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Byron Shire Council

Byron Shire Coastal Hazard Assessment Study

Byron Shire CMPs Stage 2

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Document Summary

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Accessibility

Byron Shire Council is committed to ensuring equal access to the information we produce.

This document is not completely accessible as it is a detailed scientific report containing complex information, which can be difficult to provide in accessible format. Note that the Executive Summary conforms to accessibility guidelines.

This Coastal Hazard Assessment is a key component of a larger program and final outcomes of the overall program will be produced in fully accessible format.

If you have trouble accessing any information provided in this document, or for more information or alternatives (read alternate text of figures, etc.), please speak with Council's Coast and Estuary staff on (02) 6626 7000.

Acknowledgement of Country

In preparation of this document, Council acknowledges the Bundjalung of Byron Bay – Arakwal people are the Traditional Custodians of the land in Byron Shire, and form part of the wider Aboriginal nation known as the Bundjalung.

Byron Shire Council and the Traditional Custodians acknowledge the Tweed Byron Local Aboriginal Land Council and the Jali Local Aboriginal Land Council under the *Aboriginal Land* Rights Act 1983.

Council also acknowledges all Aboriginal and Torres Strait Islander people who now reside within the Shire and their continuing connection to country and culture.

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Executive Summary

The Byron Shire's coastline extends from the local government area's southern boundary on Seven Mile Beach to its northern boundary at South Golden Beach. The Shire's coastline is a highly dynamic coastal environment and has experienced numerous coastal erosion events and a variety of coastal management responses.

Coastal management strategies are often expensive and robust scientific knowledge is essential for effective coastal planning. To fully appreciate the dynamics along the Byron Shire coast a sand movement and coastal hazard assessment within two sediment compartments has been completed in accordance with the NSW Coastal Management Manual. The sand movement component was used to inform a Shire-wide coastal hazard assessment. The study supports the preparation of Coastal Management Programs (CMPs) by Byron 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.

This report provides a summary of the outcomes of a comprehensive study of the regional and local coastal processes operating on the Byron Shire coastline. The report covers a 35km long stretch of coastline including 25km of sandy beaches, two major headlands including mainland Australia's most easterly point, three coastal lagoons and the Brunswick River estuary. It is a coastline that grades from highly developed within Byron Bay township to natural along other sections. It is a coastline that is impacted by waves, tides, river flows, wind and human modification, all of which vary alongshore. Combined, these present an extremely complex and dynamic natural system that within and through which, there is considerable sand movement.

The study adopts a data-driven approach. At its centre is an analysis of the Byron coastal sand budget, which maps historical sand volume changes in 64 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 Byron 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 Byron Shire is from south to north and ranges from 450,000m^3/year along its southern coastline to 510,000m^3/year along its northern coastline (±20%). 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.
- A net gain in sand volume was observed at Tallow Beach which led to shoreline accretion along this stretch of coast. This is likely due to an extensive lower shoreface sand body that is reasoned to promote onshore supply of sand to the Broken Head to Cape Byron beach compartment.
- Headland bypassing around Cape Byron results in a highly variable sand supply to the southern embayment with the annual range estimated to be from around 150,000 to over 900,000m^3/year. When coupled with the wave propagation characteristics of the embayment, the variable sand supply leads to a highly variable shoreline in the southern embayment.
- Sand movement pathways within the embayment follow two pathways: a littoral pathway (4m water depth) and a cross-embayment pathway (up to 15m water depth). Based on sand volume changes determined from repeat surveys the relative split between the two pathways, when

averaged across the embayment, has been calculated to be 70 : 30 (littoral : cross embayment). This is revised from previous assessments that assumed a 50 : 50 split between the pathways.

- The Shire's geomorphic structure, including bedrock and coffee rock reefs and outcrops influence wave propagation, sand movements, shoreline dynamics and surfzone morphology. Further, the embayment's extensive reefs reduce the volume of sand that can be stored in the southern embayment.
- Existing coastal structures, including the Jonson Street Protection Works and Belongil seawalls interact with the embayment's natural sand movements, with the level of interaction (over the medium to long-term) largely controlled by the amount of sand in the embayment, which in turn is a function of headland bypassing and wave climate.
- Along the Shire's northern coastline, contemporary changes in sand volumes and shoreline position have been minimal with some sections of beach trending towards an accretionary behaviour.

In line with the *Coastal Management Act 2016* and NSW Coastal Management Manual, a coastal hazard assessment was undertaken 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 parametrised sand budget to predict the potential range of present and future coastal erosion hazards.
- A high-level geotechnical assessment of the coastal cliffs at Broken Head, Cape Byron, Wategos and The Pass.
- A coastal inundation hazard assessment for the Byron Shire open coast, including detailed assessments at Belongil Beach, New Brighton Beach and South Golden Beach.
- Estuary specific hazard assessment at Ti Tree Lake, Tallow Creek, Belongil Creek and Brunswick River. The type of hazards assessed vary for each estuary and include:
    - Coastal lake or watercourse 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 built public and private assets are located within the immediate hazard extent at Clarkes, Main, Belongil and at New Brighton (lower likelihood) beaches. By 2120, the hazard extents would affect a considerably larger number of additional public and private assets and foreshore area at the northern end of Seven Mile Beach, Broken Head to Suffolk Park, Clarkes to Main Beach, Belongil Beach, Brunswick Beach, New Brighton and South Golden Beach. 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. A detailed asset exposure and risk assessment, including possible consequences, was not completed as part of this study..
- The review of coastal cliff and geotechnical hazards did not identify any significant areas that require further detailed assessment at this time (where observed). Although some areas of

localised wedge failure or slumping were observed, they were generally minor and not representative of the overall rock mass.

- The coastal inundation assessment reveals that for the immediate timeframe, beachfront properties and areas with beach access along Belongil Beach, in southern New Brighton Beach and South Golden Beach are affected. For the 2120 planning timeframe, considering sea level rise, impacts on most beachfront properties along both the southern and northern sections of New Brighton Beach and extensive overwash along the entire beach at South Golden Beach are projected, resulting in significant coastal inundation. At Belongil, the 2120 coastal inundation hazard extends across the full width of Belongil Spit to the creek. Estimated wave overtopping volumes exceed safe thresholds for most of the abovementioned locations at varying planning timeframes, posing a potential safety hazard for individuals and property in immediate overwash areas. Other sites potentially exposed to coastal inundation but not assessed in detail as part of this study include Wategos Beach and Main Beach (Jonson Street Protection Works - assessed in Bluecoast, 2022b).
- The estuary entrances to Ti Tree Lake and Tallow Creek are relatively stable. The entrance to Belongil Creek has been observed to vary over an approximately 600m alongshore area. The migrating entrance channel and risk of breakthrough of Belongil Spit exposes surrounding land and properties to a variety of coastal and estuarine hazards. In the absence of effective and long-term coastal management of the beach and dune, a coastal storm event with a 1% annual exceedance probability could result in a breakthrough of Belongil Spit that isolated private property along the narrow sand spit. The key factors affecting the entrance stability of Belongil Creek have been identified as long-term shoreline recession, variable sand supply linked to headland bypassing and downdrift effects by existing seawalls during low beach levels. Sea level rise, including estuary sequestration of sand from the littoral zone, is likely to exacerbate the identified hazards.
- By 2040, high tides can expose public infrastructure and properties surrounding Belongil Creek to inundation. With sea level rise, land and development surrounding Tallow Creek and Brunswick River may also be exposed to tidal inundation by 2120.
- Localised bank erosion and inundation of foreshores is observed along Belongil Creek and to a greater extent within the Brunswick River estuary. Sea level rise will likely affect the frequency and duration of inundation of foreshores, further impacting bank stability and vegetation health where this is already occurring as well as affect additional areas.

The approaches adopted herein are reasonable and valid for assessing the Byron 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 will be used to undertake a detailed risk assessment of coastal hazards affecting the Byron 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 Byron Shire coastline. The study adopts a data-driven approach. At its centre is an analysis of the Byron coastal sand budget. The report presents the methodology and outcomes for the definition of coastal hazards affecting the Byron Shire coastline. The study supports the preparation of Coastal Management Programs (CMPs) by Byron Shire Council.

The purpose of the report is to provide:

- an improved understanding of coastal sand movements for the entire Byron Shire coastline
- a detailed review and update of Byron Shire 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 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 (2020-0076) and accords with Bluecoast’s proposal document (dated 21 May 2021). In accordance with the *Coastal Management Act 2016* (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

Byron Shire Council have commenced preparation of CMPs for the Shire’s coastline. The NSW Coastal Management Framework specifies 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. Council has completed and adopted two Stage 1 CMP scoping studies:

- Scoping Study for Cape Byron to South Golden Beach (BMT WBM, 2020)
- Scoping Study for the Southern Shire Byron Shire Coastline and Belongil Estuary (Rhelm, 2021).

These cover both the open coast and the Belongil and Tallow Creek estuaries. Council has yet to commence the CMP process for the Brunswick River estuary.

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.

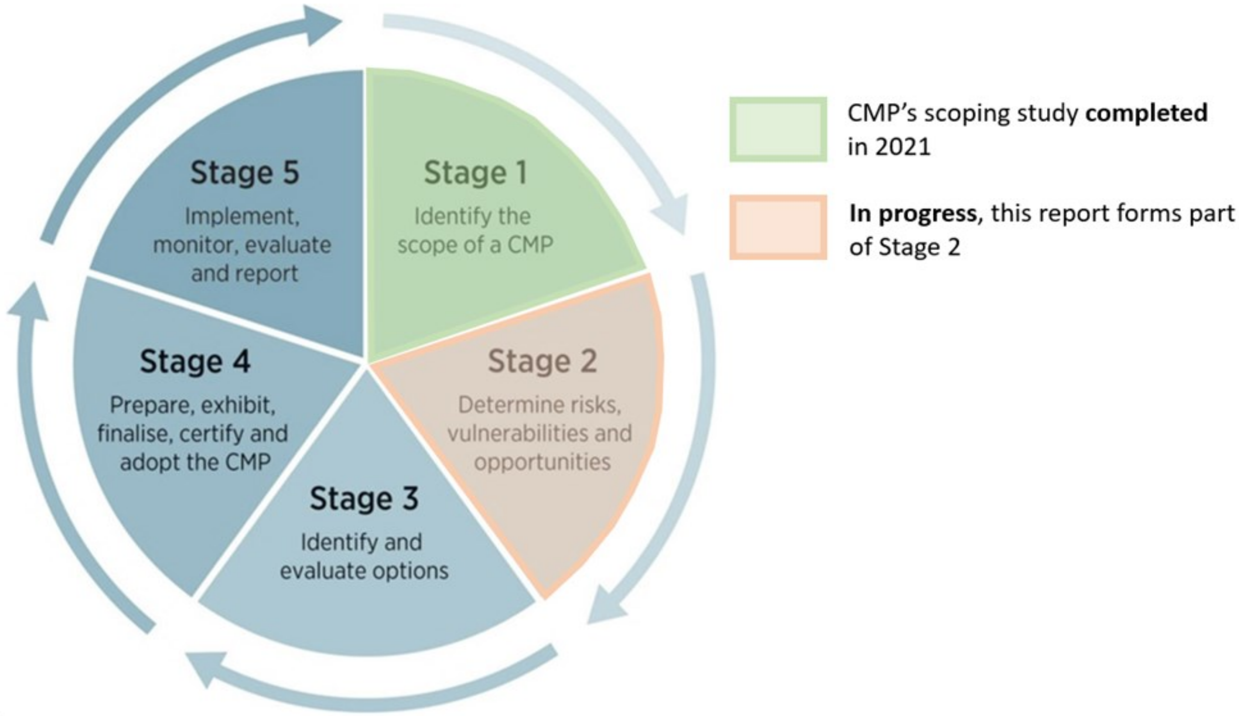

Figure 1: Stages in preparing and implementing a CMP (modified after the NSW Government).

