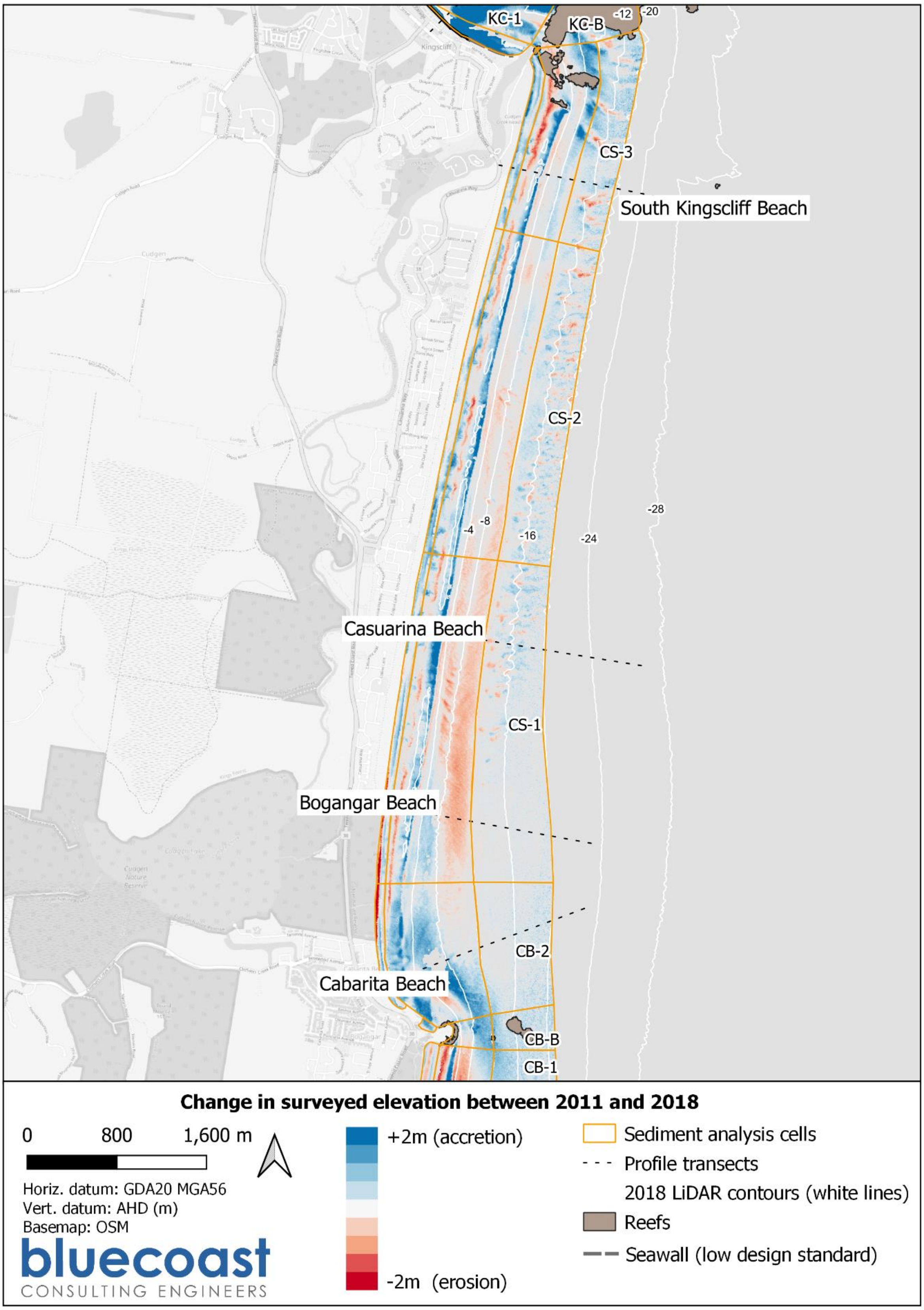

Figure 101: Surveyed elevation change along Norries Headland to Cudgen Headland compartment between 2011 and 2018.

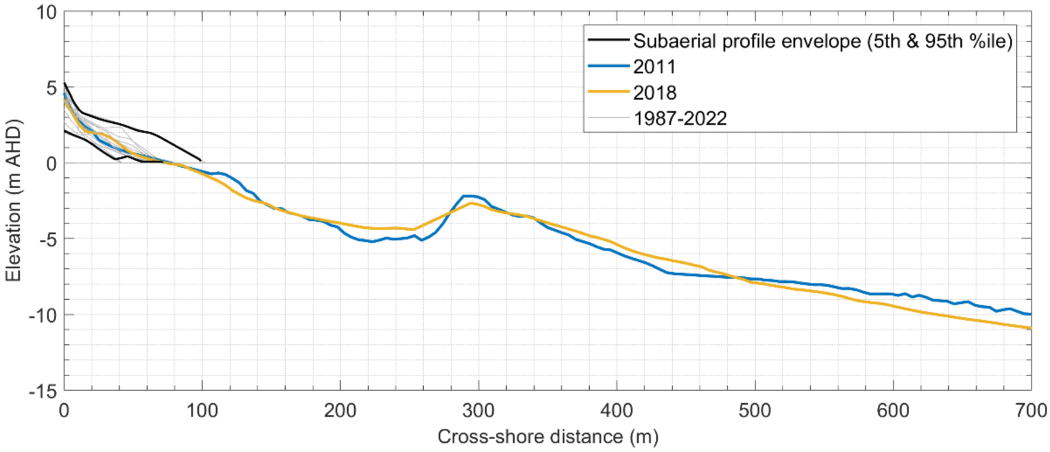

Figure 102: Profile evolution for Bogangar Beach transect.

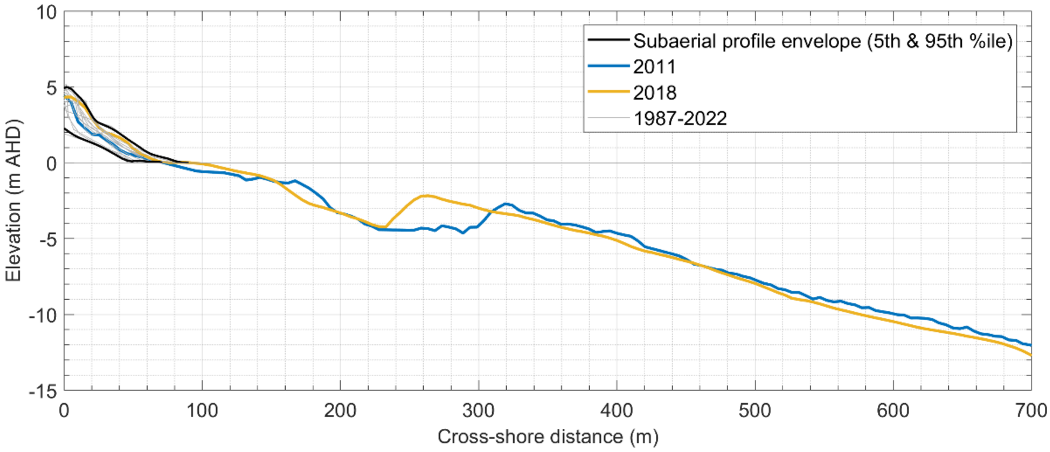

Figure 103: Profile evolution for Casuarina Beach transect.

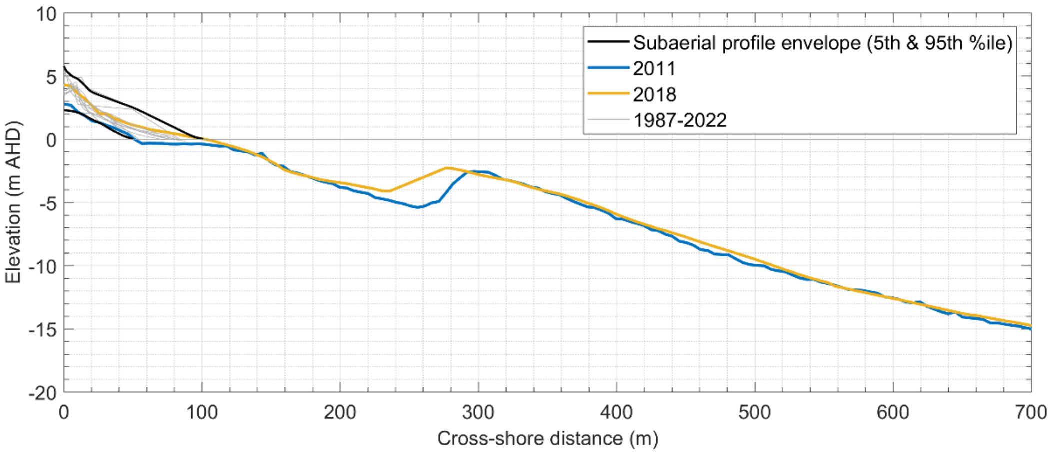

Figure 104: Profile evolution for South Kingscliff Beach transect.

Beach erosion

Figure 105 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 1999 East Coast Lows, the 2019 tropical cyclone and 2020 severe erosion event. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed. The pattern, from south to north, is described as:

- The 2019 and 2020 events show storm erosion volumes relatively constant along the embayment, except for the far north end near Cudgen Headland where storm erosion volumes increase significantly.
- The 1999 event shows significantly larger storm erosion volumes for block 3.
- Based on this data, the storm demand volumes are estimated at 150m^3/m for Bogangar and Casuarina Beaches and 200m^3/m for South Kingscliff Beach.

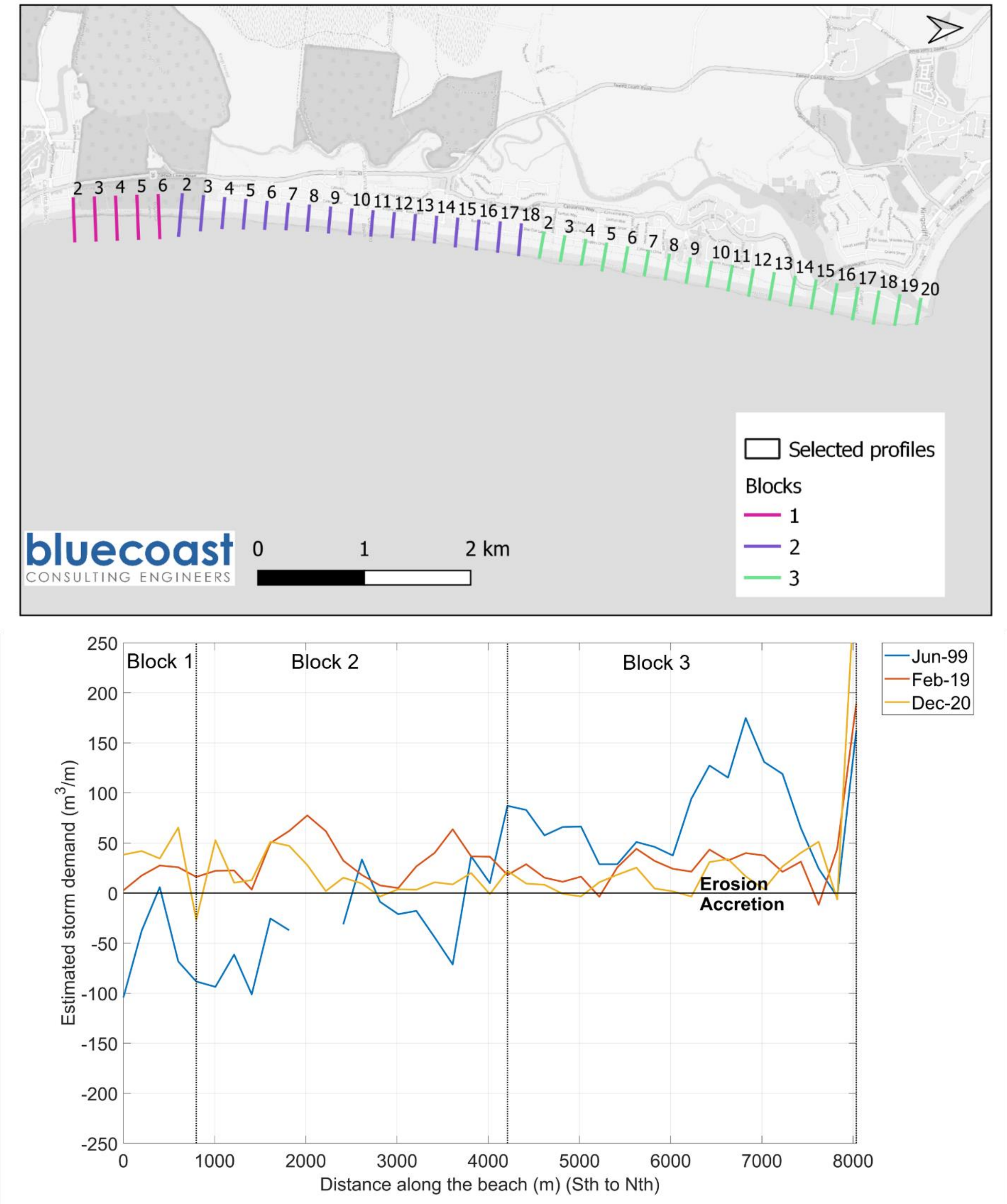

Figure 105: Alongshore storm demand estimates derived from photogrammetry for storms in 1999, 2019 and 2020.

Cudgen Headland to Fingal Head

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Cudgen Headland to Fingal Head beach compartment is 6,800m long and starts at Cudgen Creek entrance and extends to Fingal Head headland to the north (Figure 106). Table **39** provides the main characteristics of this compartment.

Table 41: Main characteristics of Cudgen Headland to Fingal Head compartment.

Parameter	Kingscliff Beach	Dreamtime Beach
Beach type	Embayment	Embayment
Sandy beach length	2,800	4,000
Orientation	East-north-east	East
Relative wave exposure (NSW Nearshore Wave Tool)	Low to high	High
Coastal land-use / Resilience SEPP mapping	Mostly suburban area (Kingscliff and Chinderah).	Extensive natural coastal area with suburban area to the north (Fingal). SEPP coastal wetland located upstream in Tweed River. SEPP littoral rainforest at Fingal Head in the north.
Key morphological features	Cudgen Creek headland to the south Cudgen Creek entrance to the south	Fingal Head headland to the north

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

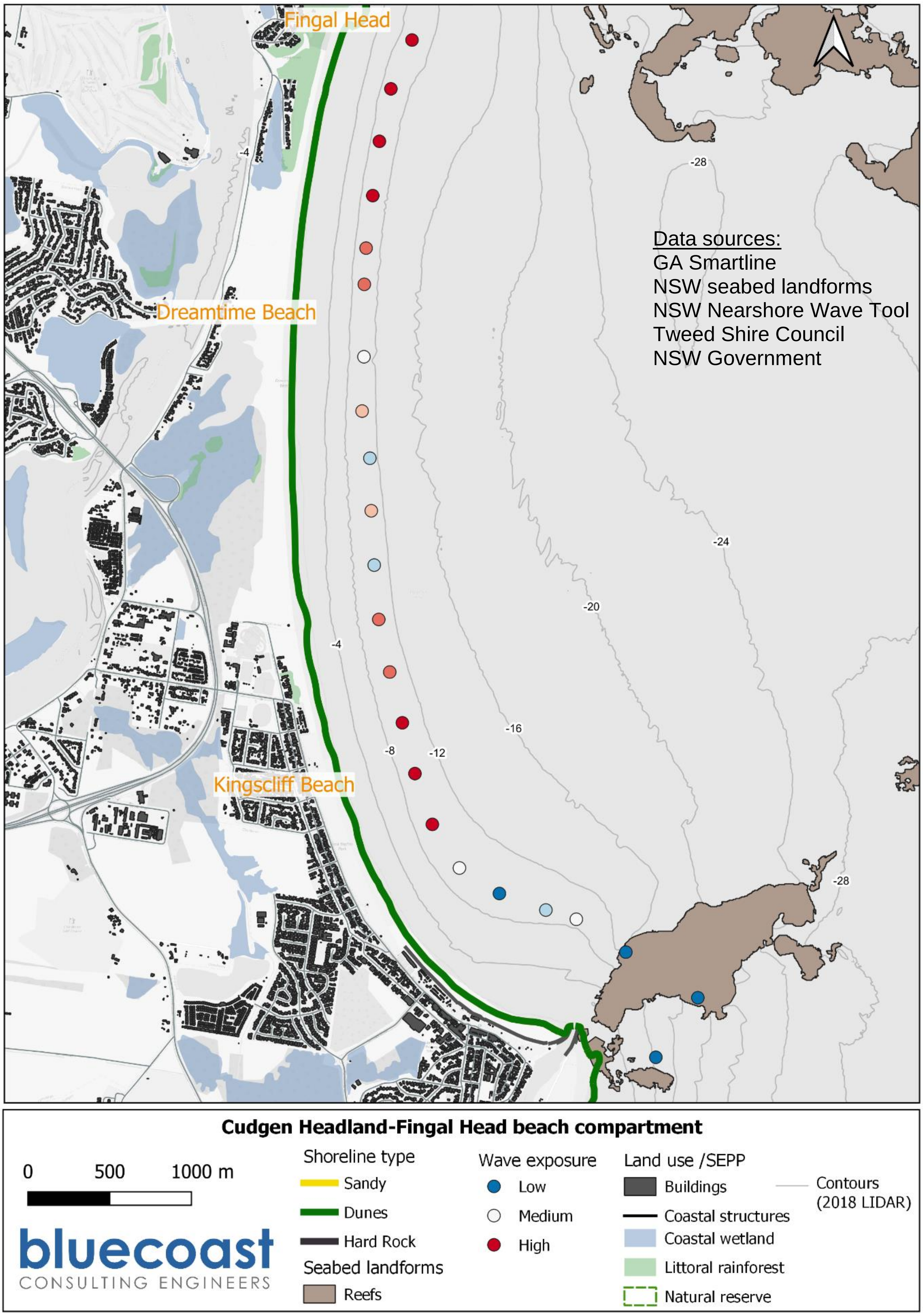

Figure 106: Overview of Cudgen Headland to Fingal Head compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Cudgen Headland to Fingal Head compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Cudgen Headland to Fingal Head compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 107.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 108.

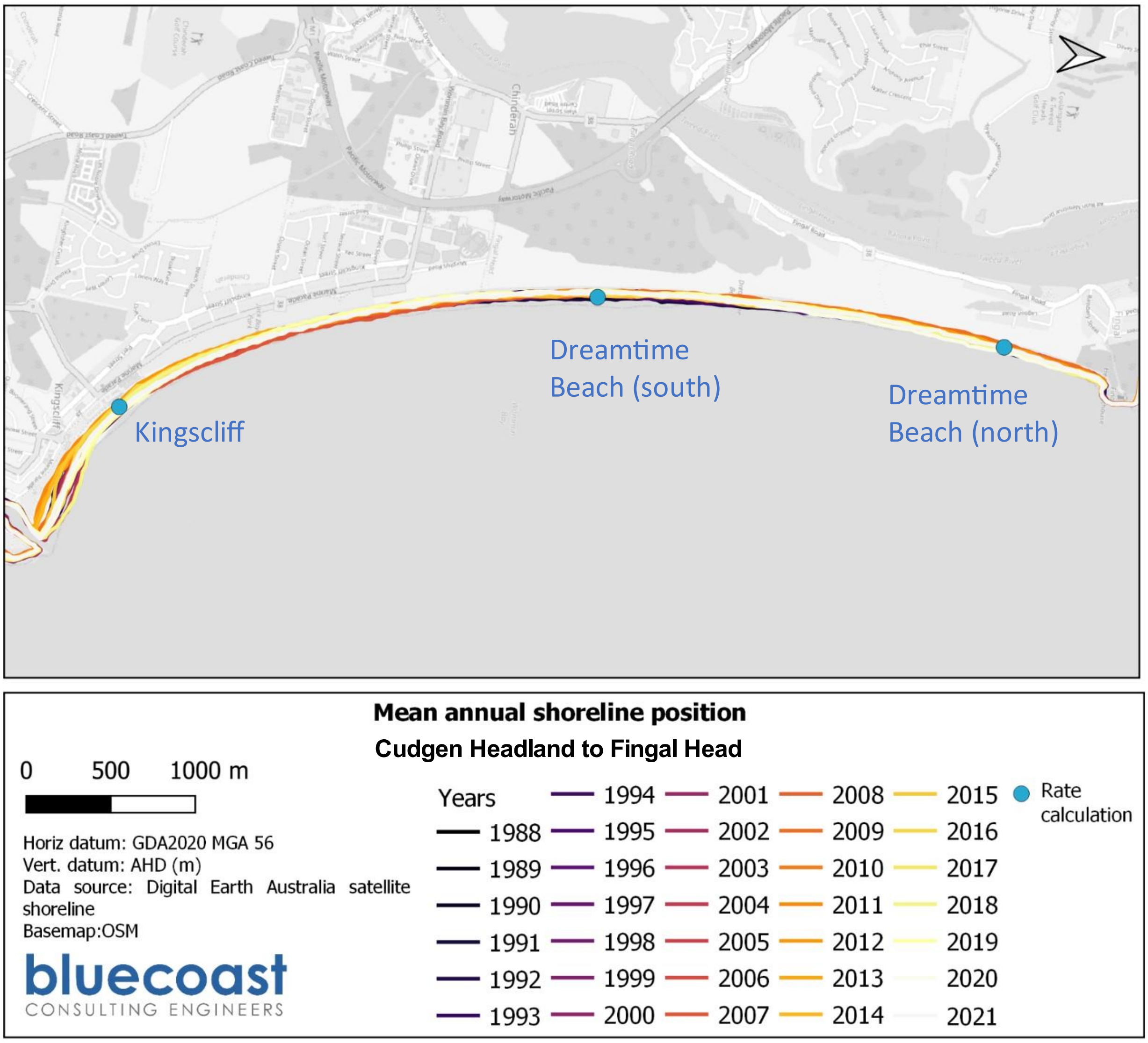

Figure 107: Mean annual shorelines within Cudgen Headland to Fingal Head compartment from 1988 to 2021.

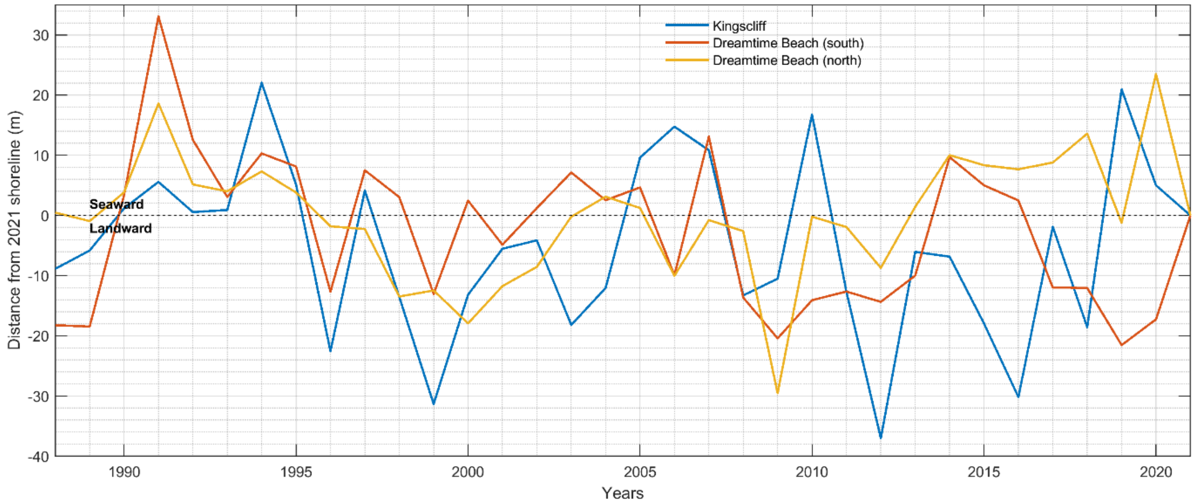

Figure 108: Mean annual shoreline position relative to 2021 shoreline for key areas within Cudgen Headland to Fingal Head compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 109 for three different periods.
- Table 42 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

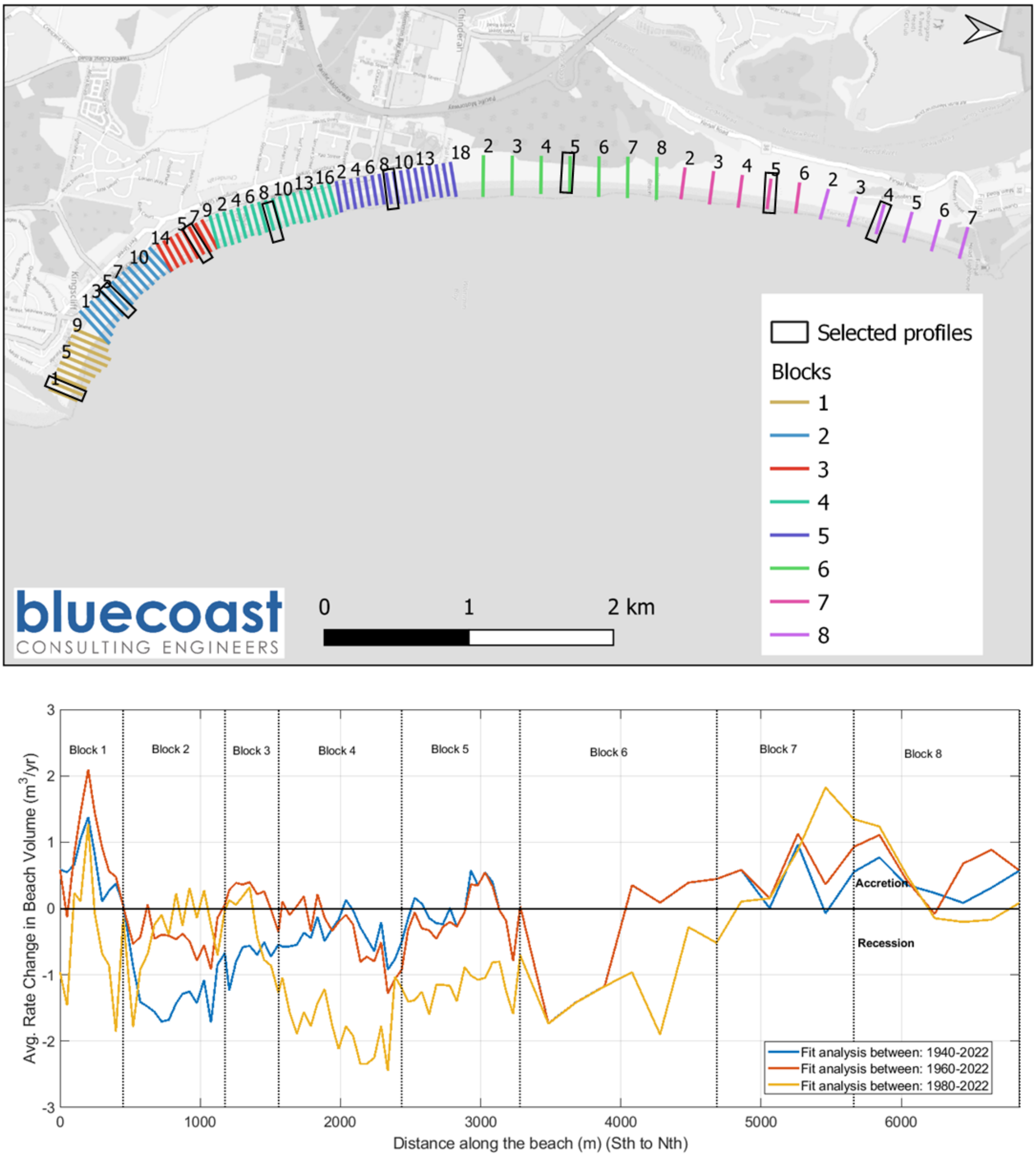

Figure 109: Profile locations and rate of change of subaerial beach volume along the Cudgen Headland to Fingal Head compartment for short, medium and long-term analysis periods.

Table 42: Overview of photogrammetry profile analysis for Cudgen Headland to Fingal Head compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Adopted period (no. of years) Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max]		
				1940-2022	1960-2022	1980-2022
Block 1	484m (10)	1947 – 2022 (75)	21 (varies)	0.05, 0.58, 1.38	-0.13, 0.82, 2.09	-1.85, -0.44, 1.27
Block 2	685m (14)		23 (varies)	-1.72, -1.31, 0.67	-0.91, -0.42, 0.06	-1.78, -0.33, 0.31
Block 3	380m (8)		23 (varies)	-1.24, -0.71, -0.51	-0.35, 0.19, 0.4	-1.27, -0.33, 0.32
Block 4	890m (18)		24 (varies)	-0.93, -0.4, 0.13	-1.28, -0.39, 0.21	-2.44, -1.74, -1.02
Block 5	925m (17)	1955 – 2022 (67)	20 (varies)	-0.79, 0, 0.57	-0.79, -0.09, 0.54	-1.59, -1.15, -0.7
Block 6	1387 (7)	1962 – 2022 (60)	13 (varies)	-1.73, -0.43, 0.44	-1.73, -0.43, 0.44	-1.89, -1.13, -0.28
Block 7	950m (5)	1947 – 2022 (75)	16 (varies)	-0.07, 0.41, 0.96	0.15, 0.63, 1.13	0.11, 0.86, 1.82
Block 8	1140m (6)		16 (varies)	0.08, 0.38, 0.77	-0.08, 0.6, 1.11	-0.2, 0.22, 1.23

Note: BMT WBM (2013) adopted the following values (m/yr) [min, best estimate, max]: Cudgen Ck to Bowls Club [0.12, 0.15, 0.2], Kingscliff North [0.10, 0.12, 0.14], Dreamtime Beach south [0.08, 0.10, 0.12], Dreamtime Beach north [0.04, 0.05, 0.06]

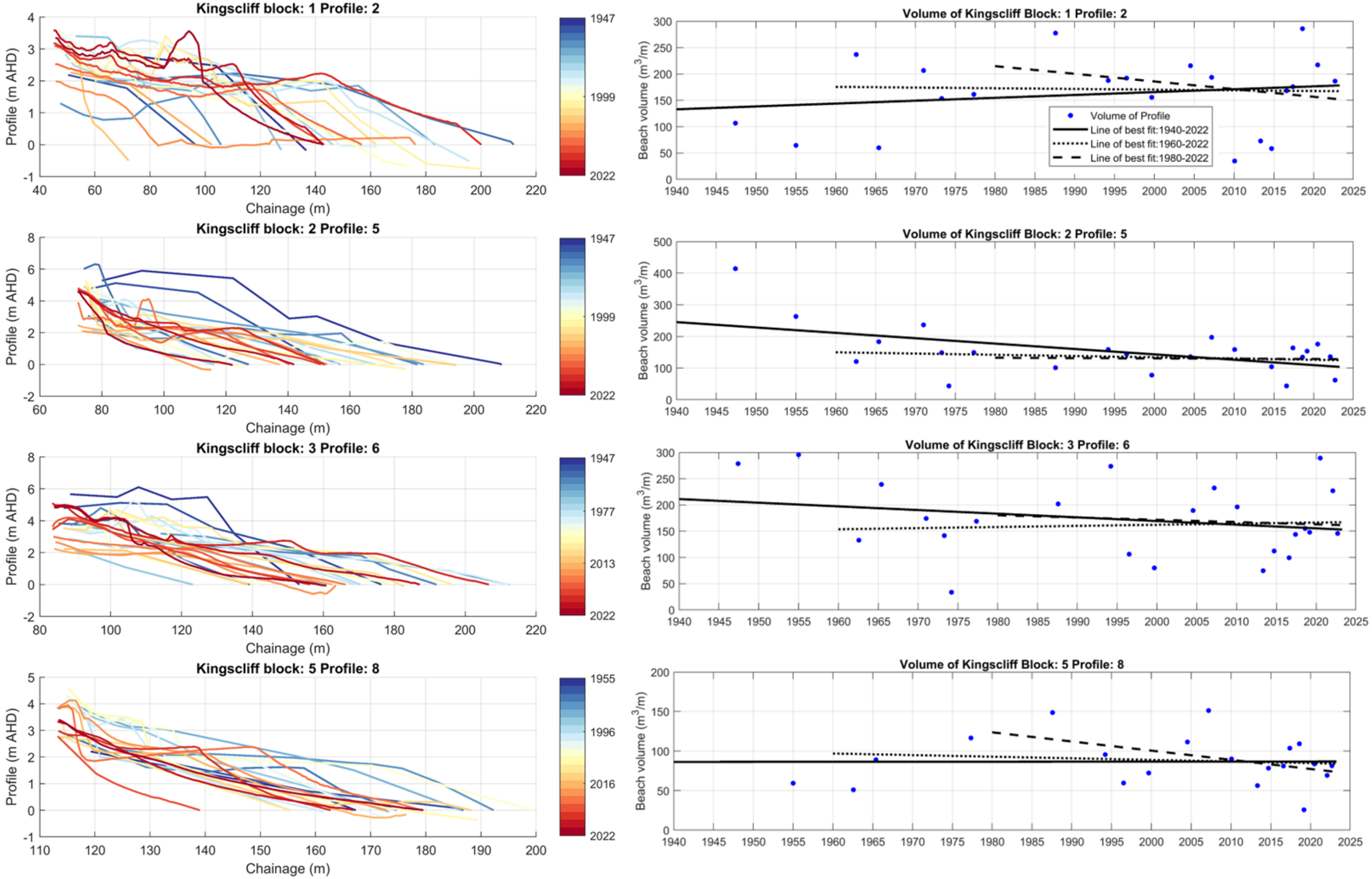

Figure 110: Photogrammetry beach profiles and (left) associated beach volume change over time (right).

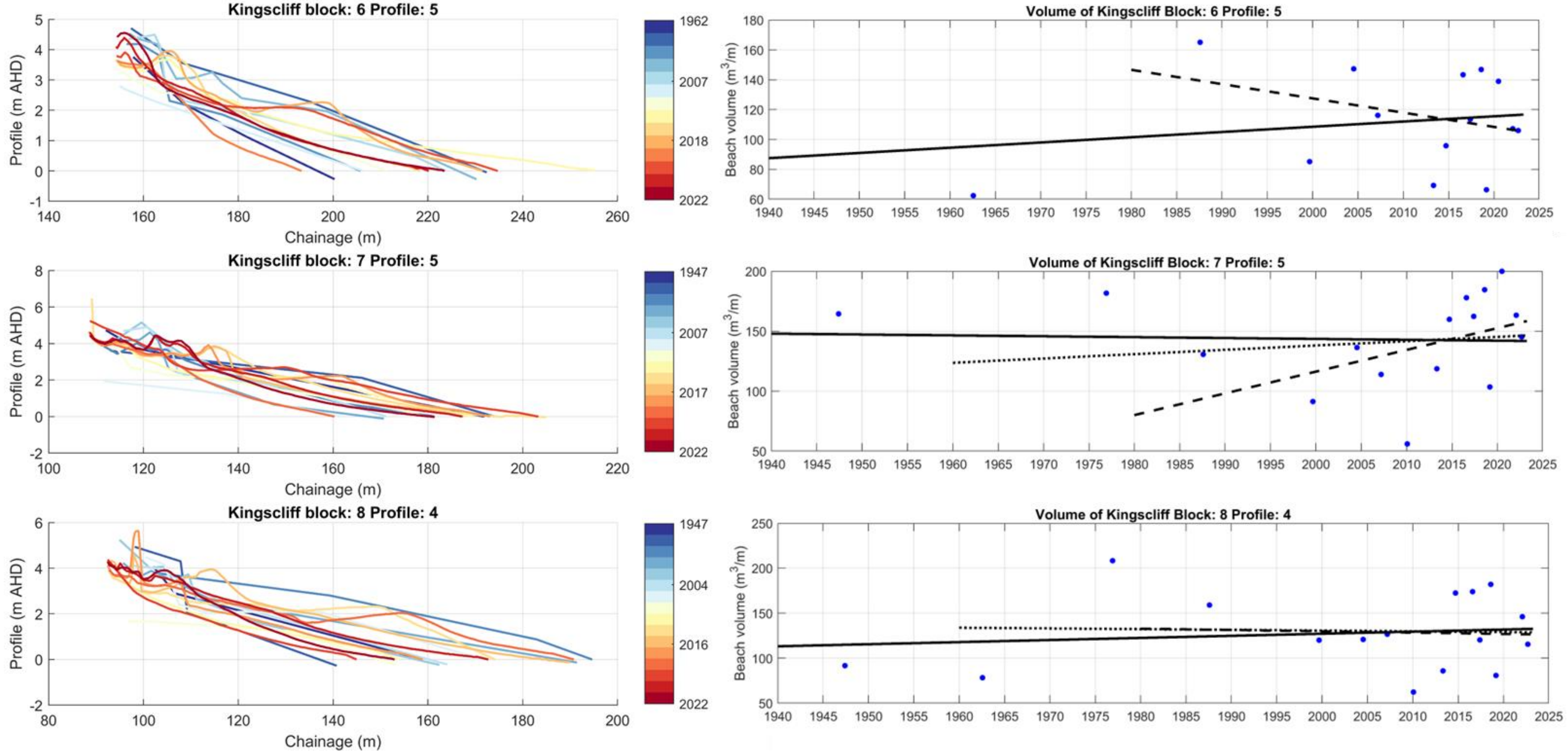

Figure 111: Photogrammetry beach profiles and (left) associated beach volume change over time (right).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 112. Individual beach profiles for Kingscliff Beach and Dreamtime Beach are shown in Figure 113 and Figure 114.

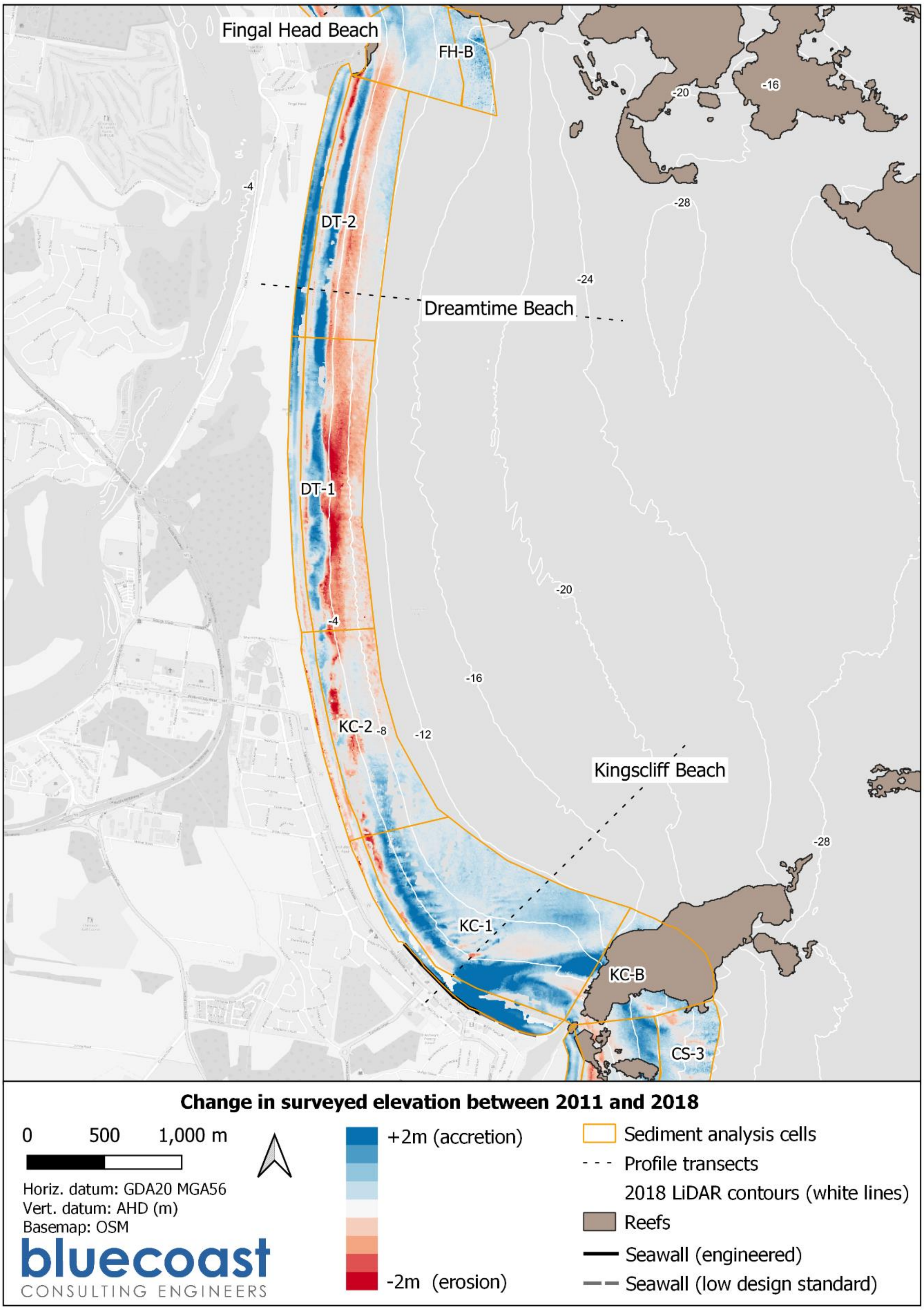

Figure 112: Surveyed elevation change along Cudgen Headland to Fingal Head compartment between 2011 and 2018.