Byron Shire Council anticipates preparing individual CMPs for the following Byron Shire coastal zones:

1. **CMP for Tallow Estuary** – includes estuary and catchment issues and actions including entrance opening/management activities for flood mitigation.
2. **CMP for Belongil Estuary** – includes estuary and catchment issues and actions including entrance opening/management activities for flood mitigation.
3. **CMP for the Byron Shire Open Coast** – includes the entire Byron Shire open coast and may be split into three management segments such as Cape Byron to South of the LGA border; Cape Byron to the Brunswick River; Brunswick River to the North of the LGA border. The spatial extents are not yet confirmed and subject to refinement.
4. **CMP for the Brunswick River Estuary** – not yet commenced and to be completed later.

1.3 Study area

The study area (see Figure 2) includes the open beaches, foreshore, estuaries and coastal waters from the Shire's southern boundary on Seven Mile Beach to the Shire's northern boundary at South Golden Beach. The study area extends inland over the foreshore to the extent of the predicted extent of coastal hazards. The study area covers a significant proportion of two coastal sediment compartments, defined in the CM Act as:

- Cape Byron to Ballina: with extents from the Richmond River to Cape Byron, incorporating Byron Shire and Ballina Shire.
- Tweed: with extents from Cape Byron to Point Danger, incorporating Byron Shire and Tweed Shire.

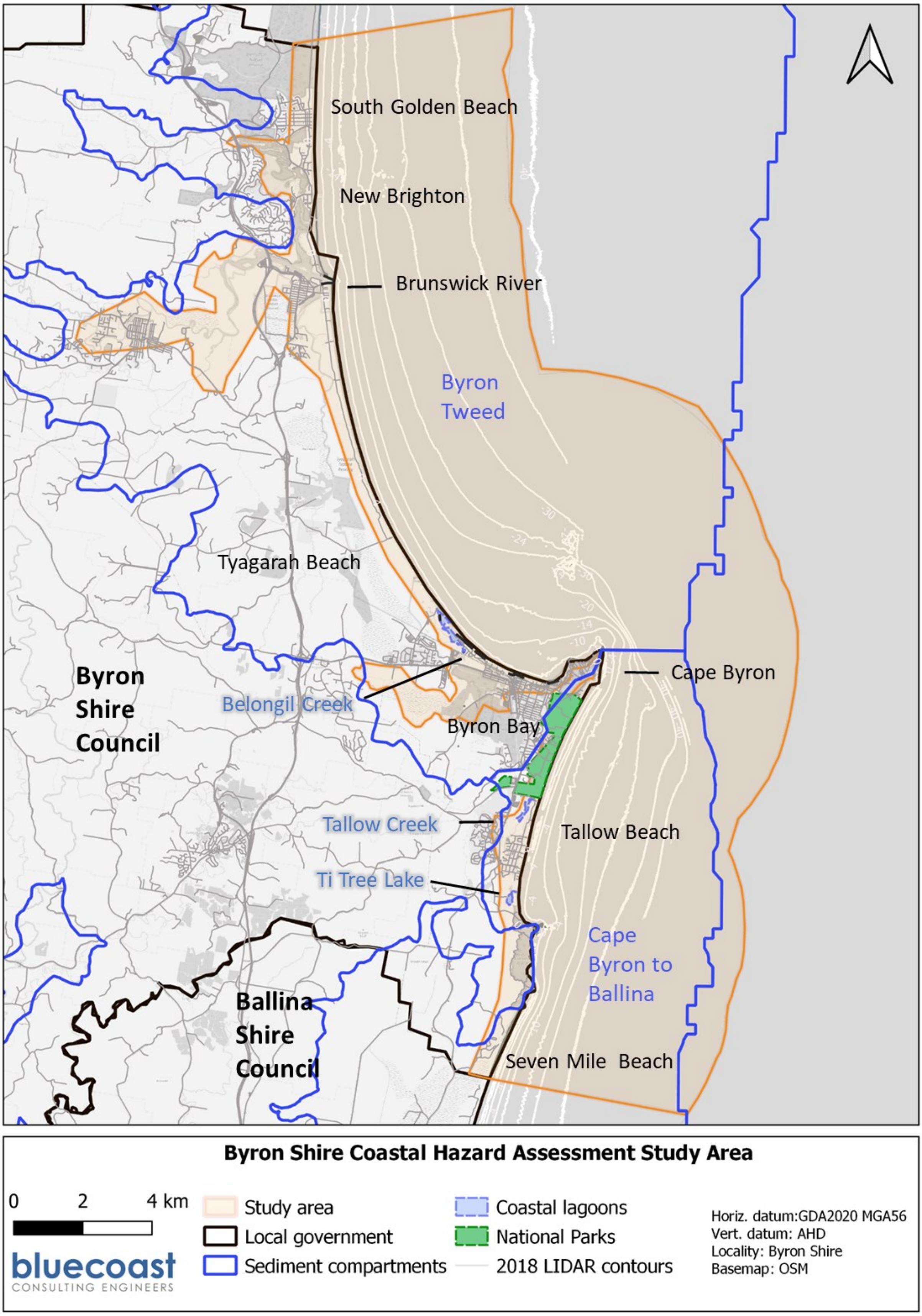

Figure 2: Study area of the Byron Shire Coastal Hazard Assessment.

The study area includes:

- The Shire's open coast consisting of:
  - around 25 km of sandy beaches including Seven Mile Beach, Brays Beach, Kings Beach, Broken Head Beach, Tallow Beach, Little Wategos Beach, Wategos Beach, The Pass, Clarkes Beach, Main Beach, Belongil Beach, Tyagarah Beach, New Brighton Beach, South Golden Beach and Wooyung Beach
  - around 6 km of headlands and rocky coastlines including Jews Point, Broken Head and Cape Byron with Cape Byron being the most prominent of a series of major controlling headlands in the study area.
- Three coastal lagoons and creeks being Ti-Tree Lake (also known as Taylors Lake), Tallow Creek and Belongil Creek as well as the Brunswick River estuary.

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 hazards.
- Section 3: Provides a description of regional coastal geomorphology, processes and hazards.
- Section 4: Describes the Shire's sand budget and presents a quantified conceptual sand movement model.
- Section 5: Describes the probabilistic assessment of beach erosion and shoreline recession.
- Section 6: Identifies potential areas where cliff instability could pose a coastal hazard.
- Section 7: Provides a coastal inundation analysis including wave runup and overtopping.
- Section 8: Provides a hazard assessment specific to the study area's estuaries.
- Maps: Provides a compendium of the mapped coastal hazards.

1.5 Statement of assumptions and uncertainties

The approaches adopted herein are reasonable and valid for assessing the Byron 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. Specific assumptions, limitation 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 Byron Shire (where possible or in high-risk areas), nearshore coastal processes (wave, currents etc) and sand movements.

2. Background information

2.1 Introduction

Written records of severe coastal erosion periodically occurring along the northern NSW coast, including Byron Shire, extend back over a century. Since a period of extensive storm erosion in the late 1960's / early 1970's, there has been greater awareness of coastal erosion and other coastal hazards in Byron Shire. The study area has been the subject of numerous studies to assess coastal and estuary processes. Available literature was reviewed to inform this study and is referred to throughout this document wherever relevant. A non-exhaustive list of key regional coastal hazard assessments is presented below in chronological order:

- Byron Bay- Hastings Point Erosion Study (PWD, 1978): The Department of Public Works carried out a beach erosion study from Byron Bay to Hastings point. The prime objective was to gain an understanding of the coastal processes governing erosion in the region. The findings from this report informed the coastal erosion hazard extents currently adopted in the Byron Development Control Plan 2010 (see Chapter 1: Part J – Coastal Erosion Lands of the 2010 DCP).
- Byron Shire Coastline Hazard Definition Study (WBM Oceanics, 2000a): This report identifies and defines the coastline hazards (coastal erosion, coastal inundation, sand drift etc) impacting on the Byron Shire over the immediate, 50-year, and 100-year planning horizons. The study was completed to inform the preparation of a Coastline Management Plan for the Byron Shire's coastline. The assessment was later extended to include the then Byron Bay Beach Resort (now Elements Resort) at Belongil Creek (WBM Oceanics, 2000b).
- Byron Shire Coastline Hazards Assessment Update (BMT WBM, 2013): The report provides a revision of coastal hazard extents and updates the Byron Coastline Hazard Definition Study (WBM Oceanics, 2000a). The study was endorsed by Council on 10 October 2013 (Res 13-542) and informed the preparation of the Draft Coastal Zone Management Plan (CZMP) for the Byron Bay Embayment.

The BMT WBM (2013) study is the most recent investigation into coastal hazards undertaken for the Byron Shire LGA and comprises a comprehensive review of coastal processes. With around 10 years of new data available since completion, new data sources and revised best-practice methods, an update to this coastal hazard assessment was recommended in the Stage 1 CMP Scoping Studies forward plans for completion during Stage 2 CMP preparation. Through these analyses of up-to-date information some assumptions and remaining uncertainty in the previous coastal hazard assessments are addressed in the present study. For the coastal erosion and recession hazard assessment this includes adoption of a probabilistic approach in consideration of remaining uncertainty and natural variability in coastal processes as recommended in the CM Manual.

2.2 Historical timeline of key coastal events and development

A history of key events related to coastal hazards that have transpired in the Byron Shire in the last 150 years is provided in this section. A summary of the key anthropogenic influences on the coastal processes and storm events that caused extensive erosion within the study area is presented in Table 1. A graphical timeline with the key events is shown in Figure 10.

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

Year	Event description
1870s to 1890	Discovery of gold in Byron Bay's beach sand leading to the commencement of sand mining.
1888	The Public Works Department (PWD) built a 402-metre-long timber jetty extending seaward from Jonson Street. The site later became the Jonson Street Protection Works (JSPW) in the 1960s (see below) and these later works now conceal some of the old timber piles.
1890-1910	Richmond River training walls were constructed approximately 16km south of the Byron Shire LGA boundary.
1925	Wing abutments are constructed on the old jetty including the placement of '4-inch sheathing' or rock protection (using 10cm diameter rocks).
1928	The jetty at Jonson Street became unserviceable and it was replaced by a new 610-metre-long jetty at Belongil Beach.
1930's	Re-commencement of sand mining to extract zircon and rutile undertaken by Zirkon Rutile Ltd (ZRL). Sand mining started in January at Seven Mile Beach in 1935.  **Figure 3: Sand mining for mineral extraction at Main Beach (source: imagesofbyronbay.com.au).**
1933-1936	Period of severe and extensive beach erosion following a succession of tropical cyclones.
1947	Sand mining commenced on Tallow Beach at Broken Head progressively moving north to Cosy Corner.