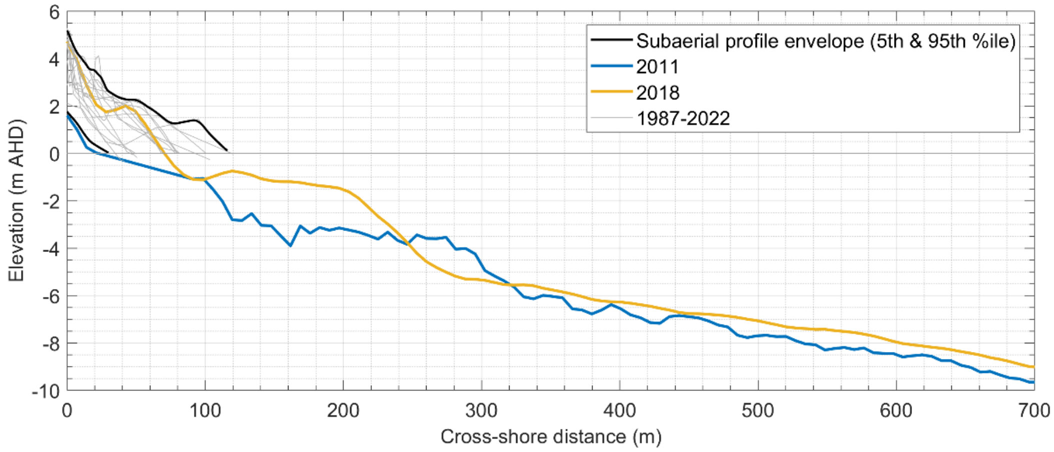

Figure 113: Profile evolution for Kingscliff Beach transect.

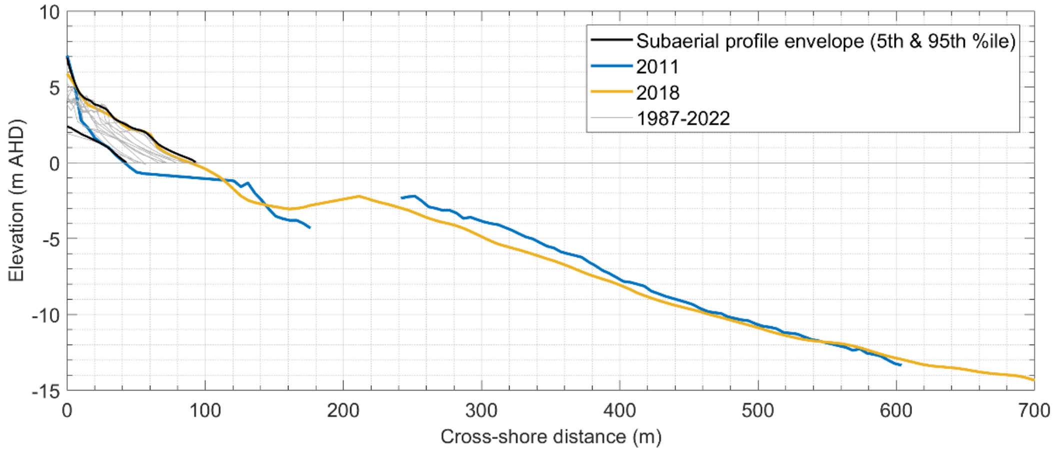

Figure 114: Profile evolution for Dreamtime Beach transect.

Beach erosion

Figure 115 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 1996 and 1999 East Coast Lows, 2009 East Coast Low and the 2019 tropical cyclone. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed. The observed storm demand is approximately 150 m^3/m along Kingscliff and Dreamtime Beaches.

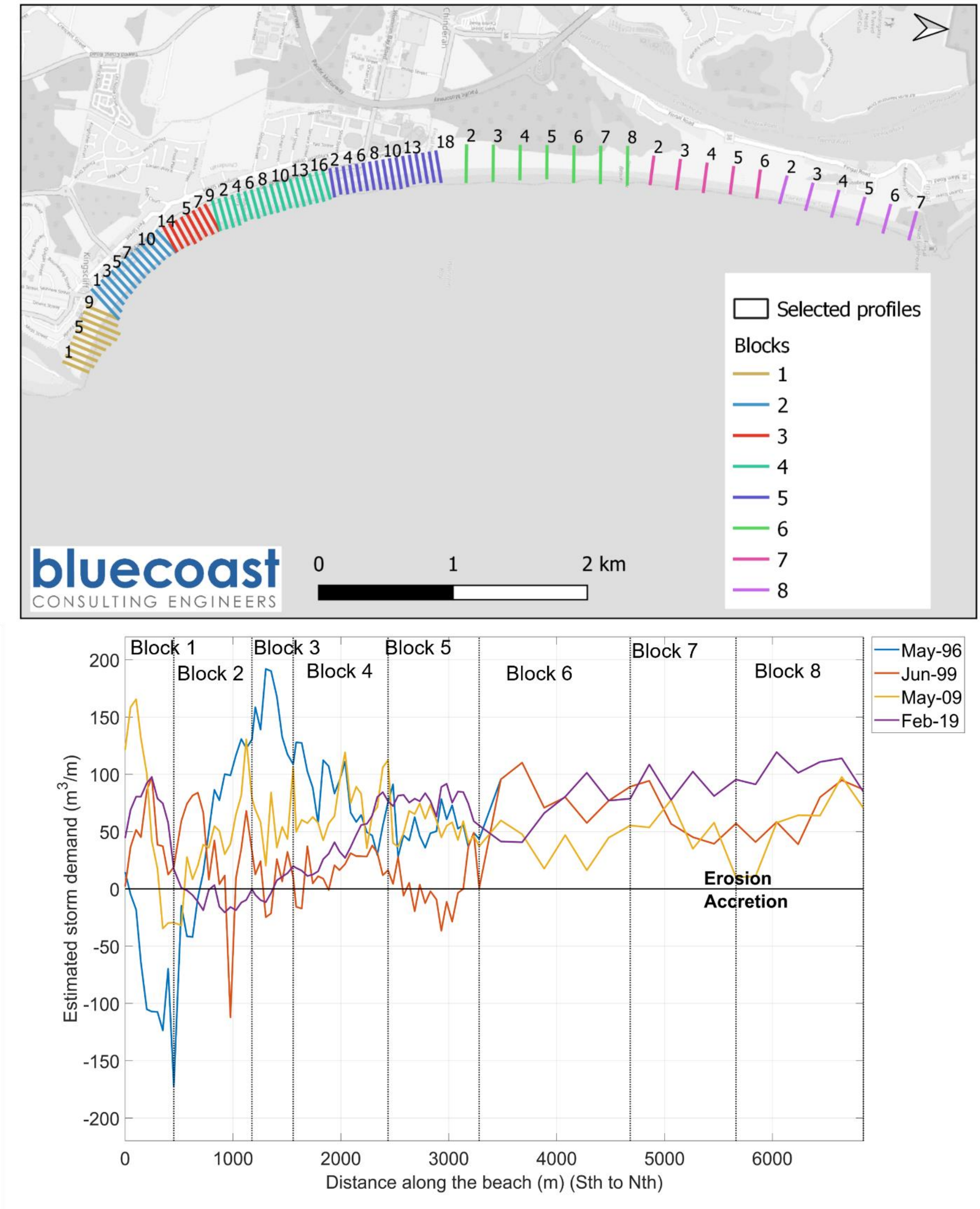

Figure 115: Alongshore storm demand estimates derived from photogrammetry for storms in 1996, 1999, 2009 and 2019.

Fingal Head to Point Danger

Beach compartment overview

The following sections describe the location specific considerations of relevance to the assessment of coastal hazards. The regional context and description of coastal processes acting at this stretch of coast is provided in the main report.

The Fingal Head to Point Danger beach compartment is approximately 4,000m long and starts at Fingal Head and extends to Point Danger (on the NSW – QLD border) to the north (Figure 116). Table **39** provides the main characteristics of this compartment.

Table 43: Main characteristics of Fingal Head to Point Danger compartment.

Parameter	Fingal Head Beach	Letitia Beach	Duranbah Beach
Beach type	Embayment	Embayment	Embayment
Sandy beach length	1,500m	2,000m	500m
Orientation	East-north-east	East-north-east	East
Relative wave exposure (NSW Nearshore Wave Tool)	High	Medium	Medium
Coastal land-use / Resilience SEPP mapping	Largely suburban (Fingal). SEPP littoral rainforest at Fingal Head in the south. SEPP coastal wetland located upstream in Tweed River.	Mostly natural coastal area. SEPP coastal wetland located upstream in Tweed River.	Urban area.
Key morphological features	Fingal Head headland to the south	Tweed River entrance to the north	Tweed River entrance to the south Point Danger to the north

SEPP - State Environmental Planning Policy (Resilience and Hazards) 2021. All coastal management areas in the LGA are within the coastal environment area. They are also all within the coastal use area except the estuary entrances (ICOLL included). Coastal wetlands and littoral rainforests areas are listed in this table where these apply.

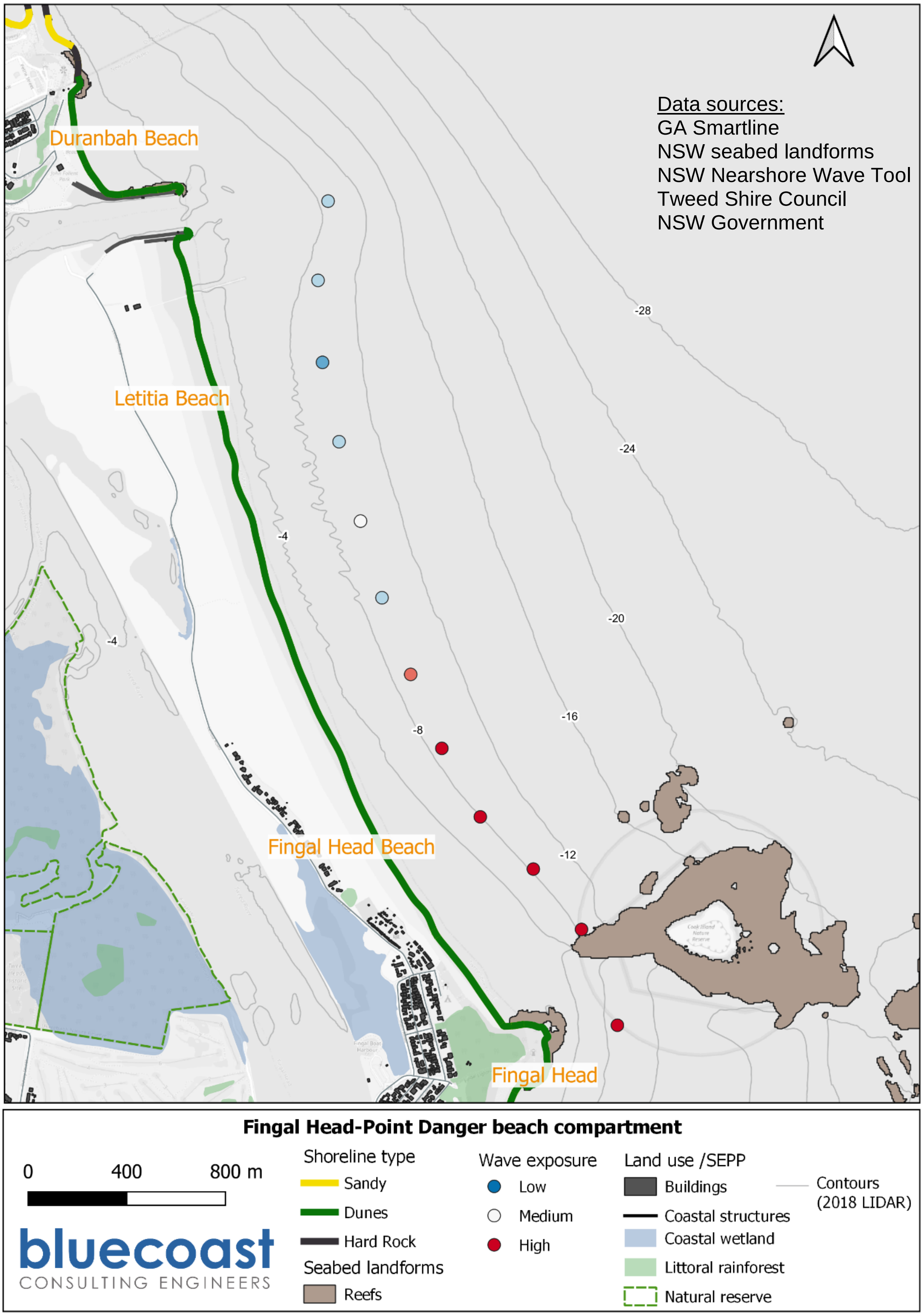

Figure 116: Overview of Fingal Head to Point Danger compartment.

Long-term beach volume and shoreline change

The following sections provide a factual description of available data and analysis results related to the observed long-term morphological behaviour of the Fingal Head to Point Danger compartment.

Shoreline change

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2021 were analysed. Results showing the historic shoreline behaviour within the Fingal Head to Point Danger compartment are presented as follow:

- Mean annual shoreline positions are shown in Figure 117.
- A timeseries of mean shoreline position change for key areas within the compartment is shown in Figure 118.

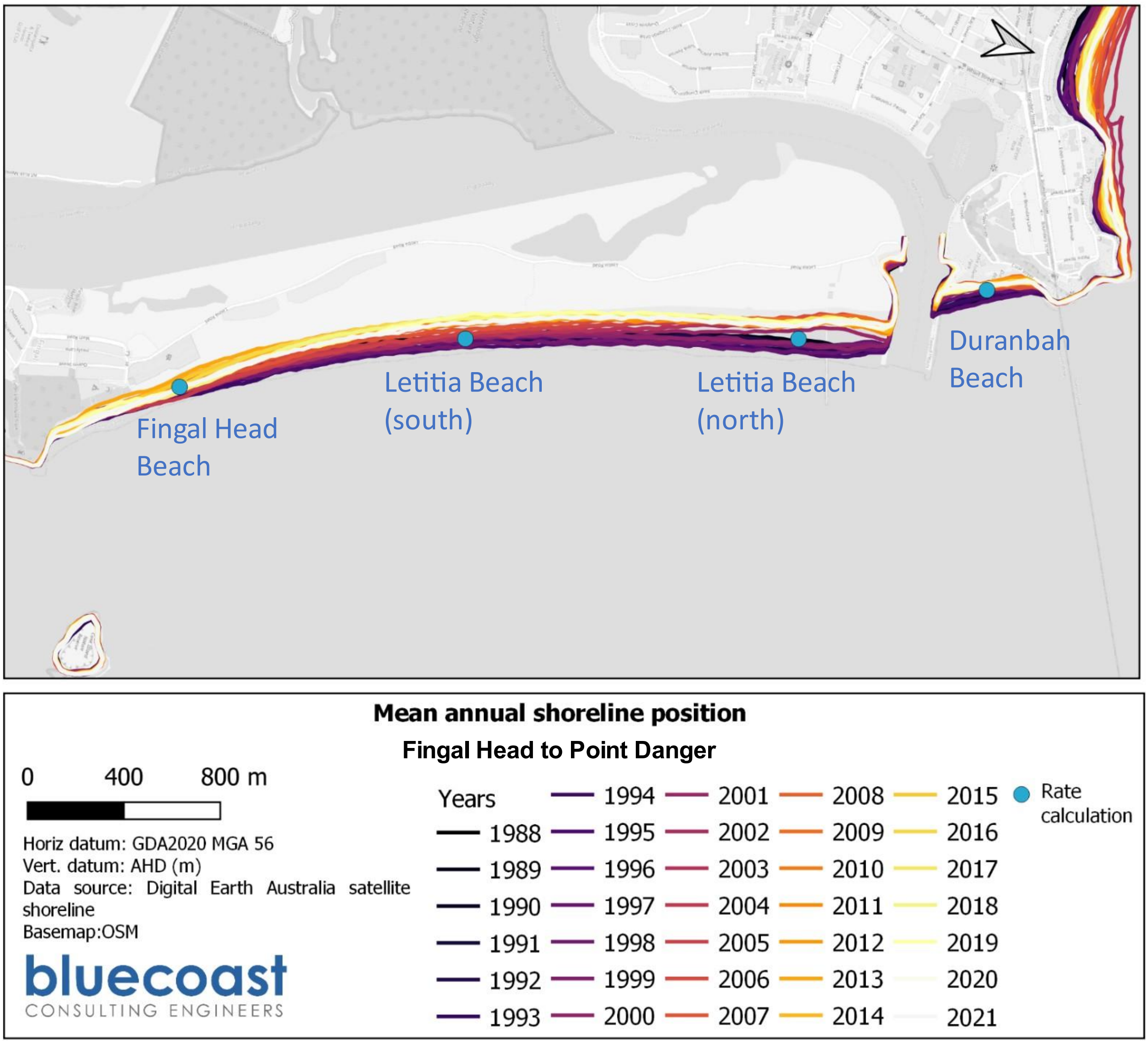

Figure 117: Mean annual shorelines within Fingal Head to Point Danger compartment from 1988 to 2021.

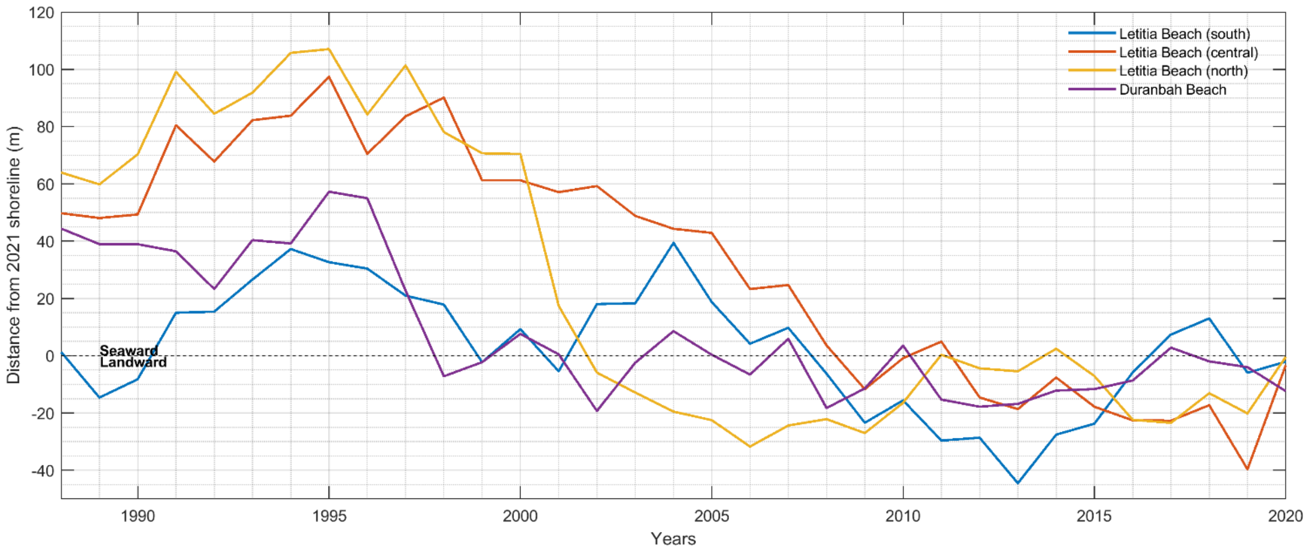

Figure 118: Mean annual shoreline position relative to 2021 shoreline for key areas within the Fingal Head to Point Danger compartment (see data point locations in figure above).

Subaerial beach change

Beach profiles from the NSW photogrammetry database were analysed for subaerial (above 0m AHD) sand volume changes. A summary of photogrammetry profile analysis is provided as follows:

- The alongshore rates of change in subaerial beach volume are shown in Figure 119 for three different periods.
- Table 44 provides a summary of the photogrammetry profile analysis and calculated subaerial volume change rates for representative sections of beach.

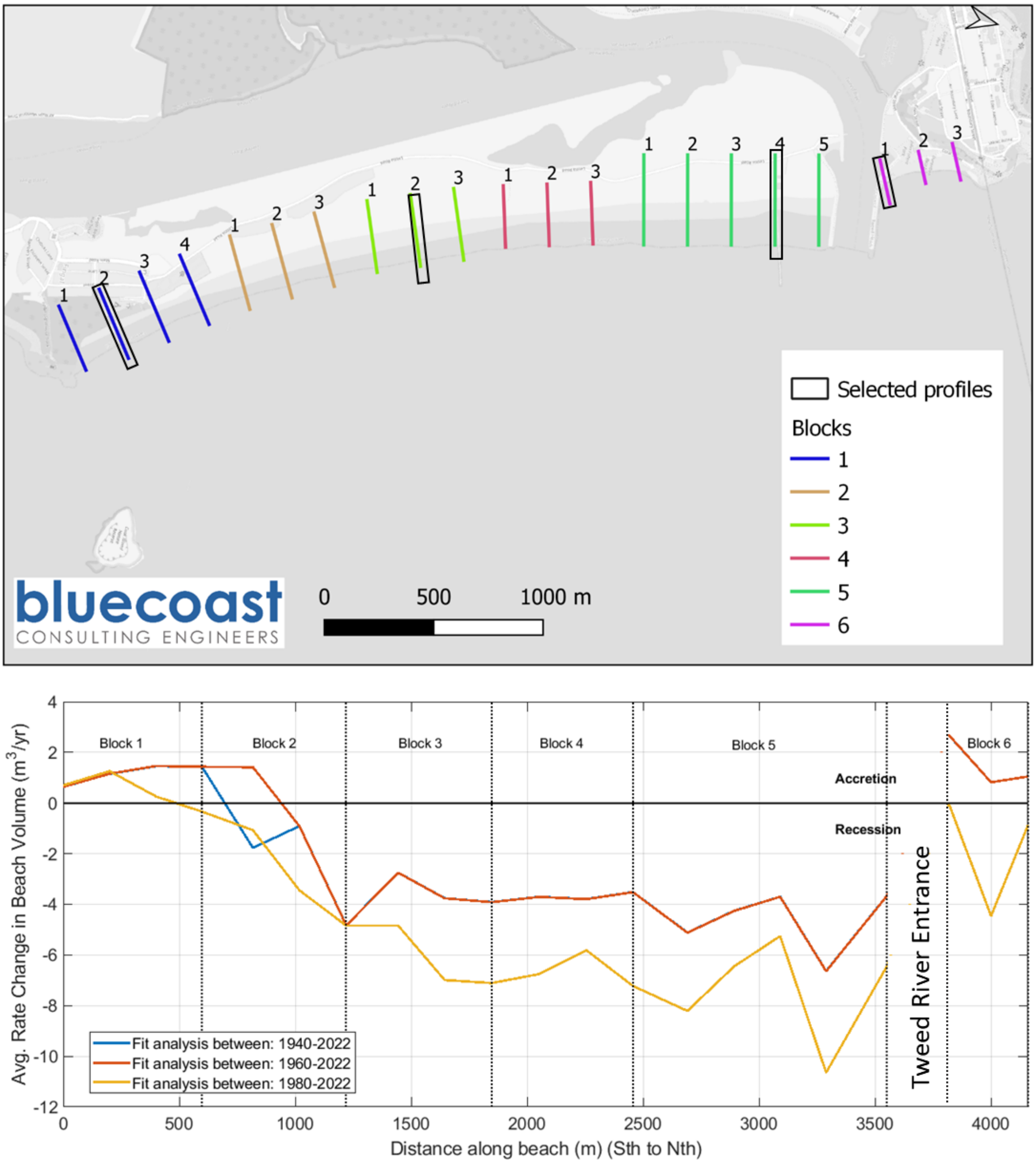

Figure 119: Profile locations and rate of change of subaerial beach volume along the Fingal Head to Point Danger compartment for short, medium and long-term analysis periods.

Table 44: Overview of photogrammetry profile analysis for Fingal Head to Point Danger compartment.

Location (Block ID)	Block length (no. of profiles)	Date range (no. of years)	No. of images	Subaerial avg. volume change rate ($m^3/m/yr$) [min, mean, max] 1940-2022	1960-2022	1980-2022
Block 1	682m (4)	1962 – 2022 (60)	13 (varies)	0.64, 1.17, 1.46	0.64, 1.17, 1.46	-0.34, 0.46, 1.25
Block 2	620m (3)	1947 – 2022 (75)	17 (varies)	-4.83, -2.5, -0.91	-4.82, -1.44, 1.41	-4.82, -3.11, -1.07
Block 3	580m (3)	1971 – 2022 (51)	15 (varies)	-3.91. -3.47, -2.75	-3.91, -3.47, -2.75	-7.08, -6.29, -4.82
Block 4	628m (3)	1971 – 2022 (51)	14 (varies)	-3.79, -3.67, -3.51	-3.79, -3.67, -3.51	-7.19, -6.57, -5.79
Block 5	967m (5)	1971 – 2022 (51)	15 (varies)	-6.63, -4.67, -3.68	-6.63, -4.67, -3.68	-10.6, -7.37, -5.23
Block 6	380m (3)	1962 – 2022 (60)	2 (varies)	0.82, 1.52, 2.7	0.82, 1.52, 2.7	-4.44, -1.76, 0.02

Note: BMT WBM (2013) adopted a recession rate of 0.10m/yr at Fingal Head and 0.05m/yr at Central Letitia Spit.

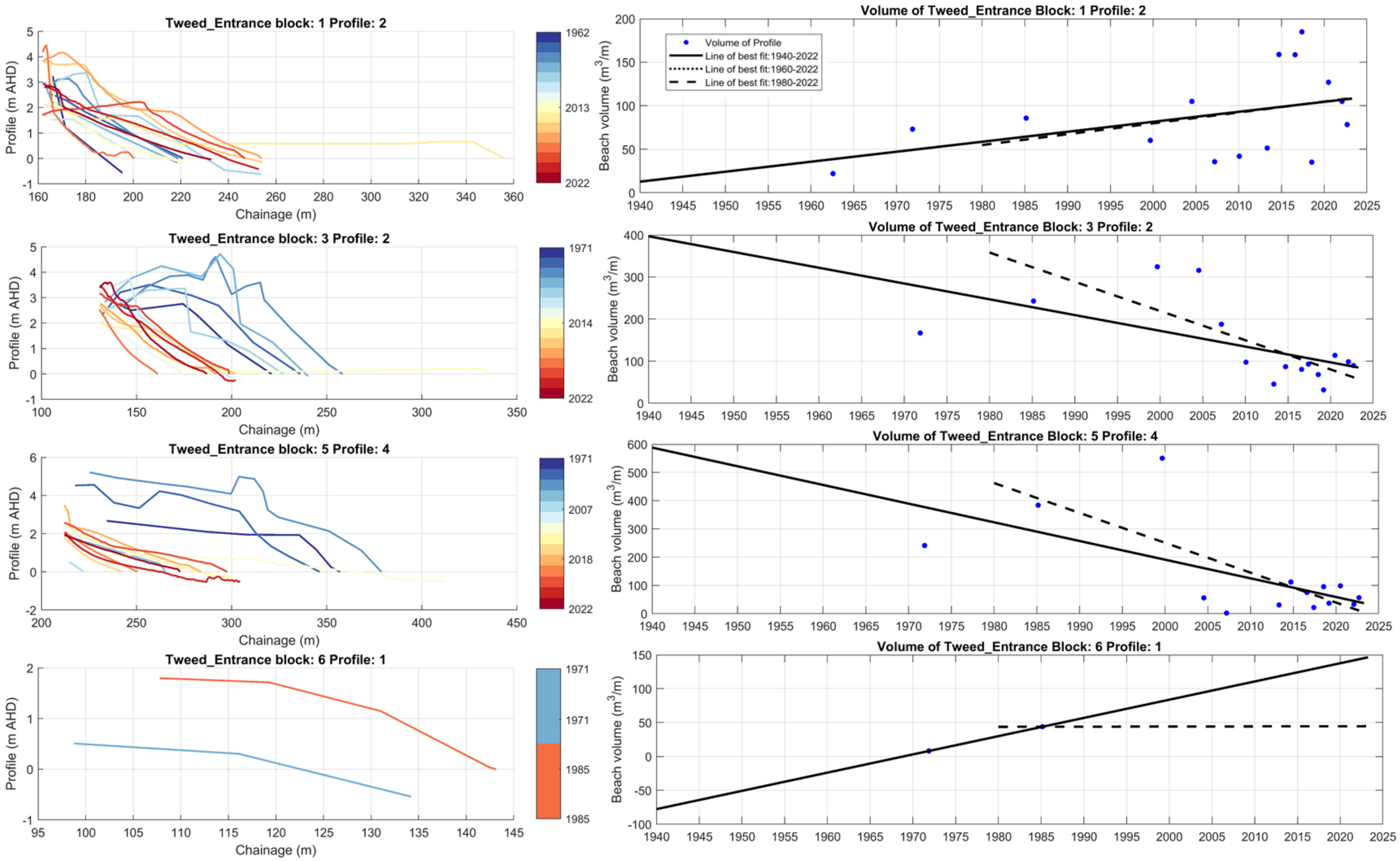

Figure 120: Photogrammetry beach profiles and (left) associated beach volume change over time (right).

Subaqueous beach change

Profile transects were analysed for subaqueous (below 0m AHD) sand volume changes based on nearshore LiDAR data from 2011 and 2018. Transect locations and profile elevation change are shown in Figure 121. Individual beach profiles for Fingal Head Beach and Letitia Beach are shown in Figure 122 and Figure 123.

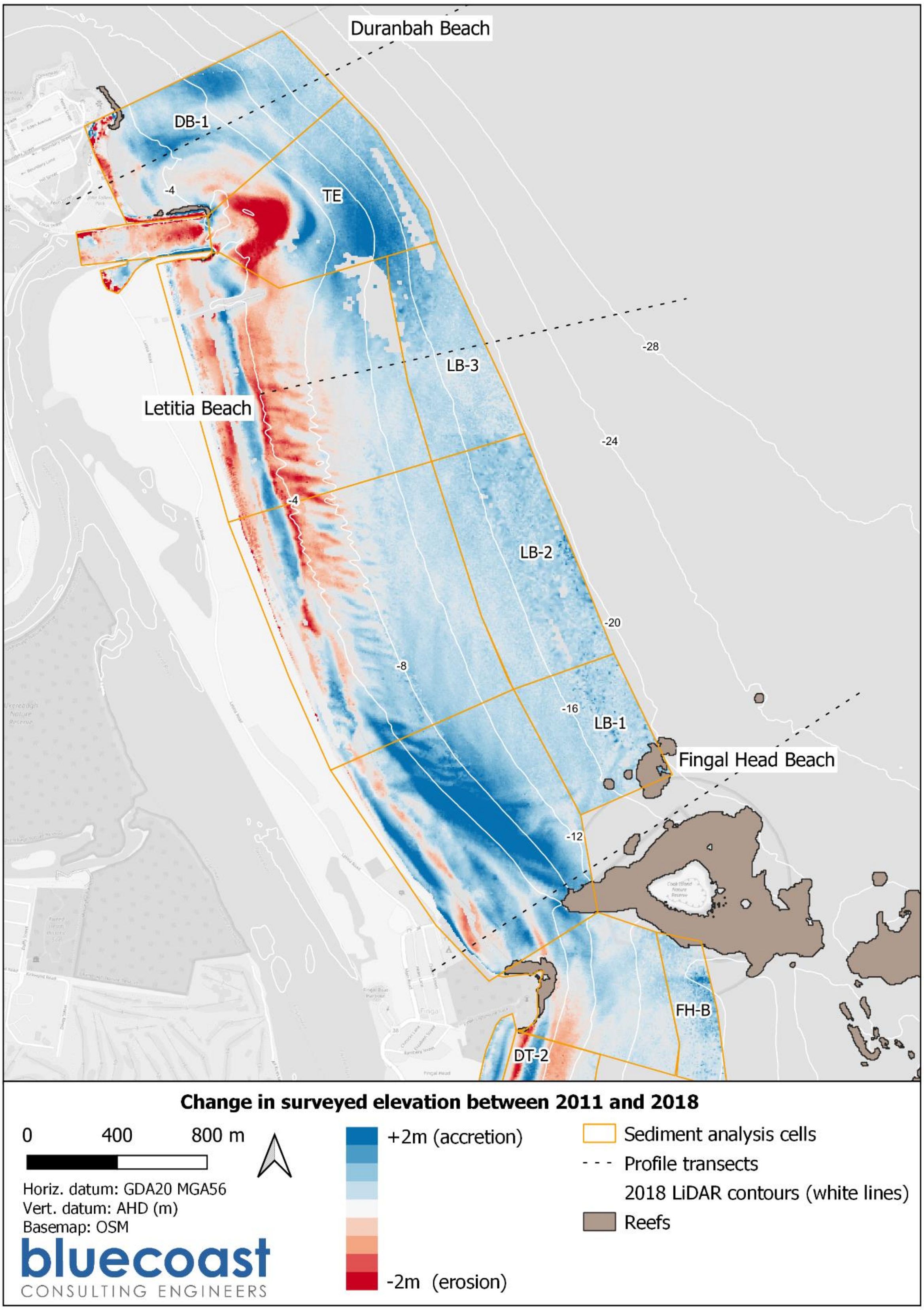

Figure 121: Surveyed elevation change along Fingal Head to Point Danger compartment between 2011 and 2018.

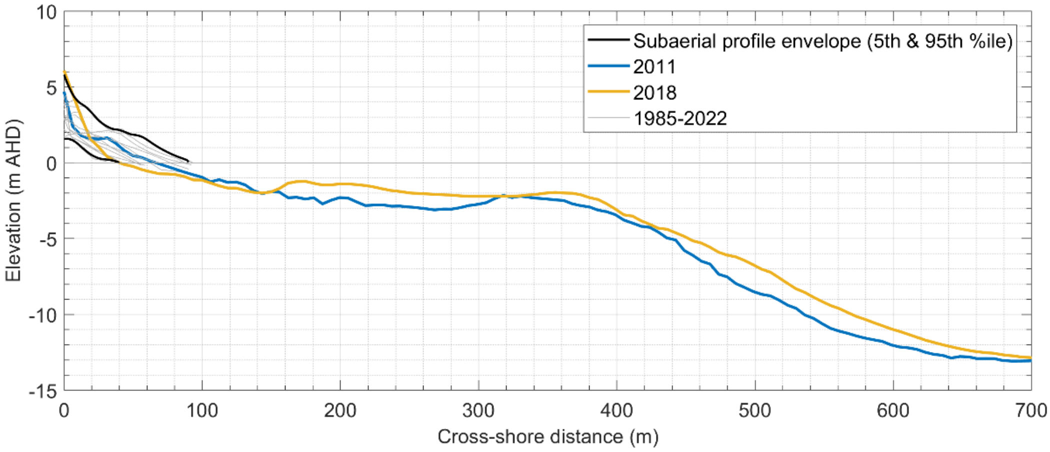

Figure 122: Profile evolution for Fingal Head Beach transect.

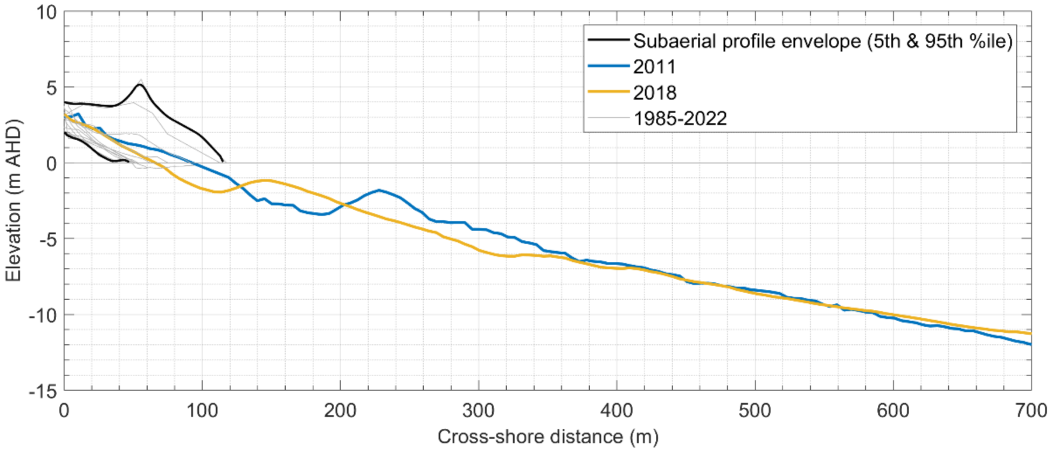

Figure 123: Profile evolution for Letitia Beach transect.

Beach erosion

Figure 124 shows the alongshore distribution of storm demands estimated from photogrammetry data for a range of storms. For this section, the storms used for analysis were the 2009 East Coast Low, the 2019 tropical cyclone and 2020 severe erosion event. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

While the alongshore pattern of estimated storm varies from storm to storm, a general pattern across the embayment is observed. The pattern, from south to north, is described as:

- Local minimum in storm erosion volumes at the southern end at Fingal Head Beach.
- High storm erosion volumes for Letitia Beach are seen from the 2009 storm event.
- Generally increasing storm erosion volumes towards the northern end of Letitia Beach shown by the 2019 and 2020 storm events.

- No photogrammetry storm demand data was available for Duranbah Beach (block 6).
- Storm demand volumes estimated to be 150m³/m along Letitia Beach. Fingal Head Beach has reduced storm demand volumes, as shown in Figure 124, and is estimated to be 100m³/m.

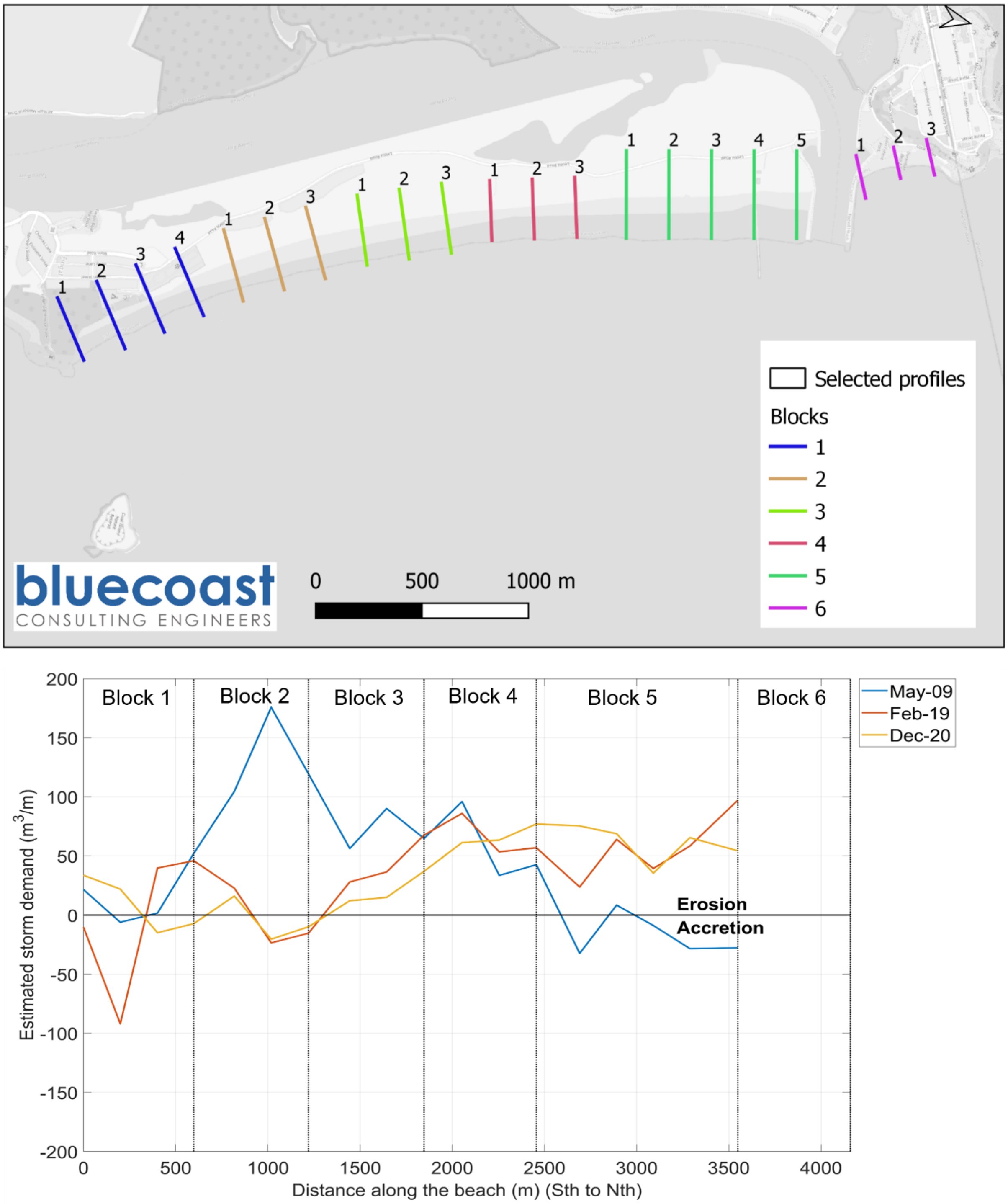

Figure 124: Alongshore storm demand estimates derived from photogrammetry for storms in 2009, 2019 and 2020.

Appendix B: Probabilistic erosion and recession hazard model setup and results

Beach profiles for each beach section

Figure 125 to Figure 130 map the cross-shore (shore-normal) beach profile lines used in the probabilistic erosion and recession hazard model for the Tweed Shire for each beach compartment.