Year	Event description
1951	ZRL began rehabilitating, reforming and replanting the mined areas; but not always with native species.
1954	Cyclone, extensive and severe erosion, damage to new jetty, all 26 fishing boats lost. The sea broke through the dune and flooded parts of Byron Bay town.
1960's	The north Richmond River training wall was extended.
1960	Sand mining moved inland and started at Main Beach and Belongil Beach.
1959-62	Brunswick River training walls were constructed.
1963 -1964	Around 1963 and in response to heavy seas and erosion, temporary coastal protection works (rock placements) were undertaken at the end of Jonson Street. In 1964, in response to severe erosion caused by tropical cyclone Audrey the first engineering drawings of what later become known as the JSPW were produced. The construction of the design saw the main section of the JSPW rock revetment built on its current alignment.  **Figure 4: Clippings from The Northern Star newspaper article from 29 June 1963.**
1967-1974	Seven tropical cyclones impacted NSW. Large waves and beach erosion claimed houses, roads and public infrastructure. A series of three cyclones in 1974, the most severe being TC Pam in February, caused significant erosion to the dunal system downdrift of the JSPW at Belongil Beach destroying permanent and holiday residences and causing damage to roads, the JSPW and the surf club. Town of Sheltering Palms near Brunswick Heads was destroyed during TC Pam.
1970	Small groyne was constructed near Gaggin Street, New Brighton. This groyne is of unknown design and construction standard. It is largely covered with sand much of the time and has little or no effect on shoreline alignment today.
1970's	Mineral extraction (sand mining) became almost non-existent on Byron Bay's beaches.
1972	The jetty at Belongil was damaged in 1954 and finally removed.
1976 -1977	The JSPW were upgraded with the construction of three groynes and restoration of sections of the pre-existing rock revetment.

Year	Event description
	A series of ad-hoc rock seawalls were built between the former FJ Walkers Meatworks (Border and Kendell Street) and Manfred Street. These works were initially piecemeal in nature, protecting individual houses along Belongil Spit (PWD, 1978). They have been progressively infilled over the years with geotextile container (geobag) and rock seawalls (around the 1990s). The rock seawalls now extend to the end of the private properties along Belongil Spit at the northern end of Childe Street.
1984	Esplanade Road on Belongil Beach lost to the sea via erosion.
1990´s	Extension of the JSPW to include emergency protection works at Cavanbah Beach comprising of two rows of boulders laid at the toe of the embankment at First Sun Holiday Park (3m AHD crest level), believed to be installed in the late 1990's. Geobag coastal protection structure in front of the (western portion) of First Sun Holiday Park were constructed shortly thereafter. Further interim and private protection structures constructed between Border Street and north of Manfred Street, Belongil using geotextile and rock materials. Low-crested rock wall protection works along Marine Parade at Wategos were likely constructed around this time. Periodic beach scraping was carried out in New Brighton Beach and South Golden beach. Sand was scraped from the tidal zone to enlarge the dune.
1996	Extensive erosion within the Byron embayment and Belongil Beach due to East Coast Low.
1999	Extensive erosion updrift and downdrift from JSPW due to storms and a large swell event.
2001	Extensive erosion at Belongil Beach due to East Coast Low.
2002	An interim single-layer geotextile container revetment was constructed by Council at the Byron SLSC. The structure was built with slopes of 1V:2H and a crest level of 3m AHD. Also constructed by Council at this time were interim works (geotextile container revetments) at Border, Don and Manfred Street beach access ways, Belongil Beach. 

Year	Event description
	Figure 5: Photograph showing the construction of the interim geotextile revetment in front of the SLSC in 2002 (source: Byron Shire Council).
Mid 2000s	Emergency protection works consisting of a geobag coastal protection structure were constructed in front of the (western portion) of First Sun Holiday Park (exact date unknown).
2009	A large East Coast Low arrived at the coast in May 2009 with maximum significant wave heights of 7.4 metres and significant wave heights over 4 metres for four days causing extensive erosion. Plans commenced for repair and reconstruction of interim revetments at Belongil.
2010	A beach scraping trial conducted along about 1.3 kilometres of the beach at New Brighton. This reportedly moved about 12-16m^3/m of sand from the lower beach to the foredune area.  **Figure 6: Machinery at work during beach scraping (source: Byron Shire Council, 2013).**
2011	Interim geotextile container revetments were reconstructed at Don, Border and Manfred Street, Belongil.
2013	Tropical cyclone Oswald and successive storms caused extensive erosion.
2015	Replacement of Manfred Street geotextile container revetment with interim rock wall (crest level up to 4.5 m AHD). Construction of temporary protection works (approx. 200m length) using geotextile sand containers by Elements Resort at the western entrance to Belongil Creek.
2017	Beach scraping of about 15,000m^3 at New Brighton Beach.
2019	Severe erosion at Clarkes Beach in July 2019 caused damage to Reflections Holiday Park and exposure of coffee rock. Emergency protection works were constructed by Reflections immediately at the erosion scarp comprising of single-layer geotextile bags, 4 courses high with slopes of approximately 1V:1.5H and a crest level of 3m AHD.

Year	Event description
	 **Figure 7: Erosion at Clarkes Beach in July 2019 (source: Bluecoast).**
2020-2021	Widespread erosion occurred along Clarkes Beach and Main Beach linked to intermittent sand supply from around Cape Byron, coupled with a large migratory rip. Emergency protection works were constructed by Crown Lands immediately at the erosion scarp comprising of single-layer geotextile bags, 6 courses high with slopes of approximately 1V:1.5H and a crest level of 3m AHD.
2022	Ex-tropical cyclone Seth caused beach erosion in January particularly from Clarkes Beach to west of Main Beach (Cavanbah towards Belongil). Erosion of incipient foredune along central to northern Tallow Beach observed.  **Figure 8: Erosion west of JSPW exposing buried coastal protection structures and coffee rock (photos taken July 2022).**
November 2022	Sand scraping and dune rehabilitation was undertaken to reinstate beach access, restore ecological values and assist in the rebuilding of the upper beach sand buffer along Main Beach.

Year	Event description
	 **Figure 9: Aerial photograph showing beach scraping operation at Main Beach.**

HISTORY OF

BYRON SHIRE

Sand mining

1870: Discovery of gold

1890: Gold mining stopped

1930's: Re-commencement of sand mining (zircon and rutile)

1934: Zirkon Rutile Ltd. was formed in Byron bay

1947: Mining at Tallow Beach

1951:ZRL started rehabilitating mined areas

1960: Mining at Main Beach and Belongil Beach

1968: Mining ceased

1972: Mine processing ceased

Storm and erosion events

1889-1896: Numerous shipwrecks from storms

1921: "MV Wolloongbar" wrecked in an easterly gale

1933-1936: Period of severe and extensive beach erosion

1954: Cyclone caused severe erosion, damage to new jetty all 26 fishing boats lost. The sea broke through and flooded part of Byron town

1964: Tropical cyclone Audrey. Significant erosion and damage in front of Jonson St.

1967-1974: Seven tropical cyclones impacted NSW and caused significant erosion and damage

1984: Esplanade Road on Belongil Beach lost via erosion

1996: Extensive erosion within Byron embayment and Belongil beach due to East Coast Low

1999: Extensive erosion updrift and downdrift JSPW due to storms

2001: Extensive erosion at Belongil Beach due to East Coast Low

2009: Extensive erosion from East Coast Low and following swell on King Tides

2013: Tropical cyclone Oswald and successive storms caused extensive erosion

2019-2021: Significant erosion at Clarkes Beach

2020-2021: Widespread erosion occurred along Clarkes Beach and Main Beach linked to intermittent sand supply from around Cape Byron

2022: Ex-tropical cyclone Seth caused beach erosion particularly from Clarkes Beach to west of Main Beach

Human constructions

1888: 402-metre-long jetty was constructed extending from Jonson Street

1890-1910: Richmond River training walls were constructed

1919: Esplanade constructed from Jonson St. to Fletcher St.

1928: The jetty at Jonson St. replaced by a 610-metre-long jetty at Belongil Beach.

1954: The jetty at Belongil was damaged

1960: North Richmond River training wall was extended

1962: Brunswick River training walls were constructed

1963: Around 122 metres of rock placed to provide protection

1964: First engineering designs of JSPW

1970: Small groyne was constructed near Gaggin Street, New Brighton.
The JSPW were upgraded with the construction of three groynes

1972: The jetty at Belongil was removed

1975: The JSPW were upgraded with the construction of 3 groynes and restoration of the pre-existing rock revetment

1977: A series of seawalls between the FJ Walker's Meatworks and Manfred Street were constructed.
Groyne constructed at Byron Bay jetty location

1990s: Emergency protection works at Cavanbah Beach. Periodic beach scraping in New Brighton Beach and South Golden Beach

2000s (~mid): Emergency protection works at First Sun Holiday Park

2002: A geotextile container revetment was constructed at the Byron SLSC

2009: Interim geotextile container revetment was constructed at Manfred St., Belongil

2010: Beach scraping trial at New Brighton

2011: Interim geobag revetments built at Don, Border and Manfred St.

2015: Replacement of Manfred St. geotextile container revetment with rock wall

2017: Beach scraping at New Brighton Beach

2019-2021: Emergency protection works at Clarkes Beach and Main Beach

2022: Beach scraping at Main Beach

Figure 10: Timeline of the relevant history of Byron Shire coastal events and development.

2.3 Introduction to coastal processes

Movement of water and sediments within and around the coastal profile occurs in three main areas, the shoreline and beach above the mean sea level (MSL) mark (i.e., subaerial beach), in the intertidal swash zone, and in the deeper surfzone-nearshore waters (see Figure 11). 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 in the nearshore zone 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 nearshore zone, 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 surfzone, 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 surfzone 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 surfzone 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 surfzone 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 surfzone 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 surfzone (i.e., currents outside the surfzone can run in the opposite or alternative directions to the wave driven current inside the littoral zone).
- **Cross shore sand transport** occurs across the surfzone-nearshore 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 breaker 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.

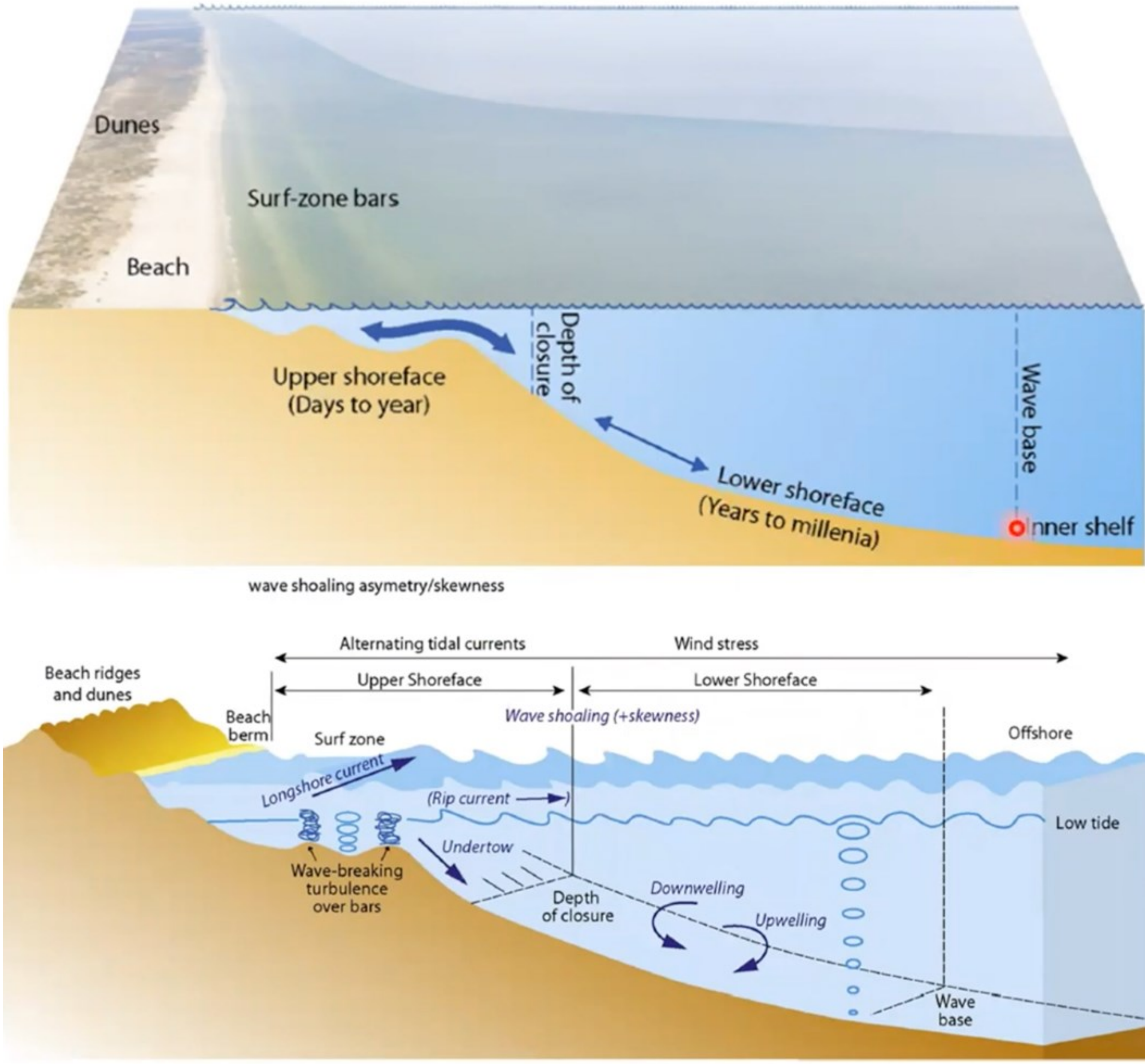

Figure 11: Definition of terms across the coastal profile (source: Cowell et al., 1999; Anthony and Aagaard, 2020).