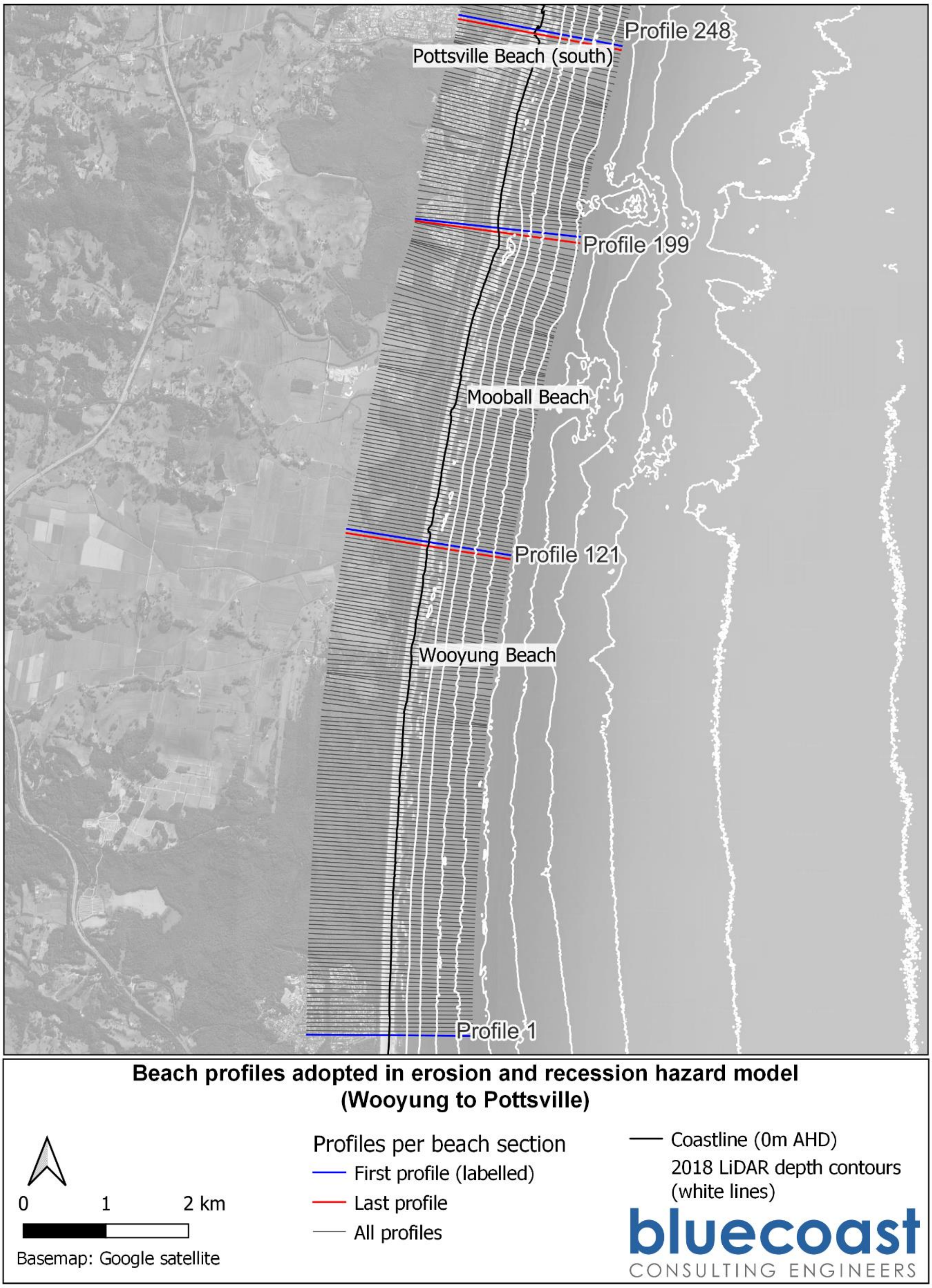

Figure 125: Hazard model profiles for Wooyung to Pottsville.

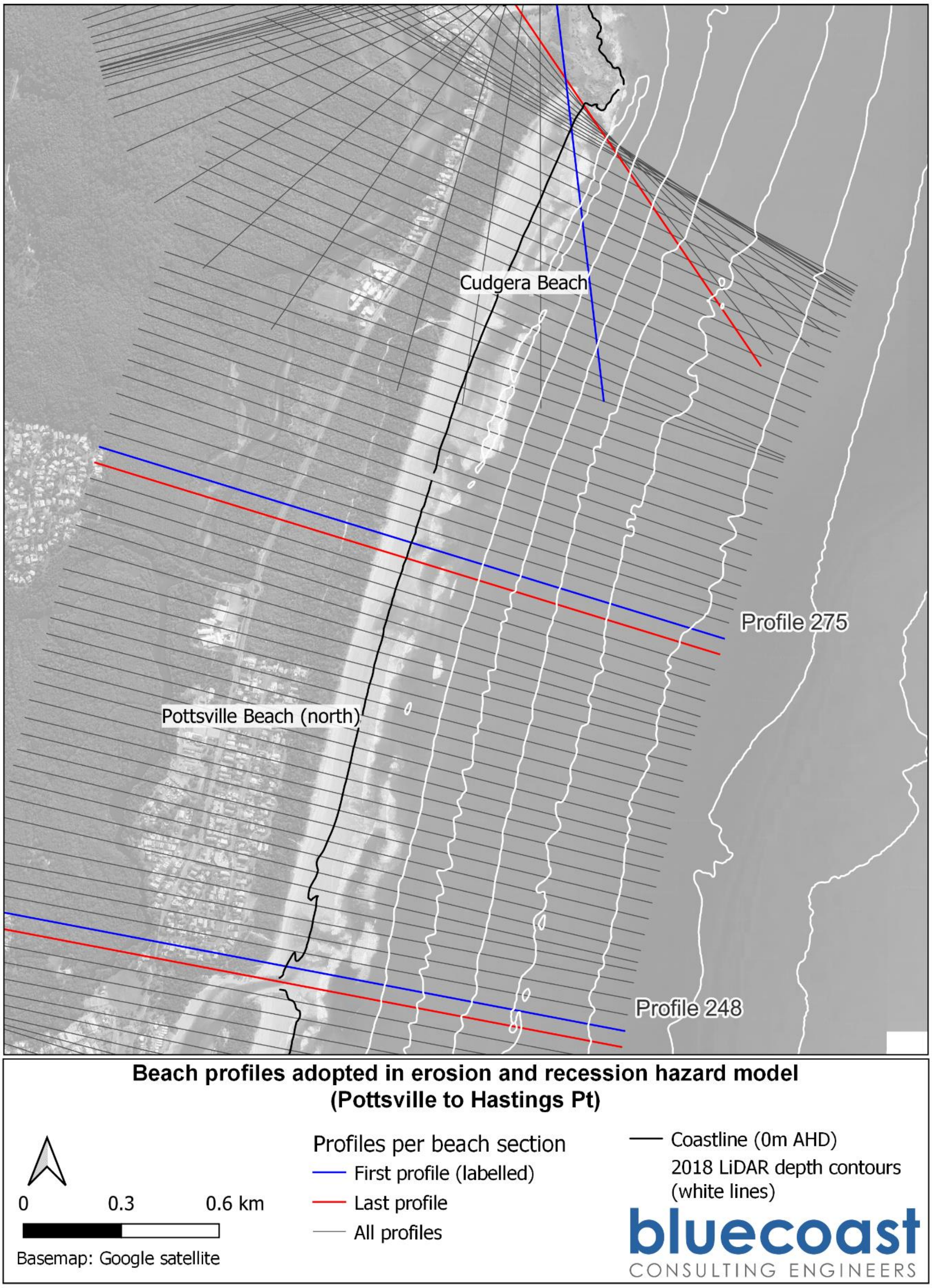

Figure 126: Hazard model profiles for Pottsville to Hastings Point.

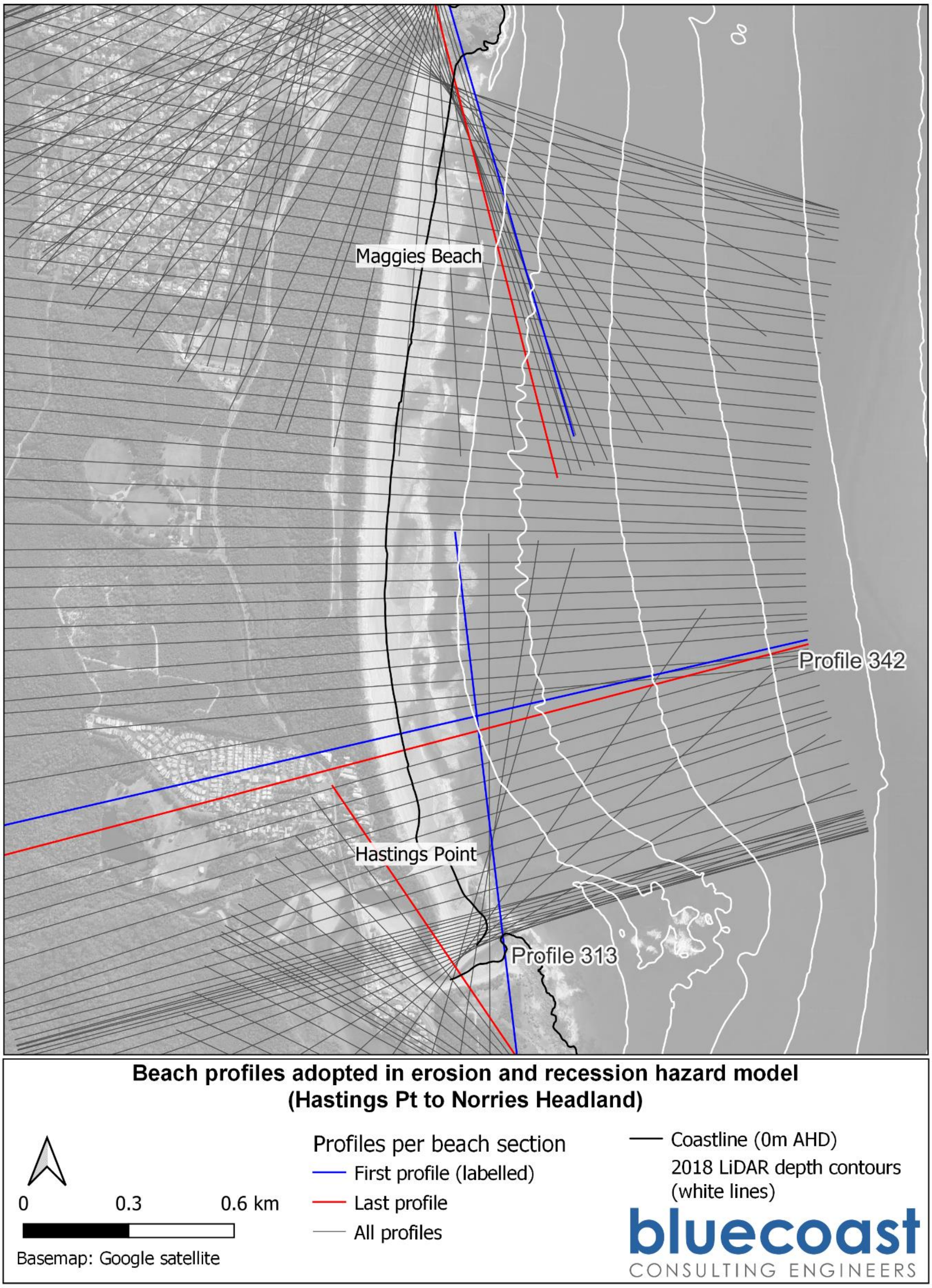

Figure 127: Hazard model profiles for Hastings Point to Norries Headland.

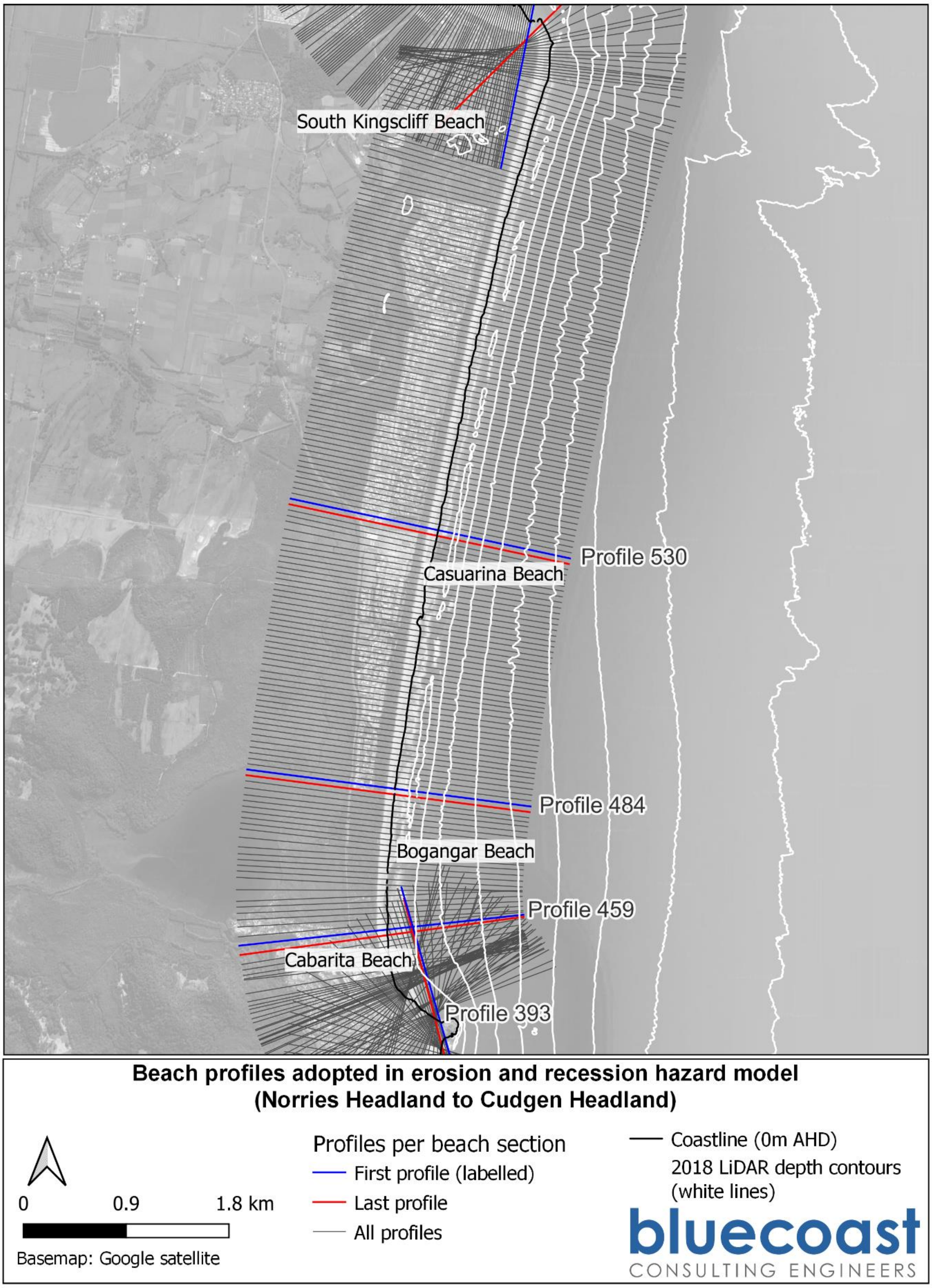

Figure 128: Hazard model profiles for Norries Headland to Cudgen Headland.

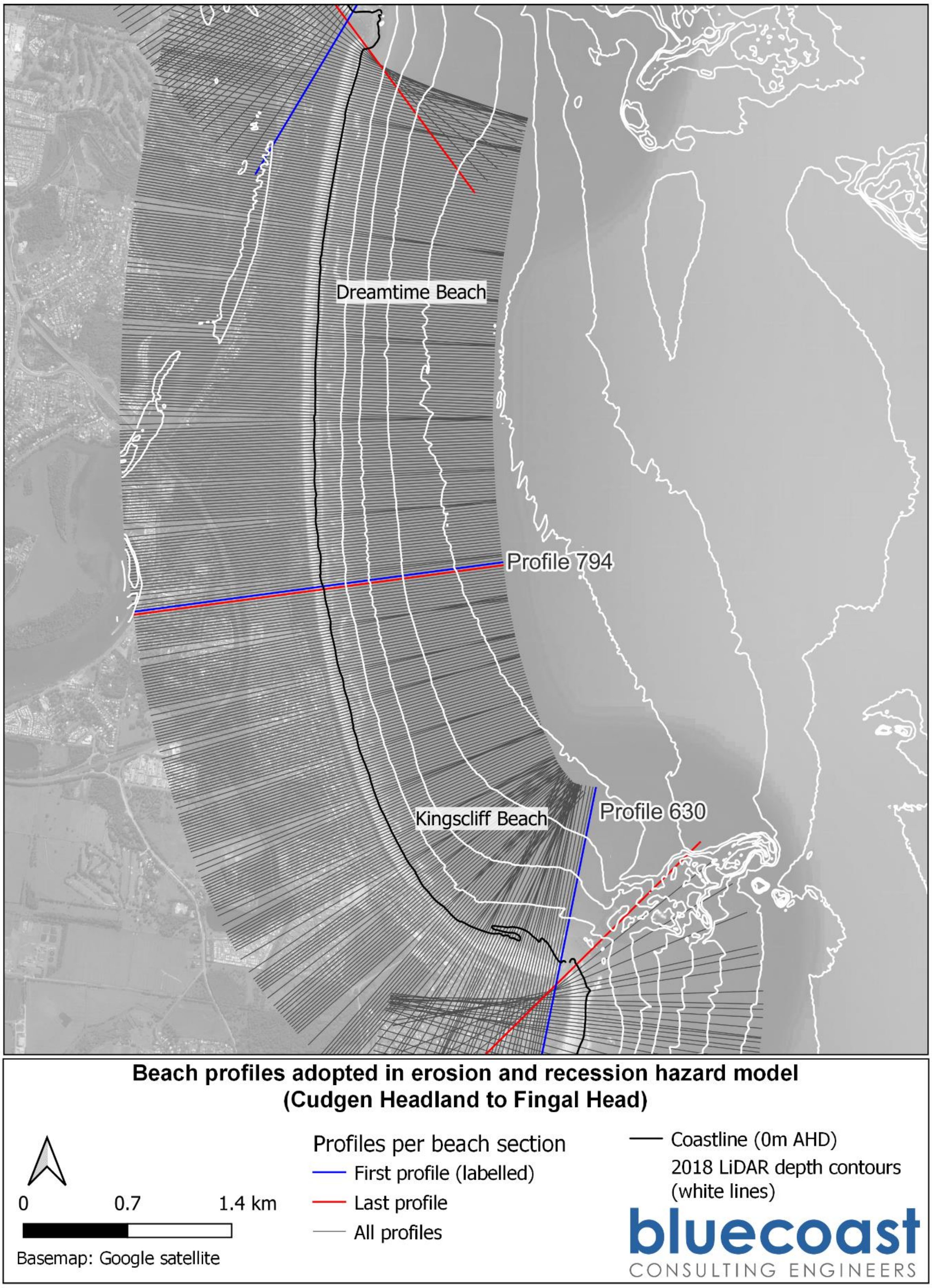

Figure 129: Hazard model profiles for Cudgen Headland to Fingal Head.

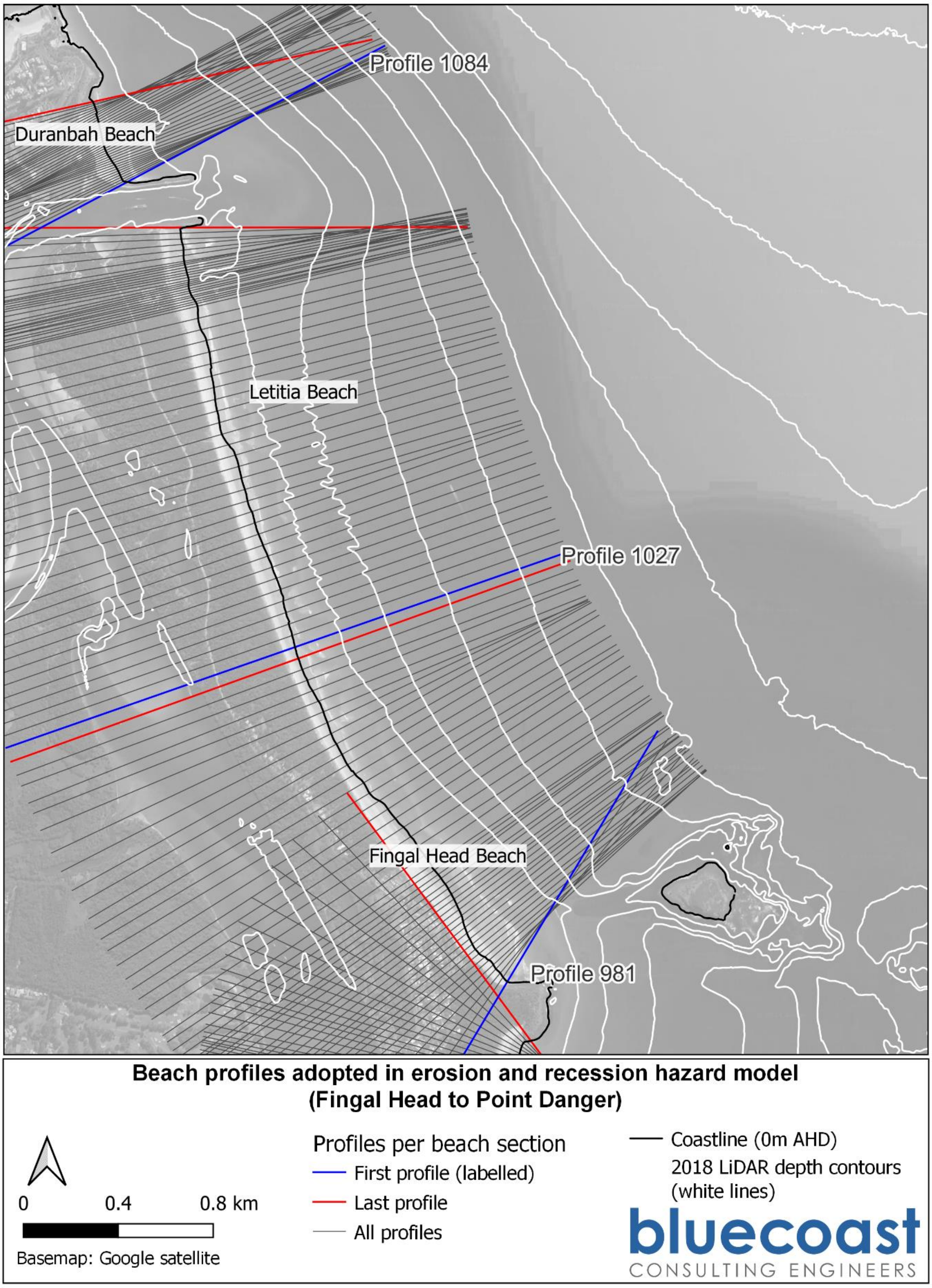

Figure 130: Hazard model profiles for Fingal Head to Point Danger.

Model results for each beach section

The probability of exceedance curves of the landward position of the ZRFC for each beach section across the five planning timeframes (immediate, 2040, 2050, 2070 and 2120) are presented below, as well as the full distribution for the landward position of the ZRFC for 2120. The distance (m) from 0m AHD (2018 baseline) is used to define the landward position of the ZRFC and was calculated for each profile. Figure 131 to Figure 146 show representative results for each of the 16 beach compartments (refer to limitations discussed in Section 5.4).

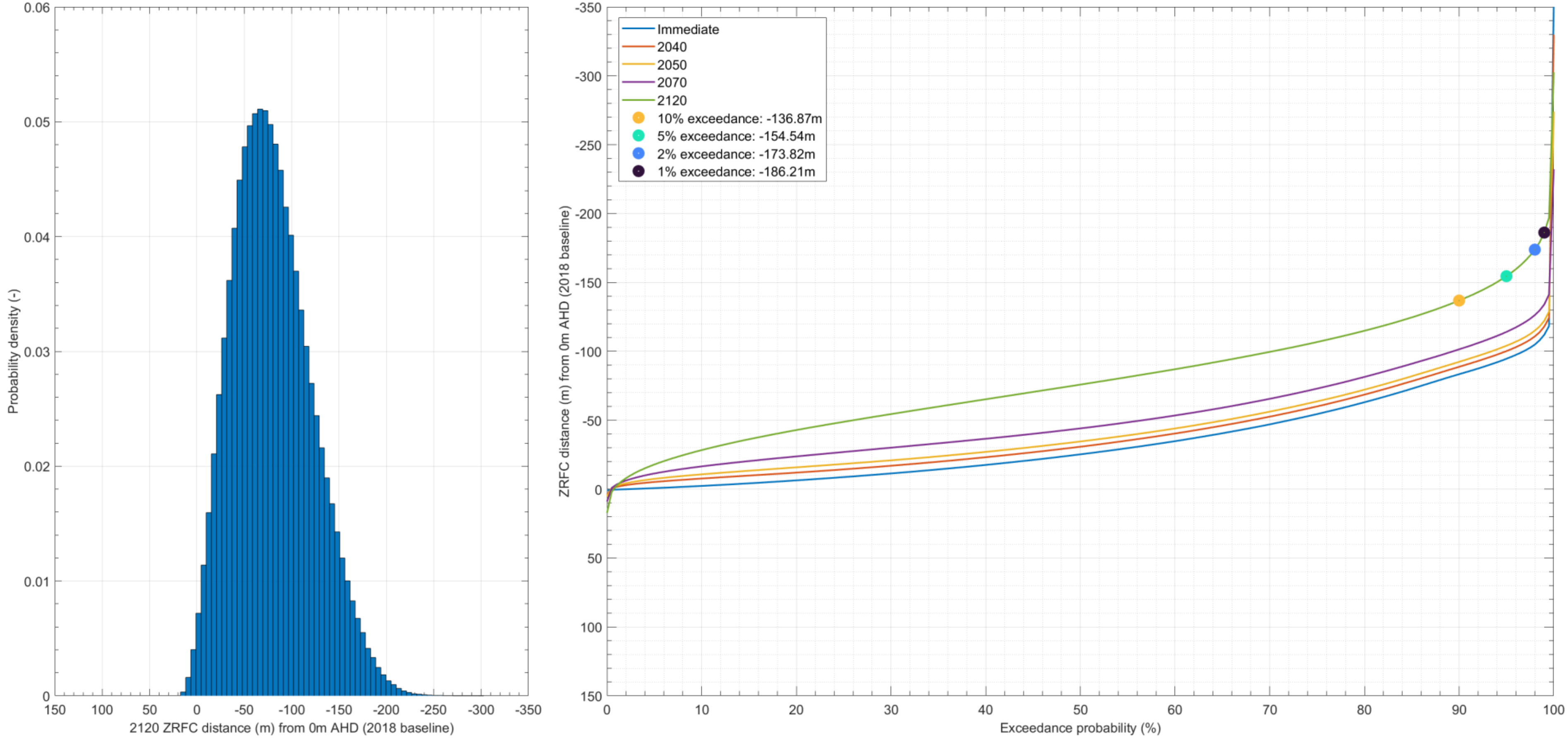

Figure 131: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Wooyung Beach (profile 94).

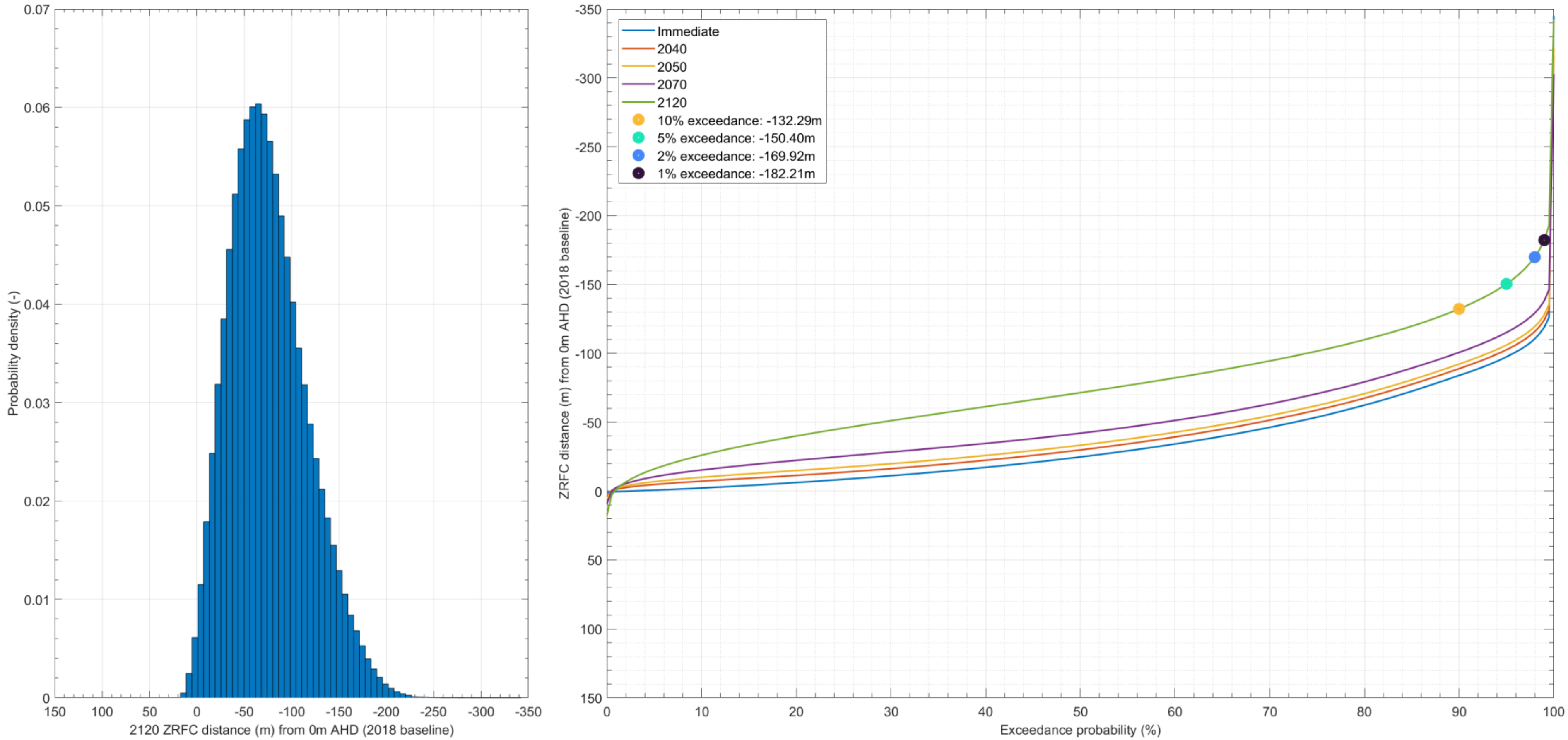

Figure 132: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Mooball Beach (profile 178).

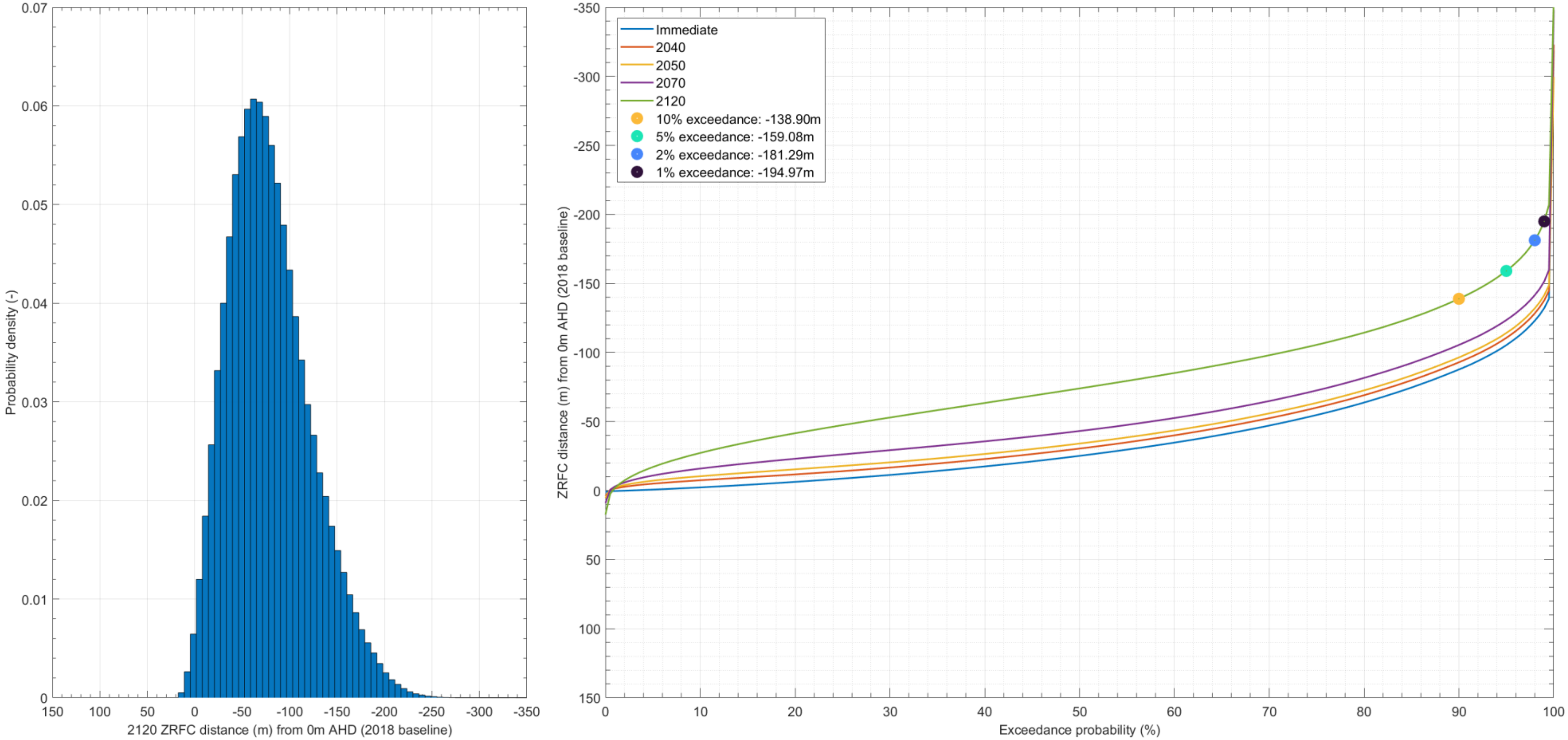

Figure 133: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Pottsville Beach (south) (profile 226).

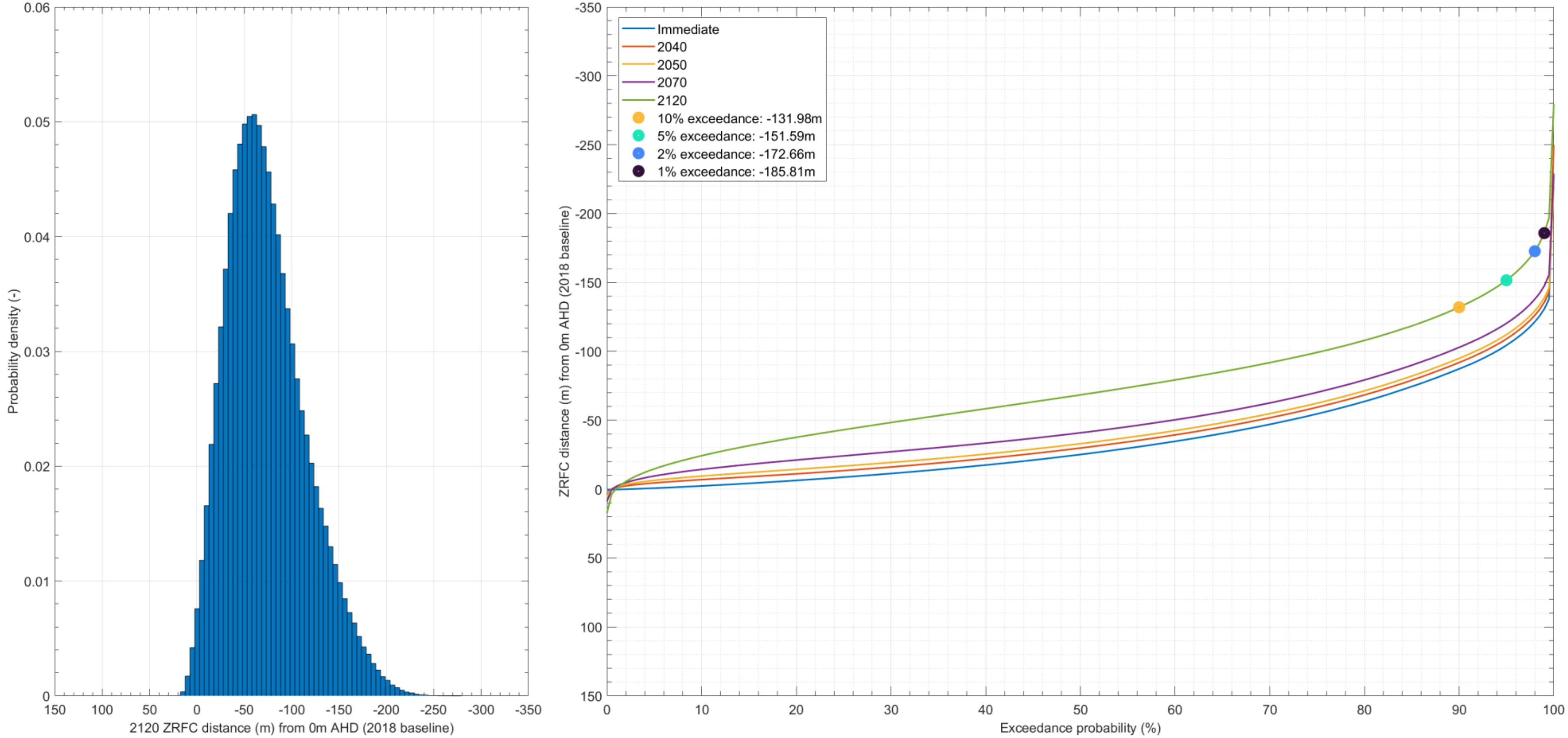

Figure 134: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Pottsville Beach (north) (profile 257).

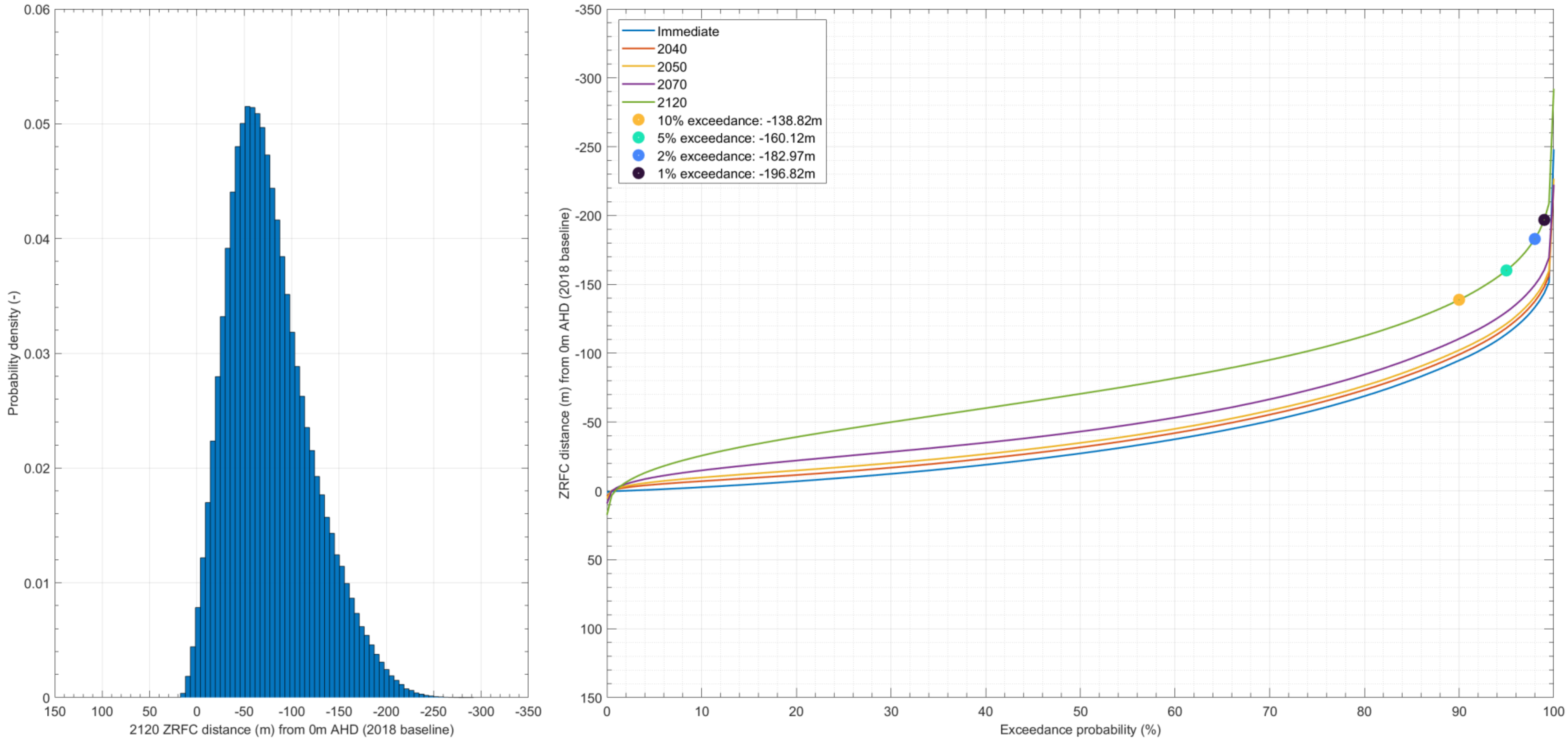

Figure 135: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Cudgera Beach (profile 287).