2.4 Previous studies

There has been numerous studies examining the coastal processes within the Byron embayment. Key studies from which this study has drawn include:

- 1978 *Byron Bay – Hastings Point Erosion Study* (PWD, 1978).
- 2013 *Byron Shire Coastline Hazard Study Update* (BMT WBM, 2013). Being the most recent comprehensive investigation into coastal processes and hazards undertaken in the Byron Shire.
- Dean Patterson's 2013 PhD thesis titled *Modelling as an aid to understand the evolution of Australia's central east coast in response to late Pleistocene-Holocene and future sea level change*
- 2013 Goodwin et. al. paper titled *An insight into headland sand bypassing and wave climate variability from shoreface bathymetric change at Byron Bay, New South Wales, Australia*

- 2020 Ribo et. al. paper entitled *Shelf sand supply determined by glacial-age sea-level modes, submerged coastlines and wave climate*
- 2022 *Main Beach Shoreline Project – Numerical modelling and geomorphic assessment of concept options* (Bluecoast, 2022)

Other studies referred to in this report are listed in the references (see Section 9).

2.5 Data used in this study

This study follows a data-driven or evidence-based approach using data kindly made available for use. A summary of these extensive datasets is presented in Table 2, with associated monitoring sites (where applicable) shown in Figure 12. Limitations to the use of this data and available time periods are discussed in relevant sections of this report.

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

ID	Description	Source	Dates
Water levels* and rainfall	Water levels from: • Billinudgel (15-minutes) • Brunswick Heads (1- and 15-minutes) • Mullumbimby (15-minutes) • Orana Bridge Ocean Shores (15-minutes)	MHL	• Jan 1986 to Feb 2022 • Feb 1986 to Jul 1999 • Jul 1984 to Jun 1999 • Nov 2002 to Oct 2021
	Rainfall data at Myocum	MHL	1986 to 2021
Waves	Measured wave heights, directions, and periods at Byron Bay wave rider buoy (WRB) in around 60-80m water depth	MHL	Oct 1976 to Oct 2021 (direction since 1999)
	Collaboration for Australian Weather and Climate Research (CAWCR) hindcast of modelled wave heights, directions, and periods offshore of Byron Bay at an hourly sampling period	CSIRO	1976 to Nov 2021
	Measured wave heights, directions and water levels at Byron Bay approx. 6 m water depth (MB01)	Bluecoast	15 Dec 2019 to 27 Feb 2020
	Measured wave heights, and water level at Byron Bay approx. 0.3 m water depth (MB02)	Bluecoast	15 Dec 2019 to 27 Feb 2020
Currents	Measured currents at Byron Bay approx. 6m water depth	Bluecoast	15 Dec 2019 to 27 Feb 2020
Winds	Ballina Airport at a 1-minute sampling period	BOM	May 2010 to Dec 2021
	Byron Bay AWS at a 1-minute sampling period	BOM	Sep 2010 to Oct 2021

ID	Description	Source	Dates
Topography and bathymetry	Digital Earth Australia (DEA) shorelines	Geoscience Australia	1988 to 2020
	Beach profile data (Photogrammetry)	DPE	1952 to 2022
	Historical chart	PWD	1883
	Single beam bathymetry and coastal topography	OEH	1993, 1994, 1997, 2003, 2005, 2007
	Drone surveys	Bluecoast	Jul, Oct 2019 Feb, Jul, Oct, Dec 2020
	Coastal lidar data at 1-meter resolution	LPI	2010
	Coastal lidar data at 5-meter resolution	DPE	2011, 2018
	Coastal lidar data at 1-meter resolution	DPE	2022
	Satellite-derived bathymetry	EOMAP	Jul 2018, May 2019, Jun 2020, Jun 2021, Aug 2022
Aerial imagery	High resolution, rectified aerial imagery	Nearmap	2012 to 2023
	High resolution, historic aerial imagery	NSW Government	1958 to 1997
Cadastre	Cadastre shapefile for Byron LGA	NSW Government	2023

Note: * No long-term water level monitoring stations exist within Belongil Creek or Tallow Creek.

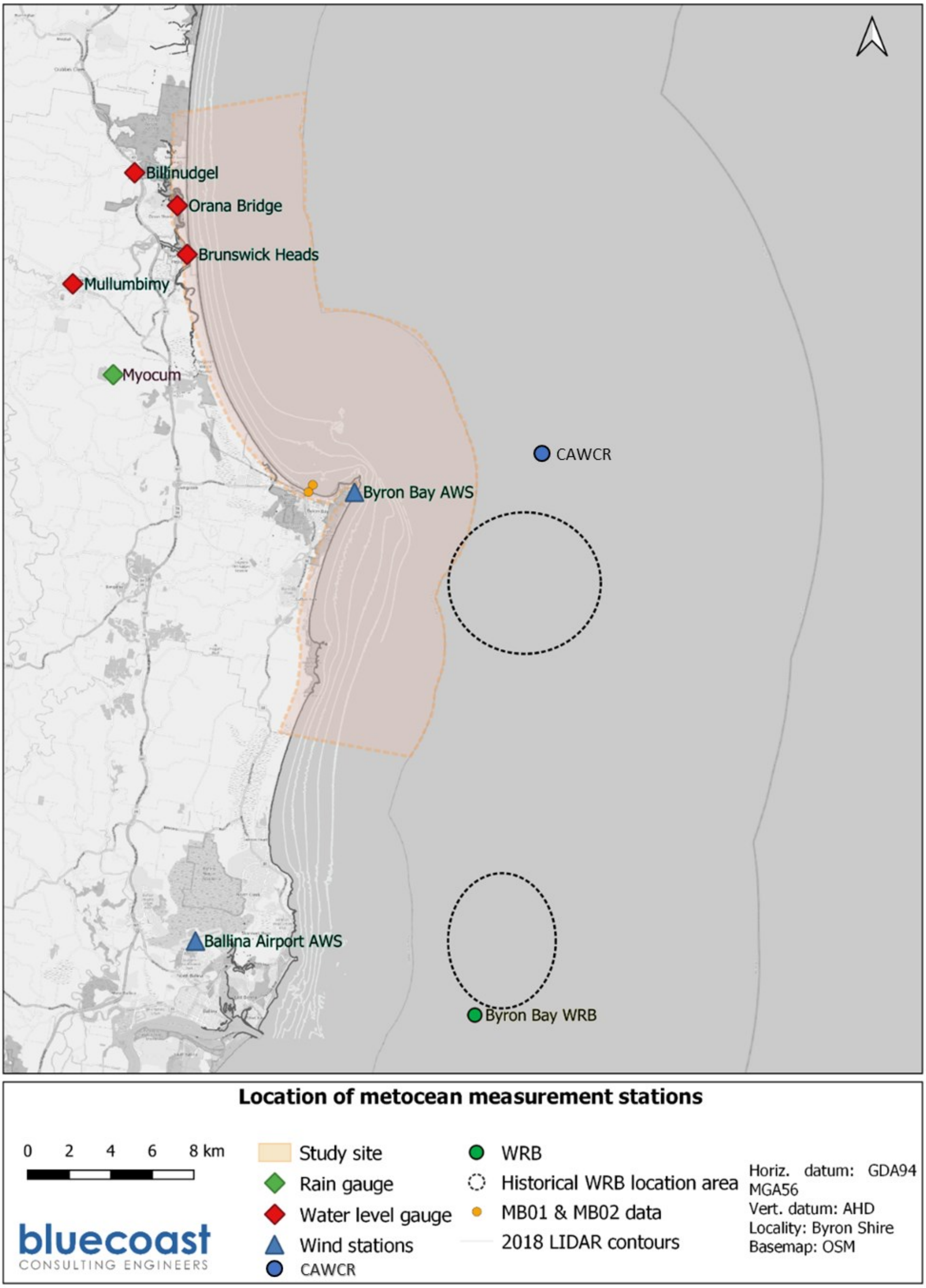

Figure 12: Location of metocean measurement stations available for this study.

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 present-day sea levels were 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 Byron Shire coast comprises a series of bedrock embayments filled with late Quaternary age marine, estuarine and fluvial sediments. The basement rock along the coast is metamorphosed sediment and forms the headlands of Broken Head and Cape Byron as well as outcrops north of Brunswick Heads (PWD, 1978). The geological formation is of Devonian Carboniferous aged Neranleigh Fernvale Beds typically comprising mudstone, shale, arenite, chert, jasper basic metavolcanics, pillow lava and conglomerate. Interbedded with these are basalts of volcanic origin from Mount Warning (Wollumbin).

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 Quaternary deposits of NSW (Troedson and Hashimoto, 2008)
- Seamless Geology dataset (Colquhoun 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
- Comprehensive surface sampling documented in PWD (1978)
- NSW seabed landforms mapping derived from marine LiDAR data captured in 2018 (Linklater et al., 2022).

The coverage of Pleistocene and Holocene sediments that form the modern geological setting of the study area is shown in Figure 13.

Pleistocene age sediments make up around 90% of the coastal deposits in the study area. In the contemporary setting, the younger Holocene sediments are found in the coastal margin where these are restricted to a narrow incipient foredune and beach as well as estuarine sand and muds. The Holocene sediment deposits are typically underlain by Pleistocene sediments.

The coastal margin extends around 1.5 to 2.8km inland with marine sand deposits up to 20m thick. The Pleistocene age sediments are modified by subaerial weathering and groundwater movements. In places this led to formation of lenses of indurated sand (or coffee rock), i.e., sand deposits 'cemented' by decaying organic matter. These coffee rock lenses can be more than 5m thick and are typically found 2 to 4m below the surface (PWD, 1978). In areas affected by erosion, the coffee rock lenses may become exposed where they are subject to subaerial weathering and coastal processes (see Figure 14).