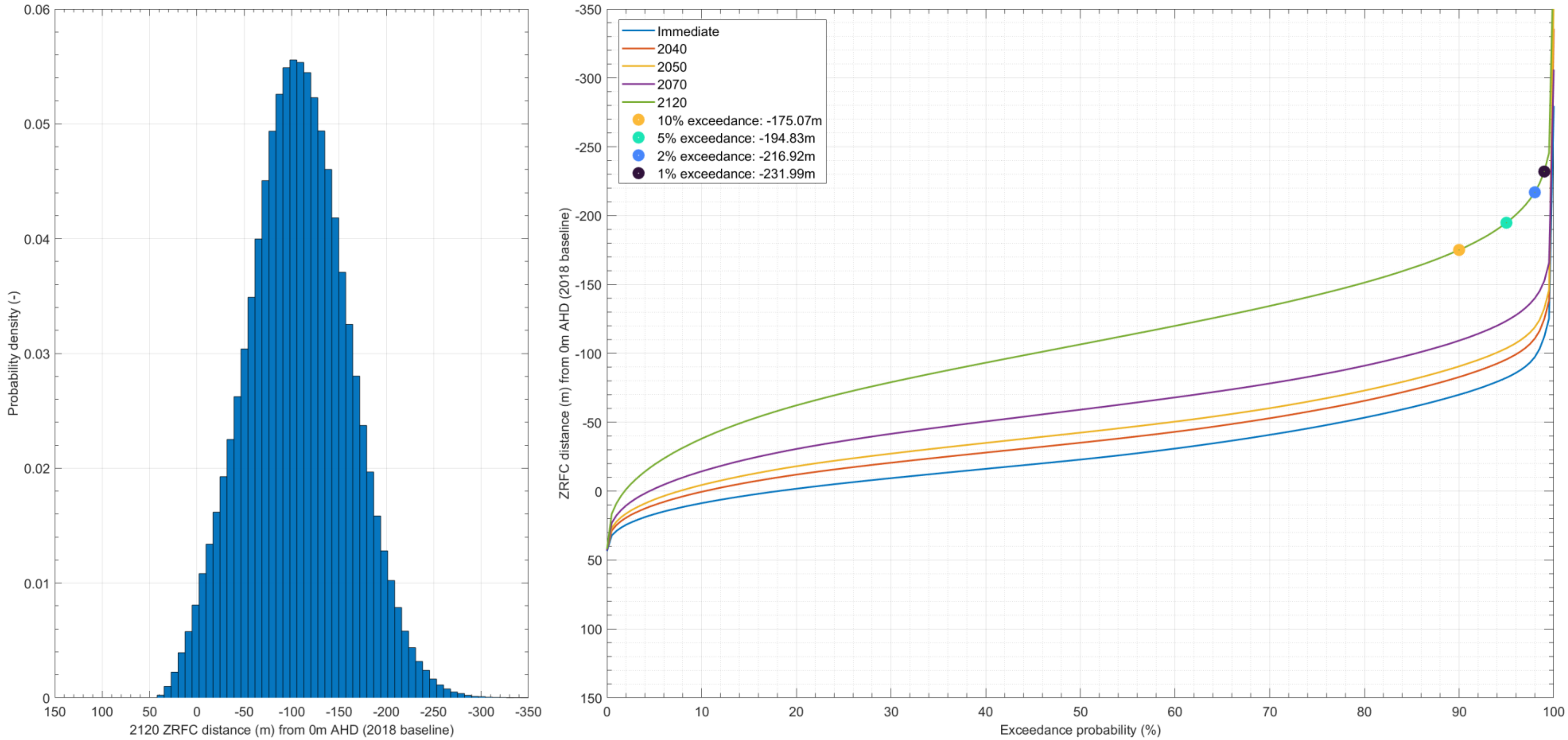

Figure 136: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Hastings Point (profile 336).

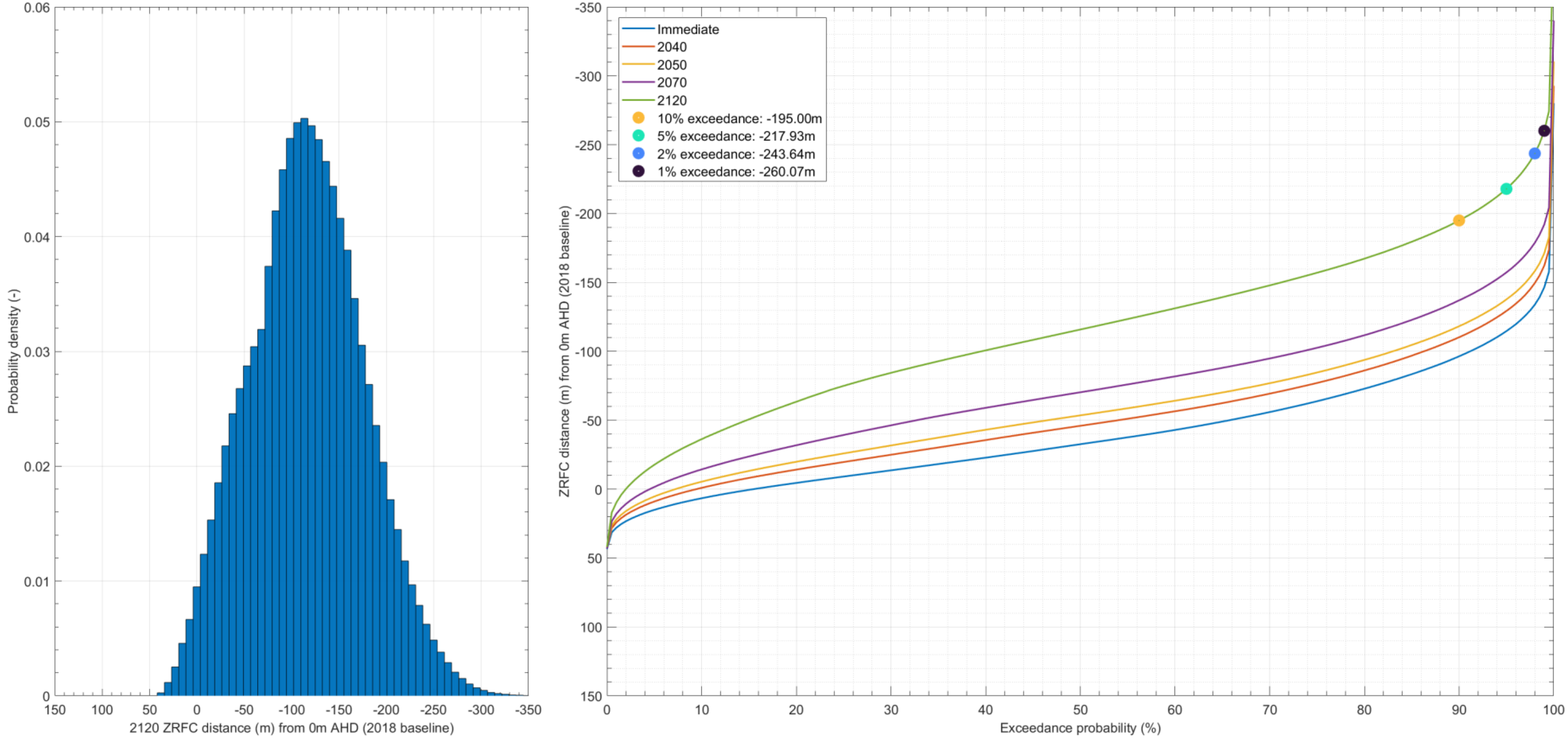

Figure 137: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Maggies Beach (profile 373).

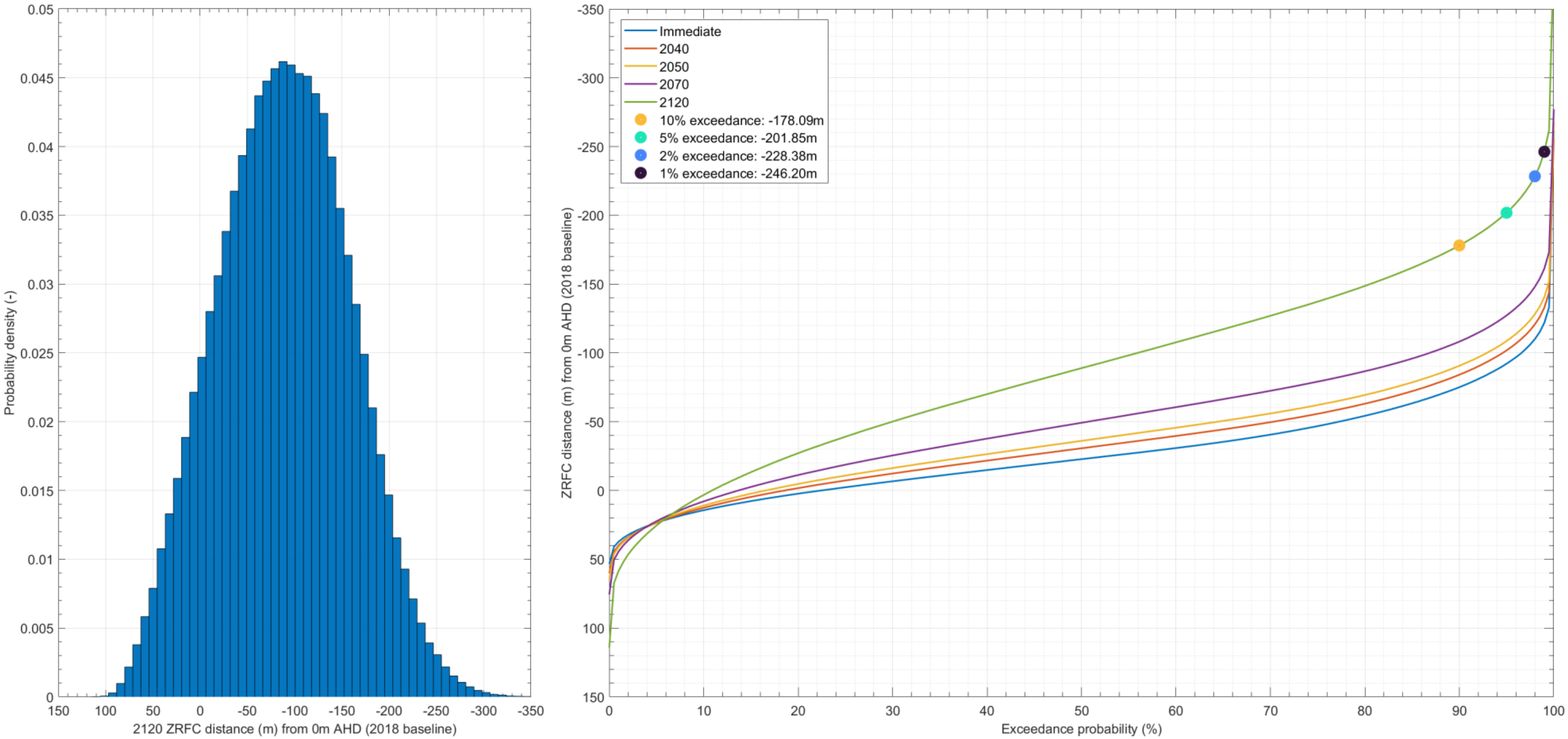

Figure 138: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Cabarita Beach (profile 450).

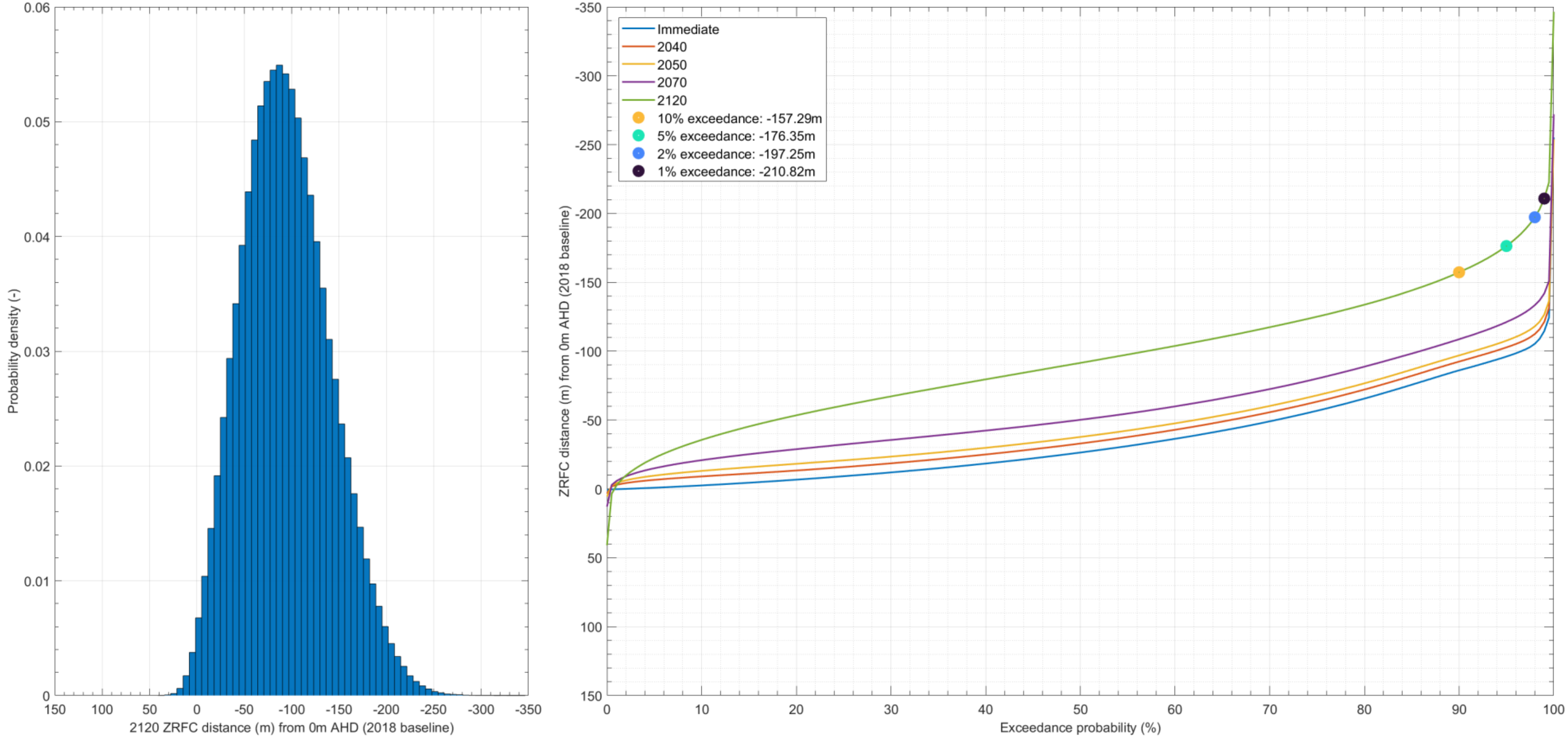

Figure 139: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Bogangar Beach (profile 482).

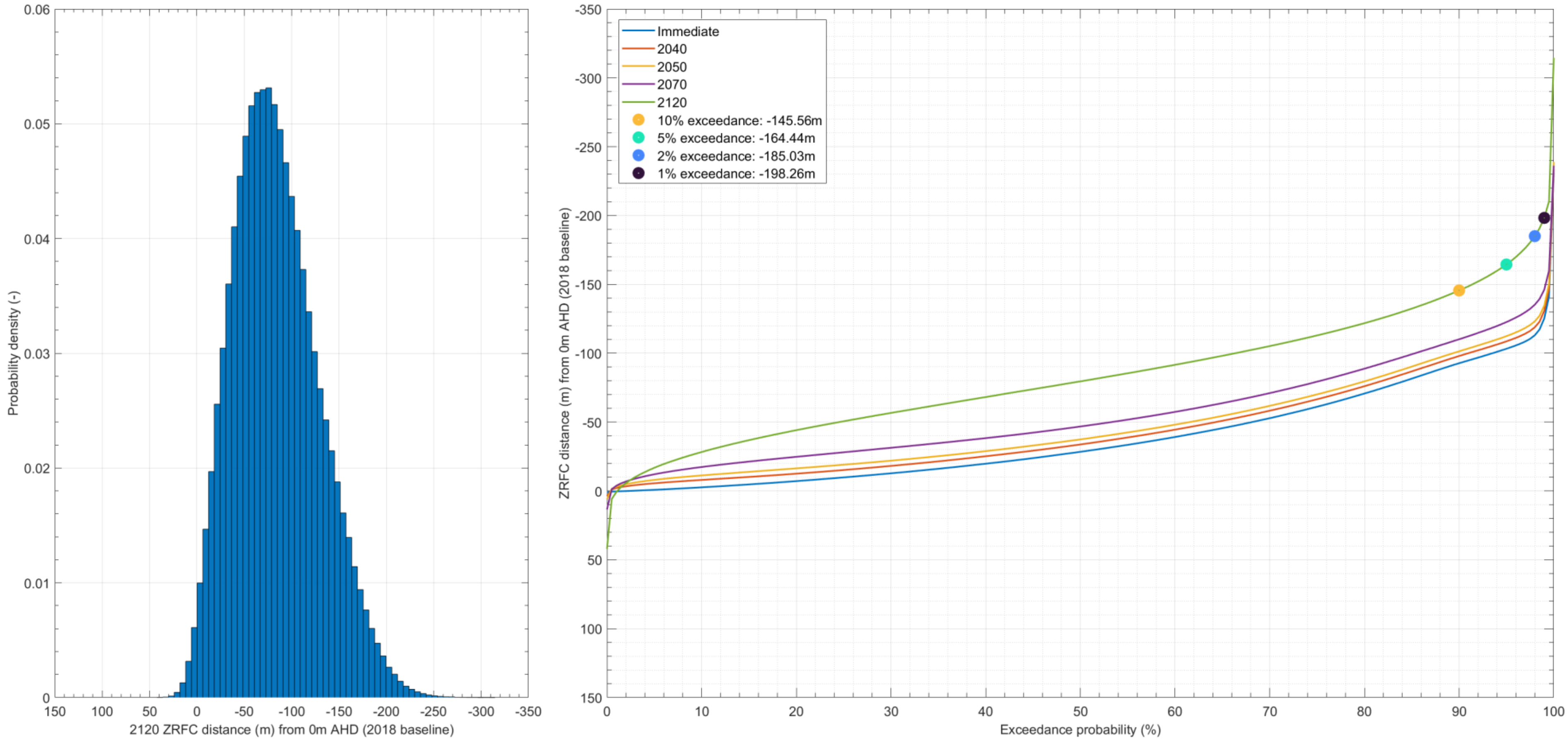

Figure 140: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Casuarina Beach (profile 515).