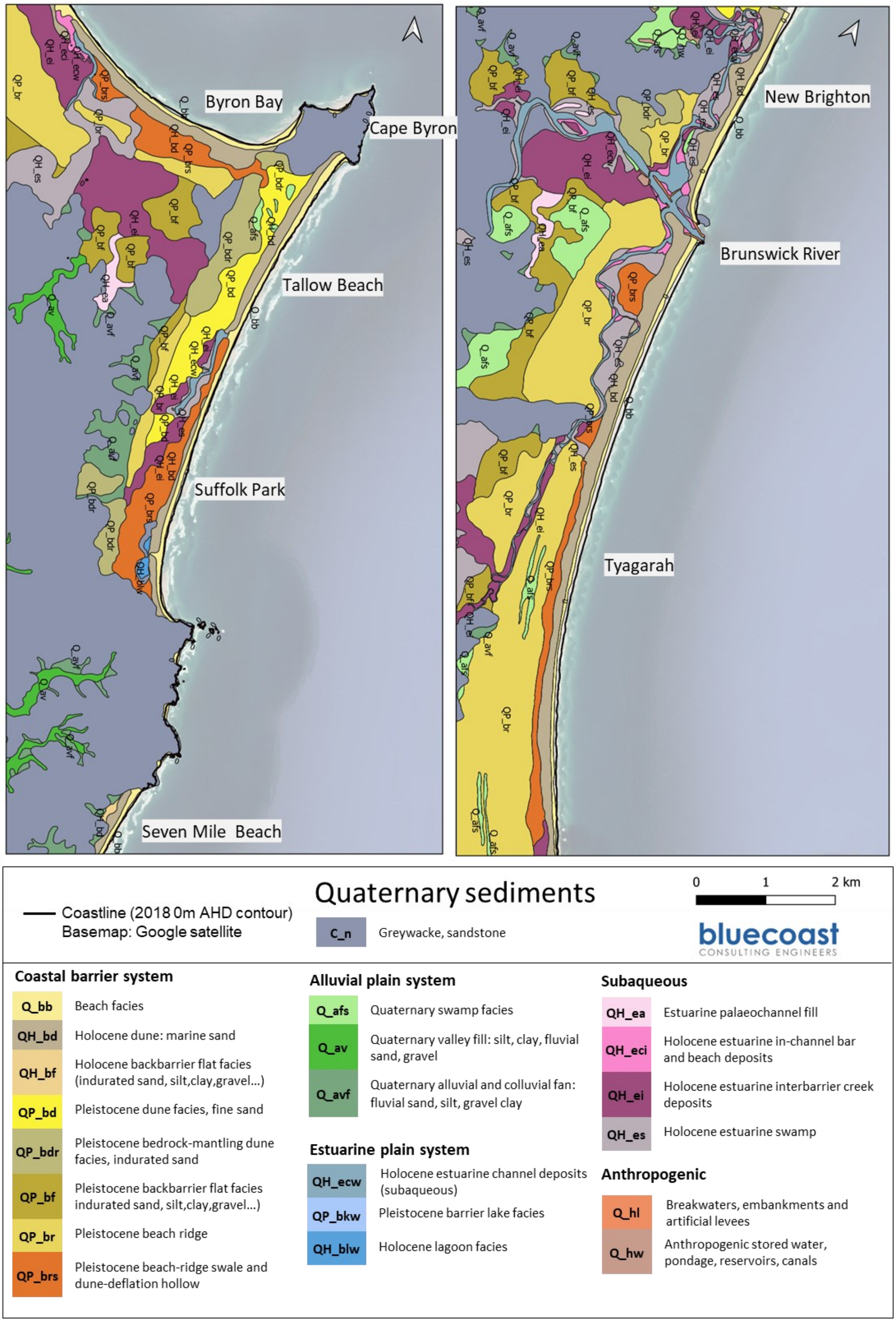

Figure 13: Quaternary coastal sediment deposits (derived from NSW Seamless Geology data).

Figure 14: Photographs showing (left) vertical structure of sediments in dune scarp at western Main Beach and (right) gravel deposits and coffee rock outcropping at Clarkes Beach (photographs captured in July 2022 and July 2020).

3.1.2 Bedrock highs and coffee rock regions

PWD (1978) documented results from a geophysical survey as well as auger drilling to map the presence of bedrock highs and indurated sand regions. Nearshore bedrock and indurated sand reefs are also mapped in the recent NSW seabed landforms data (see Section 3.1.1) and are evident in aerial imagery (see Figure 15). Photographs taken along the embayment during a period of erosion since 2019, provide evidence of exposed indurated sand lenses (coffee rock) on the upper beach and dune scarp (see Figure 14 above). Bedrock and seabed characterisation mapping for the Byron Shire coast is shown in Figure 17 and Figure 18.

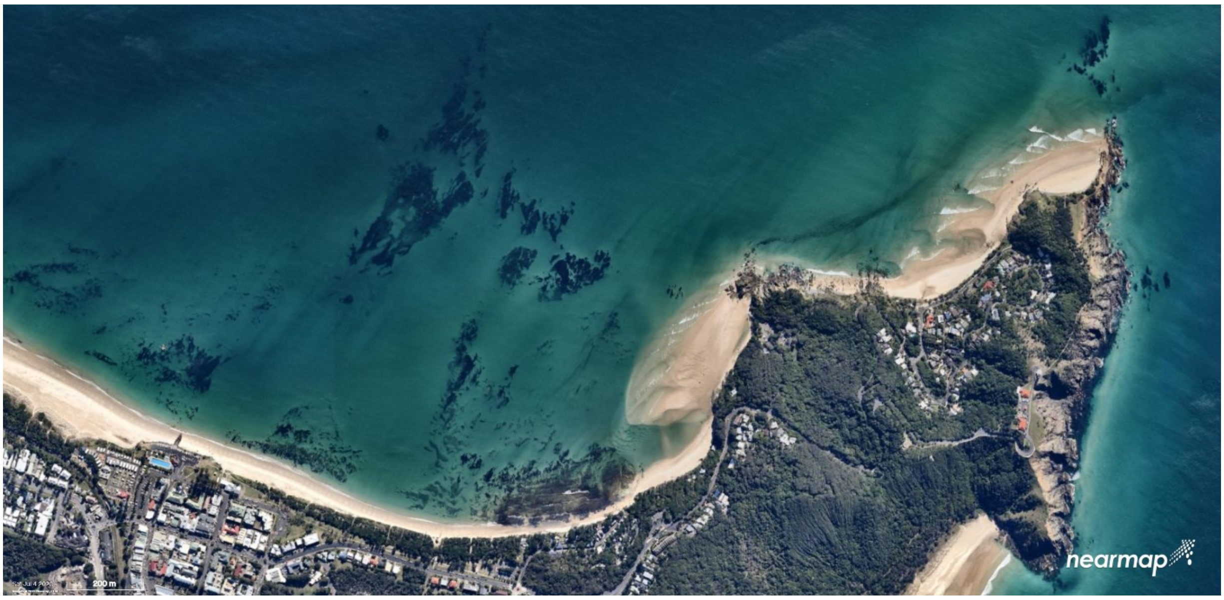

Figure 15: July 2020 aerial photography showing reefs and coffee rock outcropping (source: Nearmap).

These historical and recent observations confirm the embayment has extensive indurated sand (or coffee rock) lenses and bedrock outcrops including Julian Rocks and Middle Reef. These hard features affect wave transformation and the movement of sand through the embayment as well as influencing shoreline dynamics. Hard substrate also reduces the volume of sand that can be stored in the southern embayment.

Based on the review of the historical and recent observations the key bedrock and indurated sand features can be summarised as follows:

Onshore:

- A relatively flat bedrock layer extends along the Byron Shire coast at depths generally greater than 15m (see Figure 16)
- Bedrock surface outcrops were identified on the beach at Broken Head, Little Wategos, Wategos, The Pass, Clarkes Beach, New Brighton and at the entrance to Brunswick River
- Indurated sand regions were identified along most of the Byron embayment between Clarkes Beach and Belongil Beach to around Border Street as well as New Brighton Beach.

Offshore:

- Some bedrock outcrops are present on the seabed, but normally the nearshore bedrock is overlain by up to 35m of unconsolidated sediments, reducing to around 15m further offshore. An exception to this is within the Byron embayment between Cape Byron and Main Beach, where the seismic data suggest that bedrock lies at shallow depths beneath the surface at varying depth between 10m and the surface.
- Shallow bedrock reef was identified at:
    - Julian Rocks
    - Middle Reef in the southern embayment
    - around Cape Byron
    - off New Brighton (New Brighton Reef).
- Extensive indurated sand reefs were identified at:
    - the inner nearshore within the Byron embayment in 1m to 8m water depth
    - the surfzone at New Brighton Beach
    - north of New Brighton reef in 12m to 18m water depth.

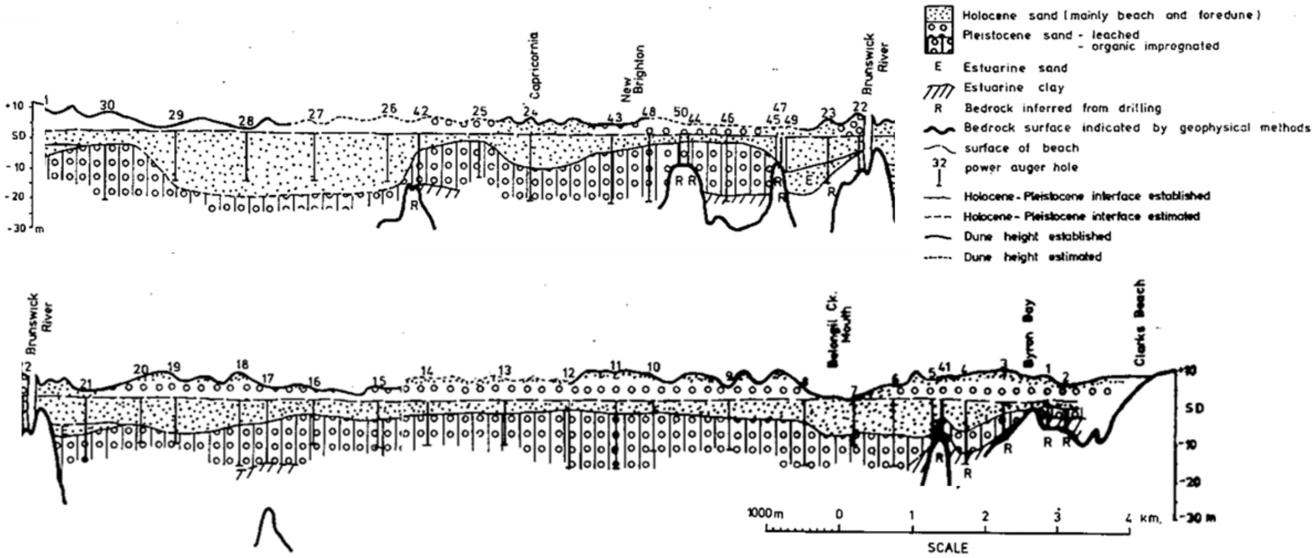

Figure 16: Section along beach and frontal dune between Wooyung and Cape Byron showing depth of bedrock and sand deposits (adapted from PWD, 1978).

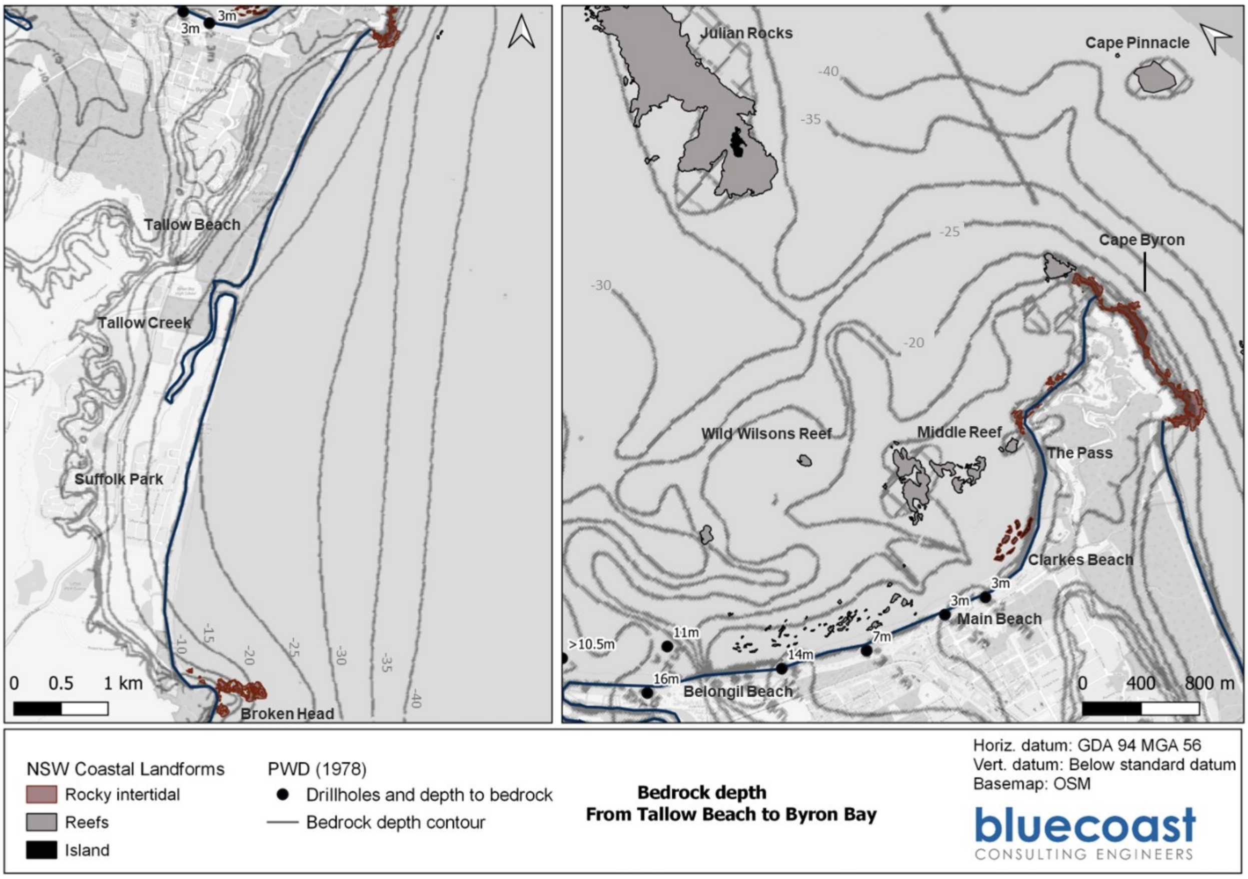

Figure 17: Map showing bedrock depth contours for Tallow Beach to Belongil Creek derived from geophysical survey and auger drilling (after PWD, 1978).

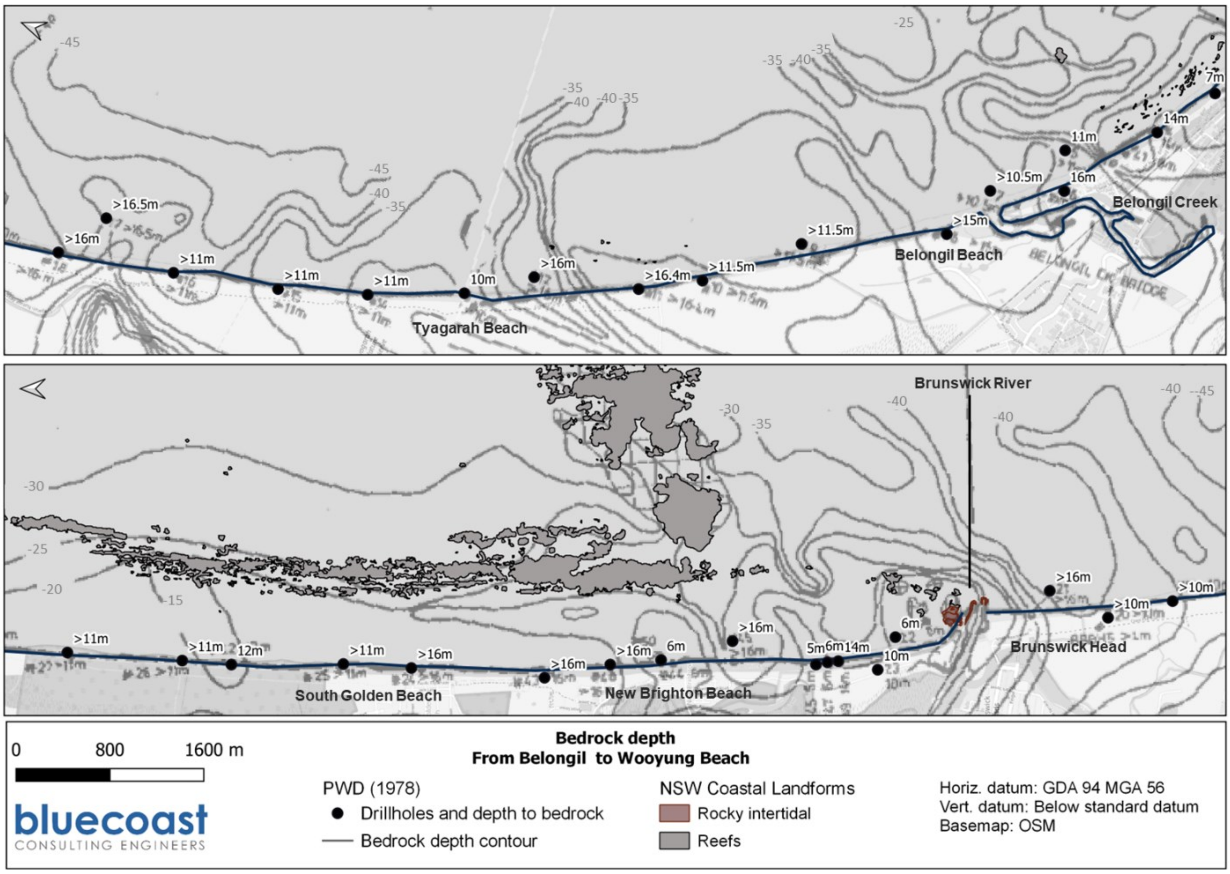

Figure 18: Map showing bedrock depth contours for Belongil Creek to South Golden Beach derived from geophysical survey and auger drilling (after PWD, 1978).

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 median grain size typically around 0.20 to 0.25mm. PWD (1978) 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 varies from depths of -2 to -4m (below MSL) between Clarkes Beach and Belongil Creek, to around -10m at Tallow Beach and -5 to -8m along most the other beaches within the CMP area.
- Outer nearshore sand – Fine grained olive grey sand with low shell content. The seaward extent of this sand deposit varies considerably along the Byron Shire coast. The seaward extent progressively increases from around 1.4km offshore in -23 to -29m depth (below MSL) at New Brighton to around 7km offshore past Julian Rocks in the southern embayment. At Tallow Beach, this sand deposit extends beyond the convex part of the profile (i.e., shelf sand body) to around -44m depth offshore of Broken Head.

A third sand type seaward of the outer nearshore sand 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 Byron Shire are shown in Figure 19.

The Byron 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 Broken Head and Cape Byron, the two embayments of Tallow Beach and Byron Bay are deeply hooked at their southern ends and more aligned with the dominant swell direction at the northern ends (BMT WBM, 2013).

The topography of Byron Shire is characterised by a low backshore and dune barrier profile with typical elevations of around 8m AHD along Tallow Beach, 6m AHD along Tyagarah Beach and around 4m AHD in Byron Bay, New Brighton and South Golden Beach. An extensive dune system is found along central to northern Tallow Beach.

From the Cape to Clarkes Beach the shape of the embayment's shoreline is controlled by the greywacke bedrock that forms Cape Byron. Further to the west, the embayment's backbeach area becomes a narrow Holocene beach barrier system comprised of marine sand deposits. As presented in Section 3.1.2, the presence of rocky reefs and outcrops is evident all along the coast.

The coastal profile slope along the open beaches is around 1V:55H. In Byron Bay the slope is gentler, around 1V:116H. The embayment beaches are interrupted by the coastal lake and estuary entrances to Ti Tree Lake (Taylors Lake), Tallow Creek, Belongil Creek and Brunswick River.

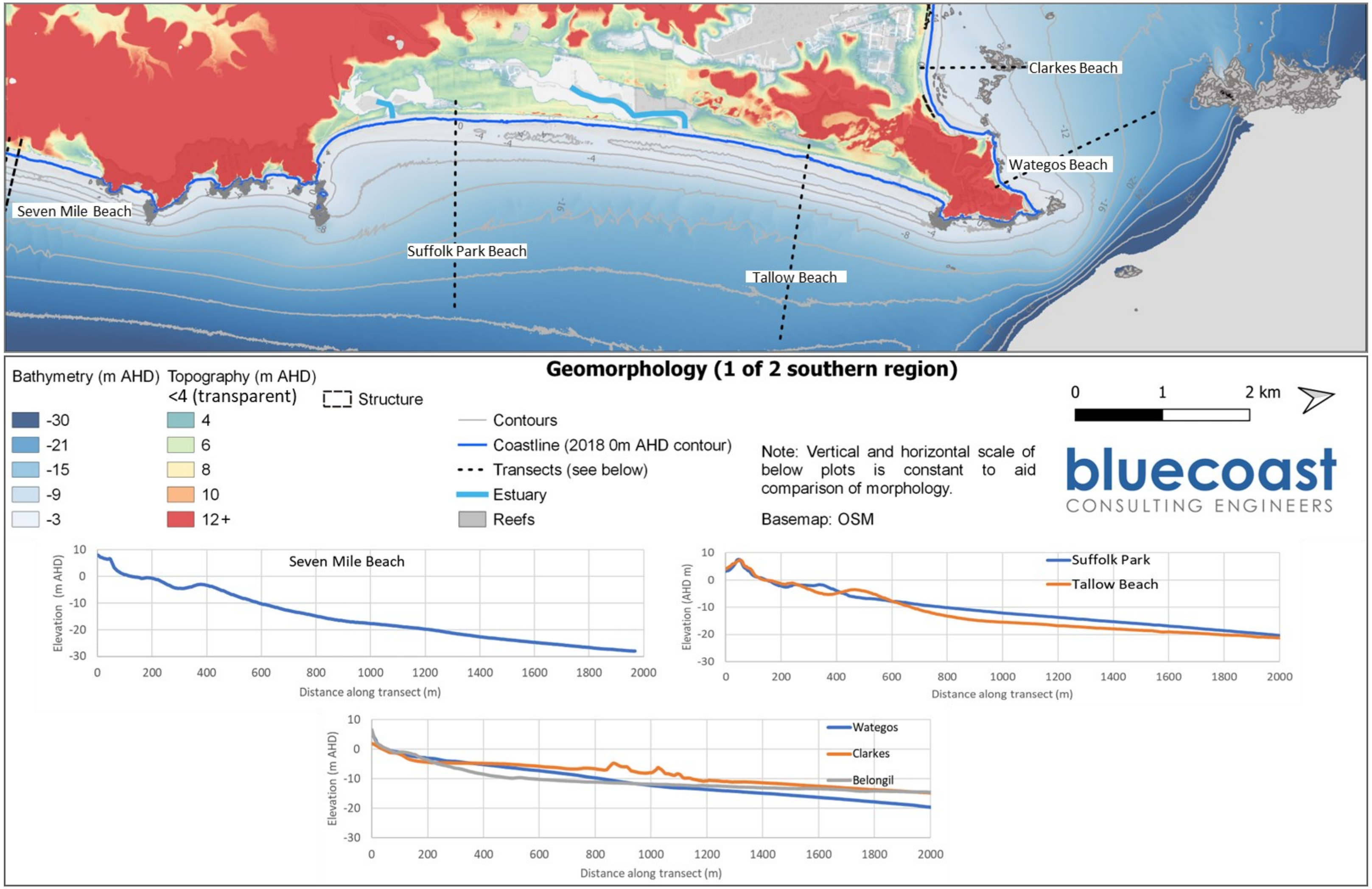

Figure 19: Geomorphic setting from Seven Mile Beach to Byron Bay based on 2018 LIDAR data.