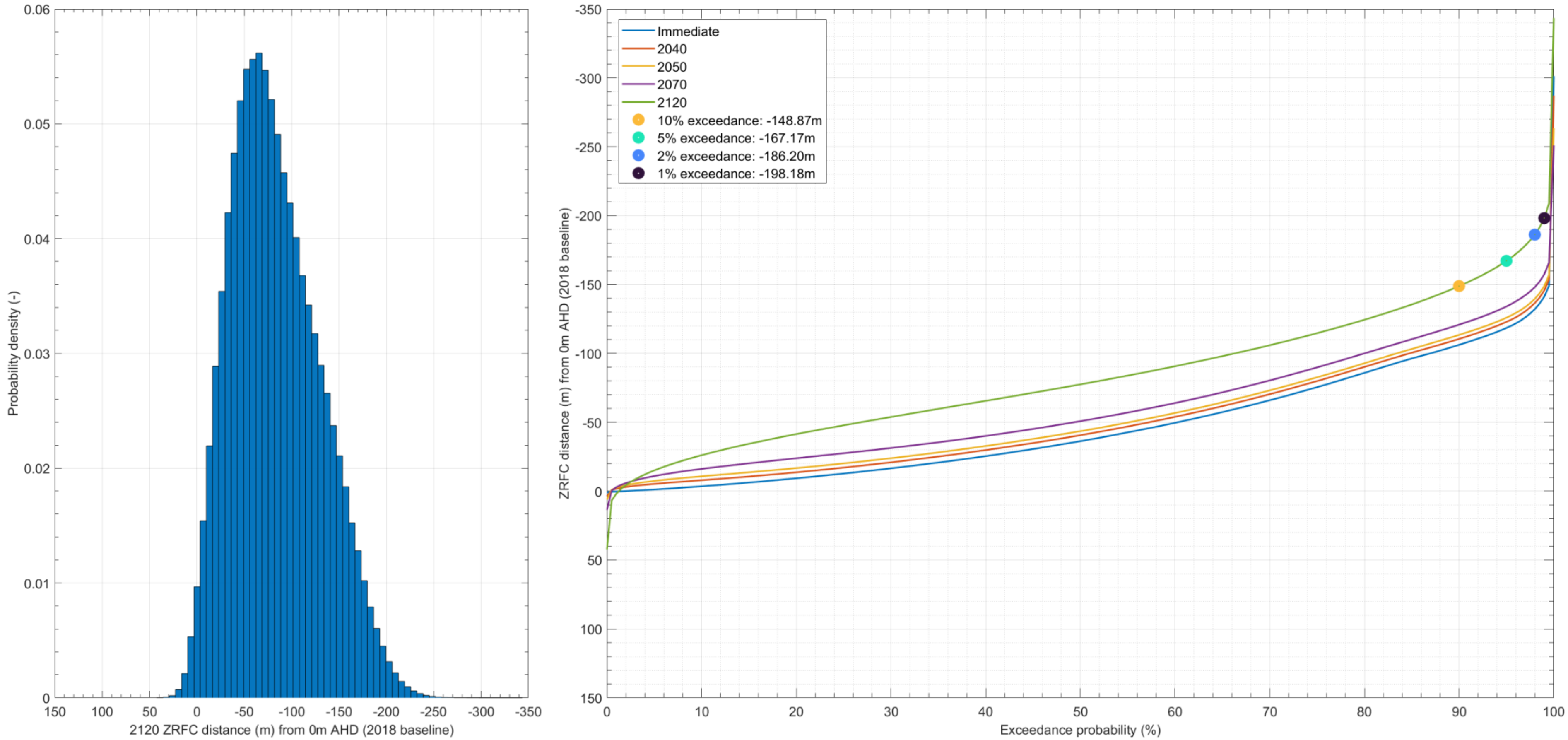

Figure 141: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for South Kingscliff Beach (profile 600).

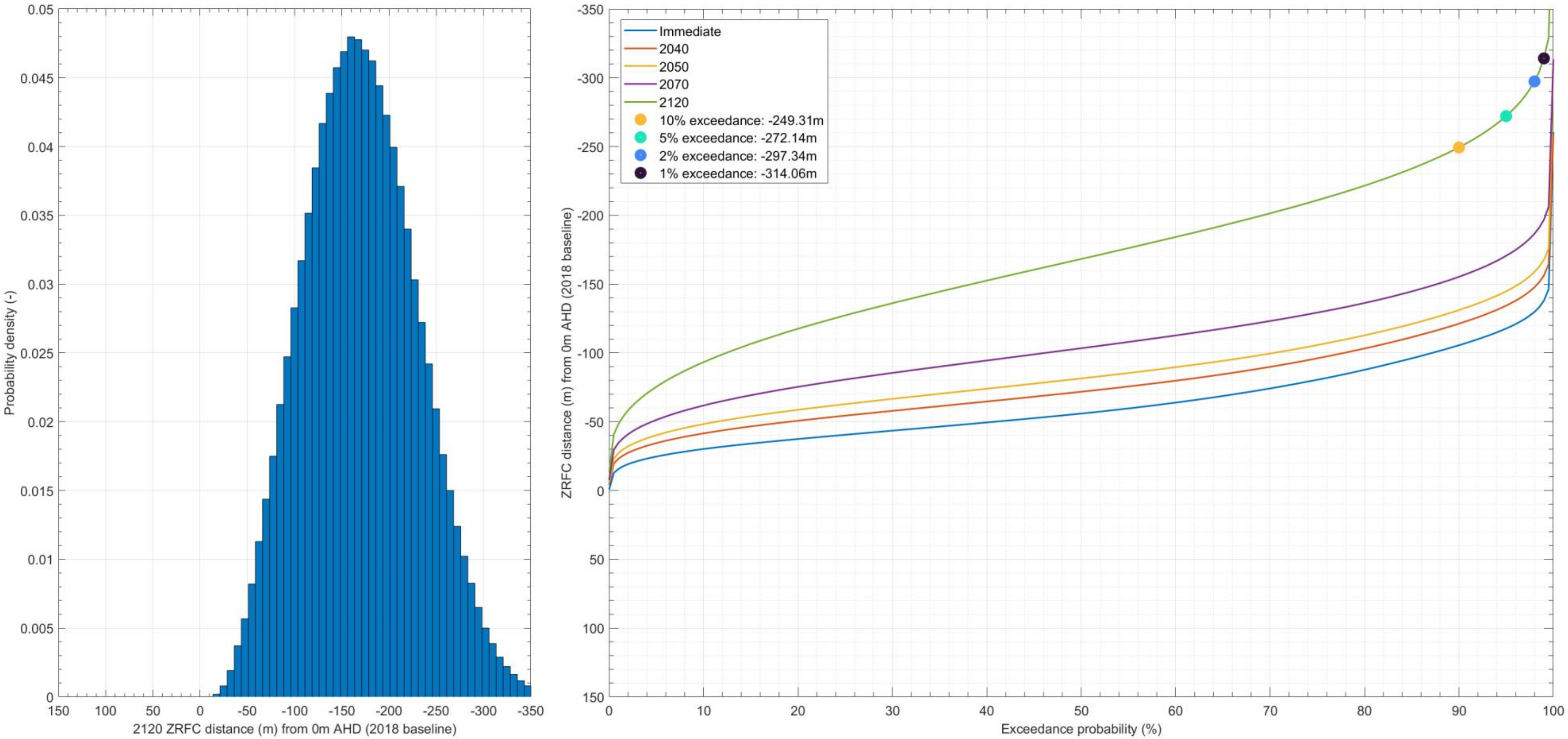

Figure 142: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Kingscliff Beach (profile 669).

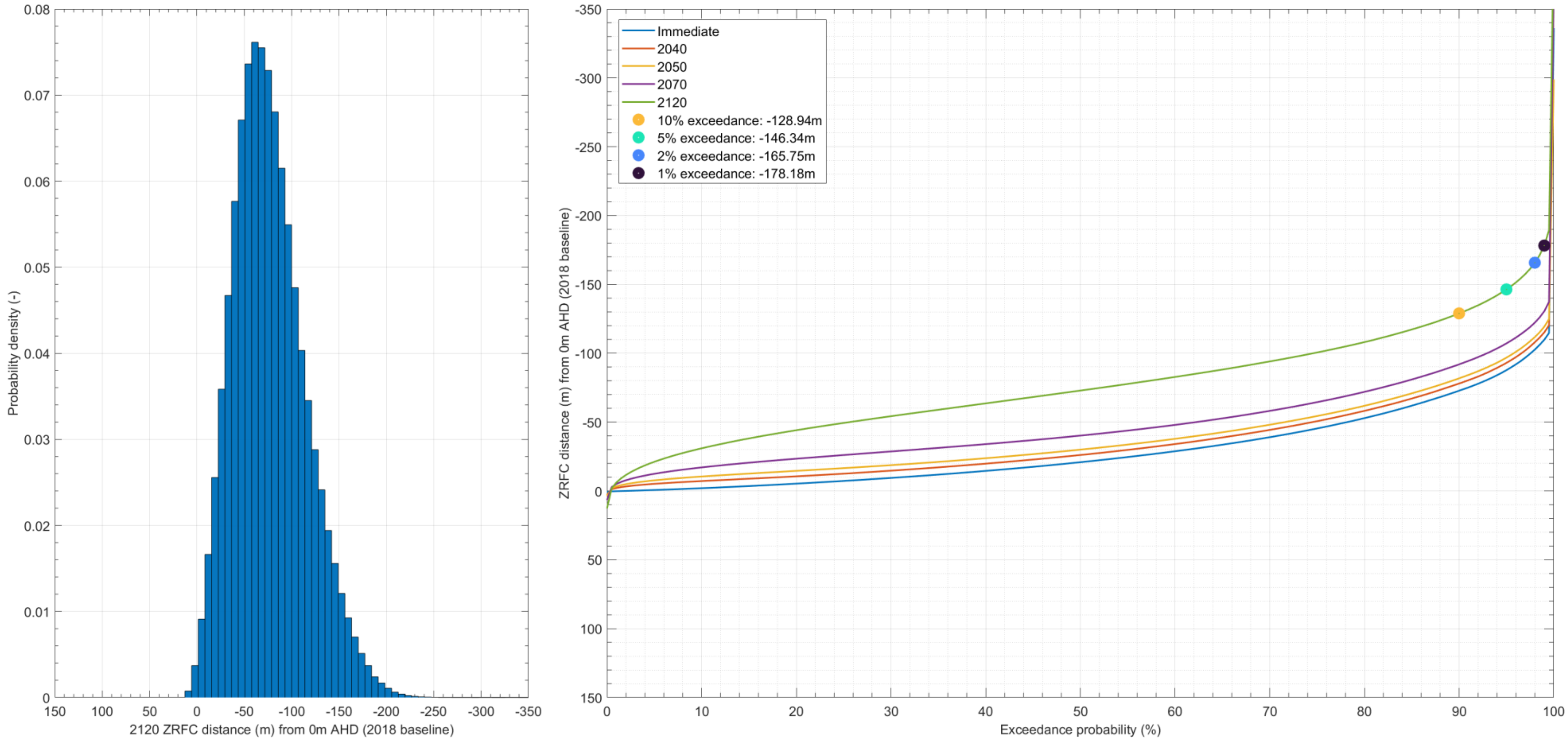

Figure 143: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Dreamtime Beach (profile 906).

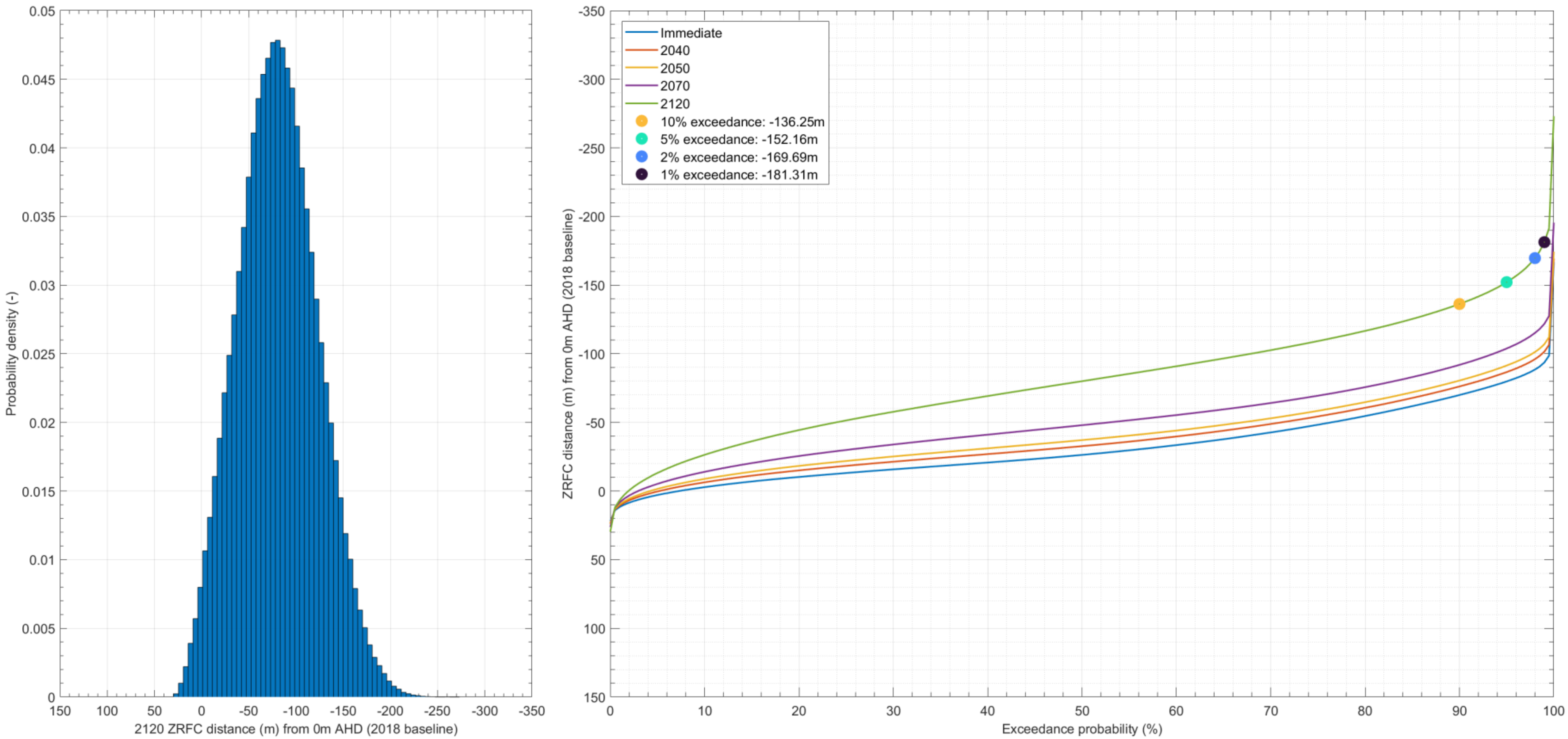

Figure 144: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Fingal Head Beach (profile 988).

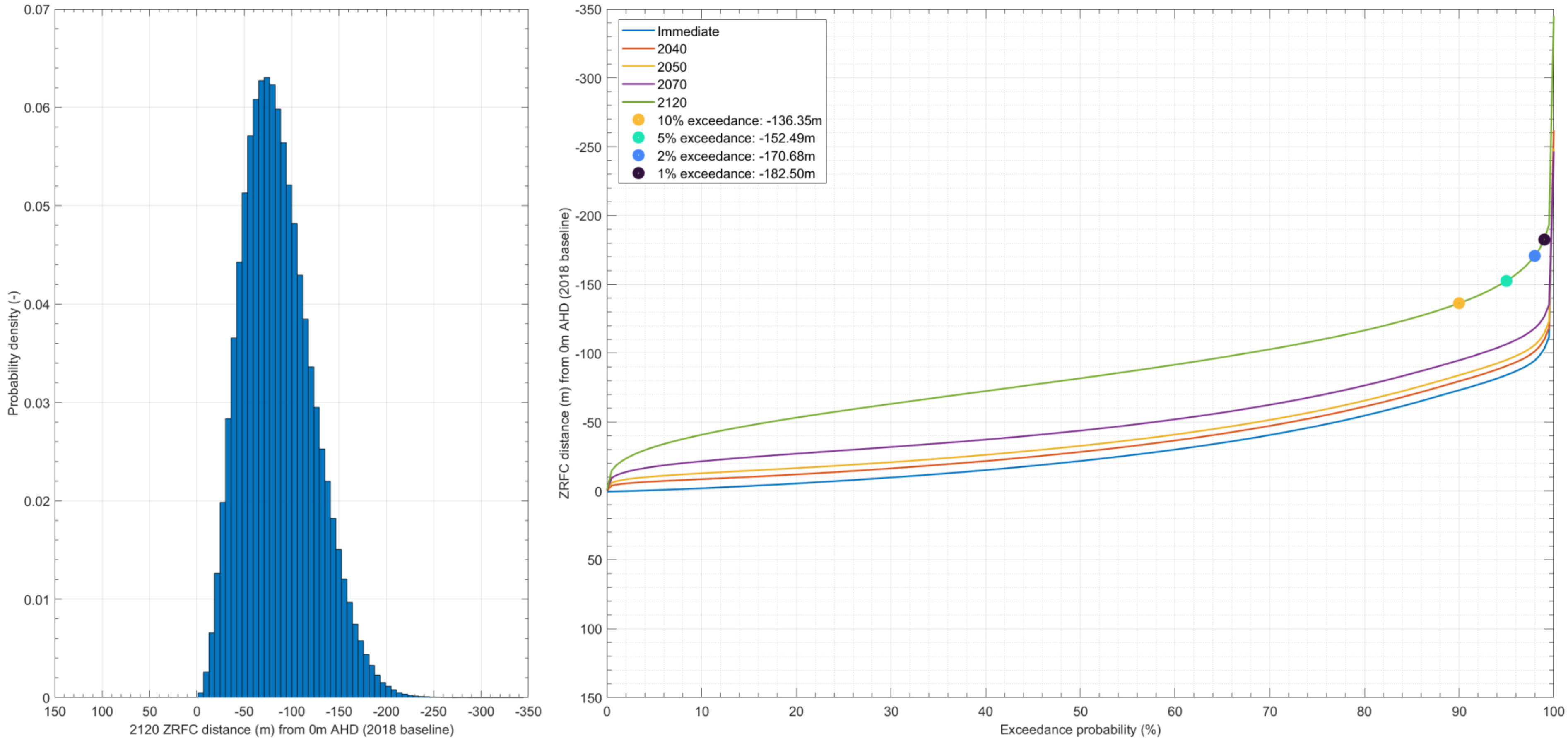

Figure 145: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Letitia Beach (profile 1050).

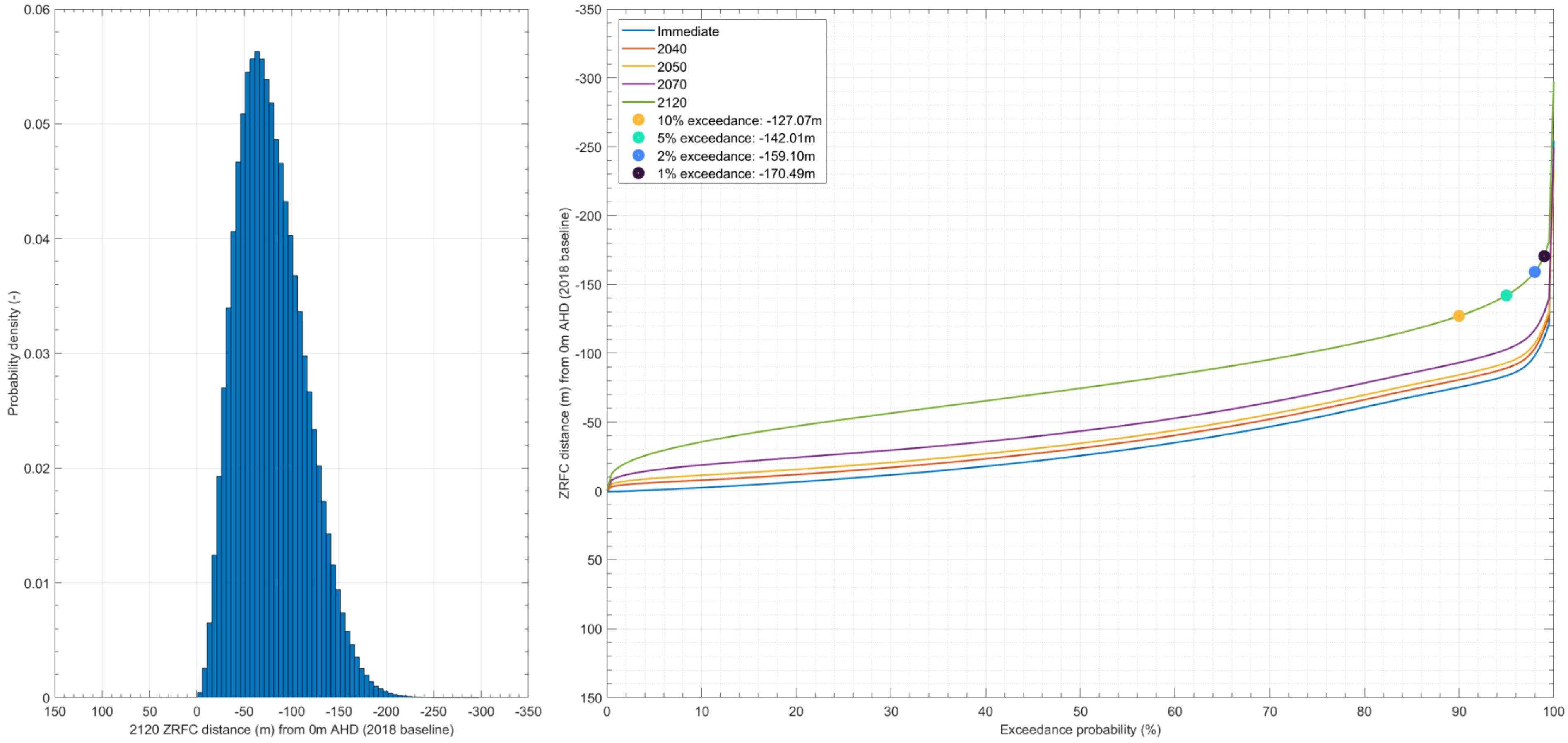

Figure 146: ZRFC (left) output distribution for 2120 and (right) probability exceedance curves for Duranbah Beach (profile 1103).

Appendix C: Tidal inundation assessment

Appendix D: Coastal asset risk assessment