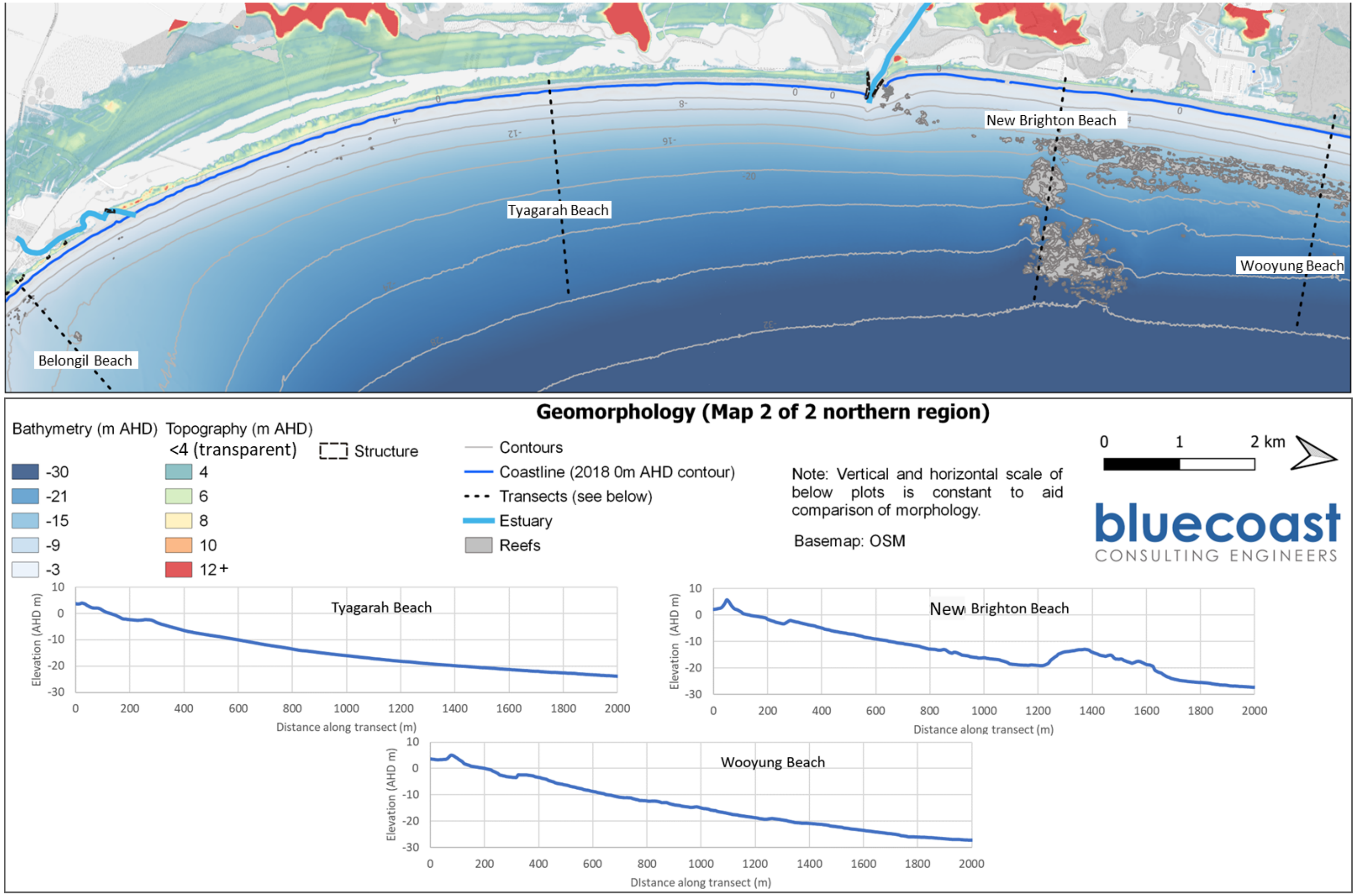

Figure 20: Geomorphic setting from Belongil Beach to Wooyung based on 2018 LIDAR data.

3.3 Wave climate

3.3.1 Offshore wave climate

The deep-water wave climate comprises a persistent long period low to moderate energy swell predominantly from southeast to east directions superimposed on a highly variable wind wave climate. Wind waves (sea) come predominantly from the east to southeast sectors and range from small, short period to large storm and cyclone waves. The mean significant wave height is 1.65m, with a 75th percentile wave height of 1.98m annually, predominately from the southeast. Storm waves from easterly lows and tropical cyclones may approach from the east-northeast to south-southeast. Large southerly swells often result from intense low pressure systems off the New South Wales coast (BMT WBM, 2013).

A review of observed wave data from the Byron Bay waverider buoy (WRB) and the CAWCR reanalysis data (Durrant et al., 2013) was undertaken. The following results are presented:

- Wave roses for sea (local sea, Tp <8s) and swell (swell waves, Tp >8s) for the Byron Bay WRB are provided in Figure 21. Swell waves dominate 79% of the time.
- The observed average as well as seasonal wave climate statistics are provided in Table 3.
- Monthly average significant wave heights and peak wave periods are presented in Figure 22.
- The joint occurrence of observed significant wave heights and peak wave directions is shown in Figure 23.

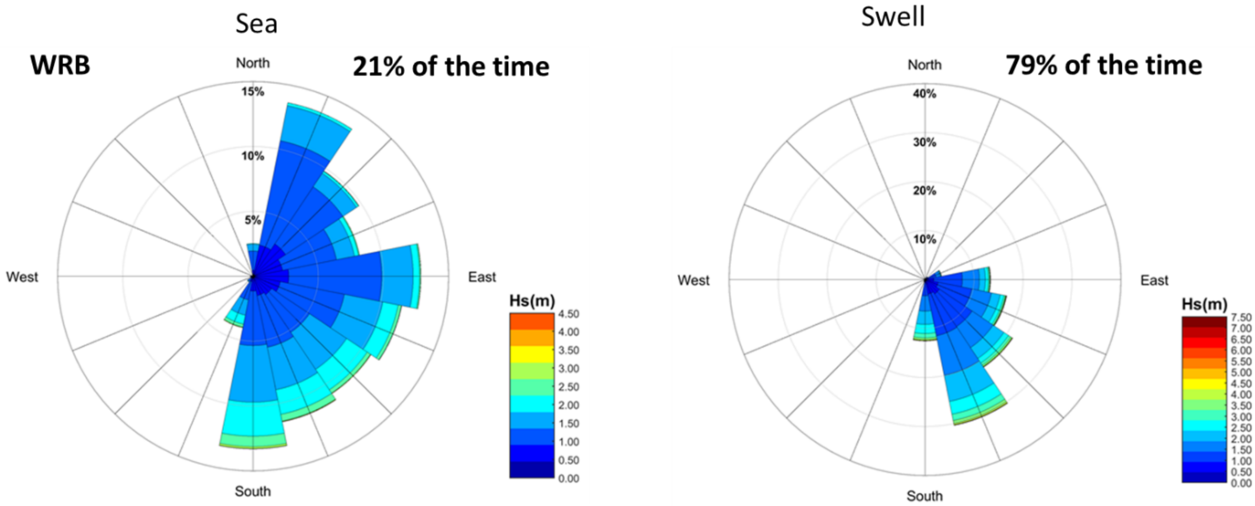

Figure 21: Long-term wave roses for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) at the Byron Bay Wave Rider Buoy.

Table 3: Wave measurement statistics derived from Byron Bay WRB.

		Long term averages (1999 to 2022)				
Parameter	**Statistics**	**All seasons**	**Winter**	**Spring**	**Summer**	**Autumn**
Significant wave height (H_s) [m]	Mean	1.65	1.67	1.54	1.60	1.76
	50%ile	1.49	1.50	1.39	1.45	1.63
	75%ile	1.98	2.07	1.80	1.89	2.11
	99%ile	3.93	3.97	3.70	3.97	3.99
	Max	7.64	5.97	5.87	6.57	7.64
Peak wave period (Tp) [s]	Mean	9.7	10.3	9.3	9.3	9.9
	50%ile	9.8	10.3	9.3	9.3	9.8
	75%ile	11.1	12.1	10.8	10.3	11.1
	99%ile	14.9	15.4	14.9	14.9	14.9
	% of time sea (Tp < 8s)	21%	15%	29%	26%	17%
	% of time swell (Tp > 8s)	79%	85%	71%	74%	83%
Peak Wave Direction (Dp) [ªTN]	Weighted mean	145	147	151	138	142
	Mean	131	140	129	120	133
	Standard deviation	38	35	44	37	33

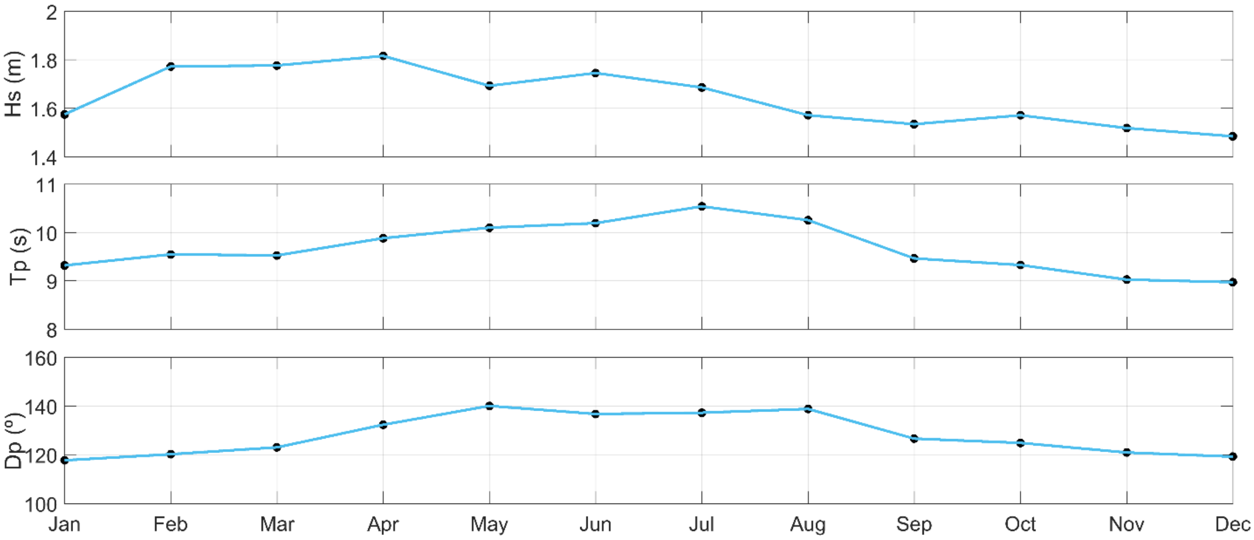

Figure 22: Monthly average significant wave heights, peak periods and peak directions at the Byron Bay WRB.

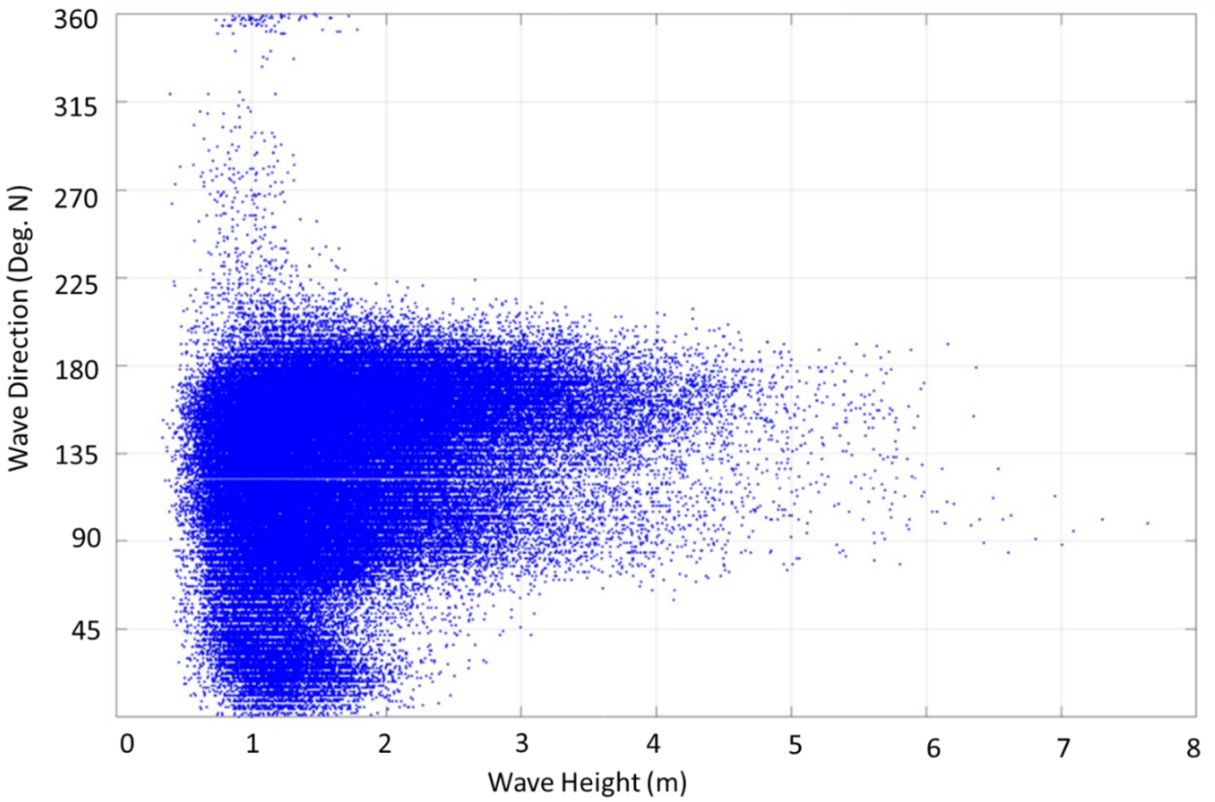

Figure 23: Joint occurrence of measured significant wave heights and peak wave directions at Byron Bay WRB.

An Extreme Value Analysis (EVA) of the available CAWCR data (spanning 45 years) was undertaken at 90-meter depth. The Byron Bay WRB data was not suitable for this analysis due to data gaps during storm events (Shand et al., 2011). A peak over threshold analysis identified the extreme events and a Weibull distribution was fitted to provide the average recurrence interval (ARI) for significant wave heights (see Table 4). Figure 24 shows the extreme value distribution of significant wave heights. The 50-year and 100-year ARI significant wave heights are 8.07m and 8.42m, respectively for a 1-hour duration.

Table 4: Average recurrence interval (ARI) wave heights for CAWCR data.

ARI (year)	H_s (m)	98% confidence limit (m)
1	5.66	5.59 – 5.74
5	6.80	6.51 – 7.09
10	7.20	6.85 – 7.56
25	7.70	7.26 – 8.15
50	8.07	7.55 – 8.58
100	8.42	7.83 - 9.01

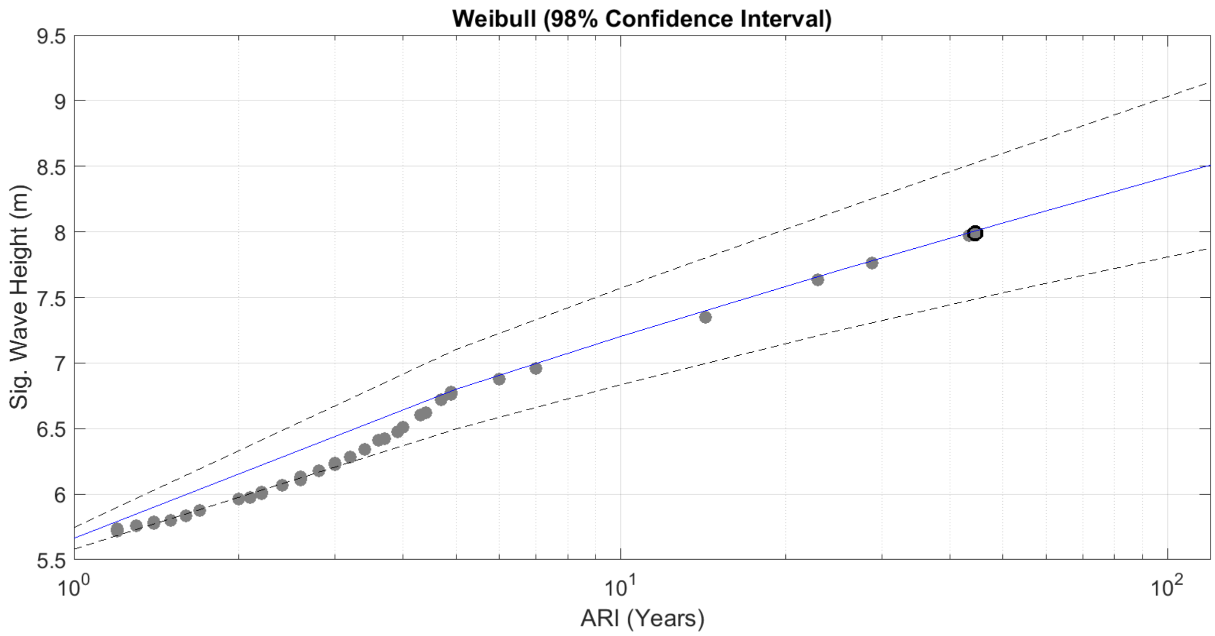

Figure 24: Results of extreme value analysis at CAWCR data site (-28.65E, 153,93S).

3.3.2 Nearshore wave climate

The nearshore wave climate was assessed using the following data:

- Nearshore wave and current measurements collected in the Byron embayment in 2019/20 as part of the Main Beach Shoreline Project. Site MB01 located at 6m of water depth monitored directional waves, currents and water levels for a 2-month period.
- 40-year wave hindcast at Byron Bay developed as part of the Main Beach Shoreline Project (2021). This wave hindcast model provides nearshore wave data in the entire study area.

The following results are provided:

- Nearshore wave roses for total, swell (swell waves, Tp >8s) and sea (local sea, Tp <8s) at Main Beach extracted from the wave hindcast (site MB01) are provided in Figure 25.
- Nearshore wave roses for Tallow Beach, Tyagarah Beach and Brunswick Heads extracted from the wave hindcast are shown in Figure 26.
- Figure 27 presents wave roses along the Byron embayment's 4m water depth contour.

The embayment is exposed to waves from the east to north-east sector, with the predominant offshore waves from the south-east sector refracting and diffracting around Cape Byron and into the embayment. The nearshore wave climate at Main Beach is dominated by low energy, medium period swell waves with a seasonal increase in the percentage of sea waves in the spring months. The waves roses show a narrow band of incoming wave directions.

Tallow Beach, Tyagarah Beach and from Brunswick Head up to Wooyung Beach are considered open coast and are exposed to east-south-east wave directions.

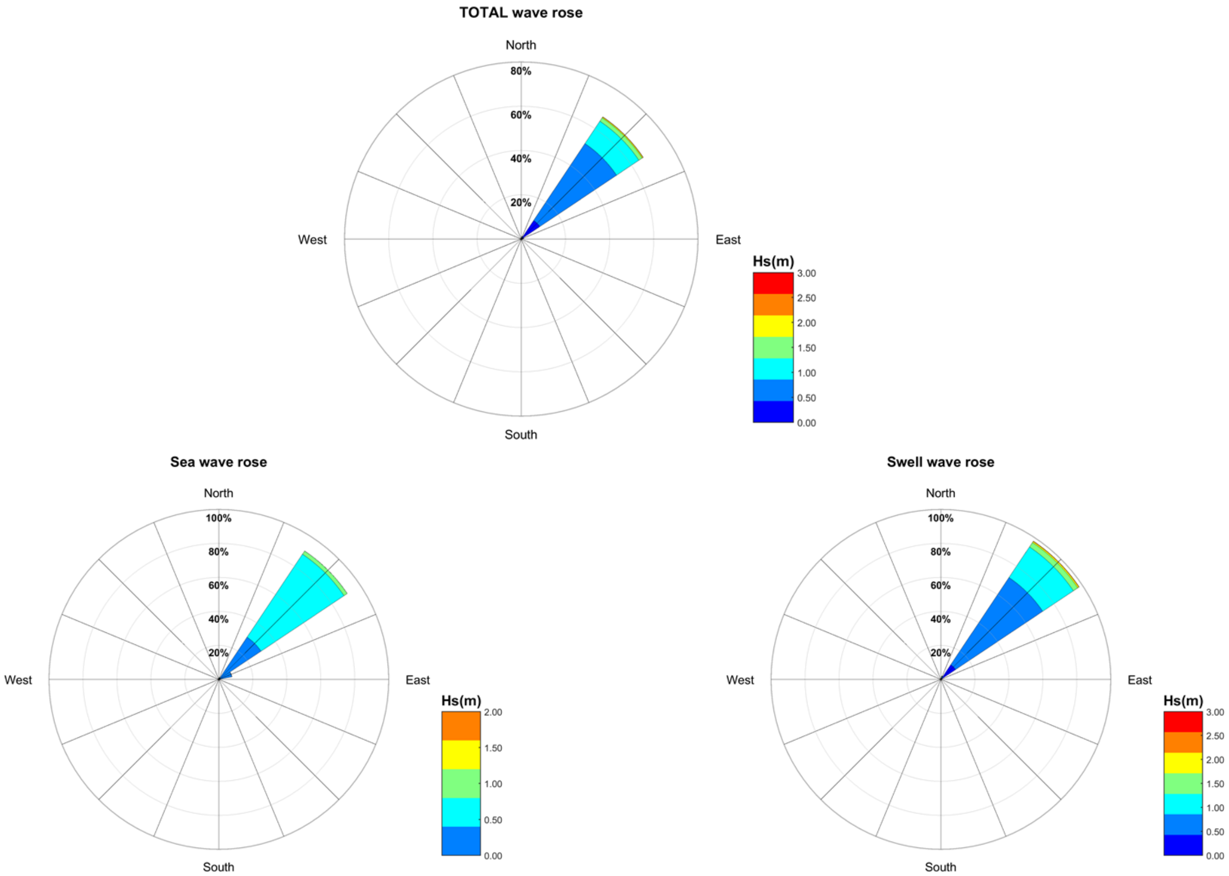

Figure 25: Total, swell and sea wave height and direction roses at the MB01 extraction location (Main Beach, Byron embayment).

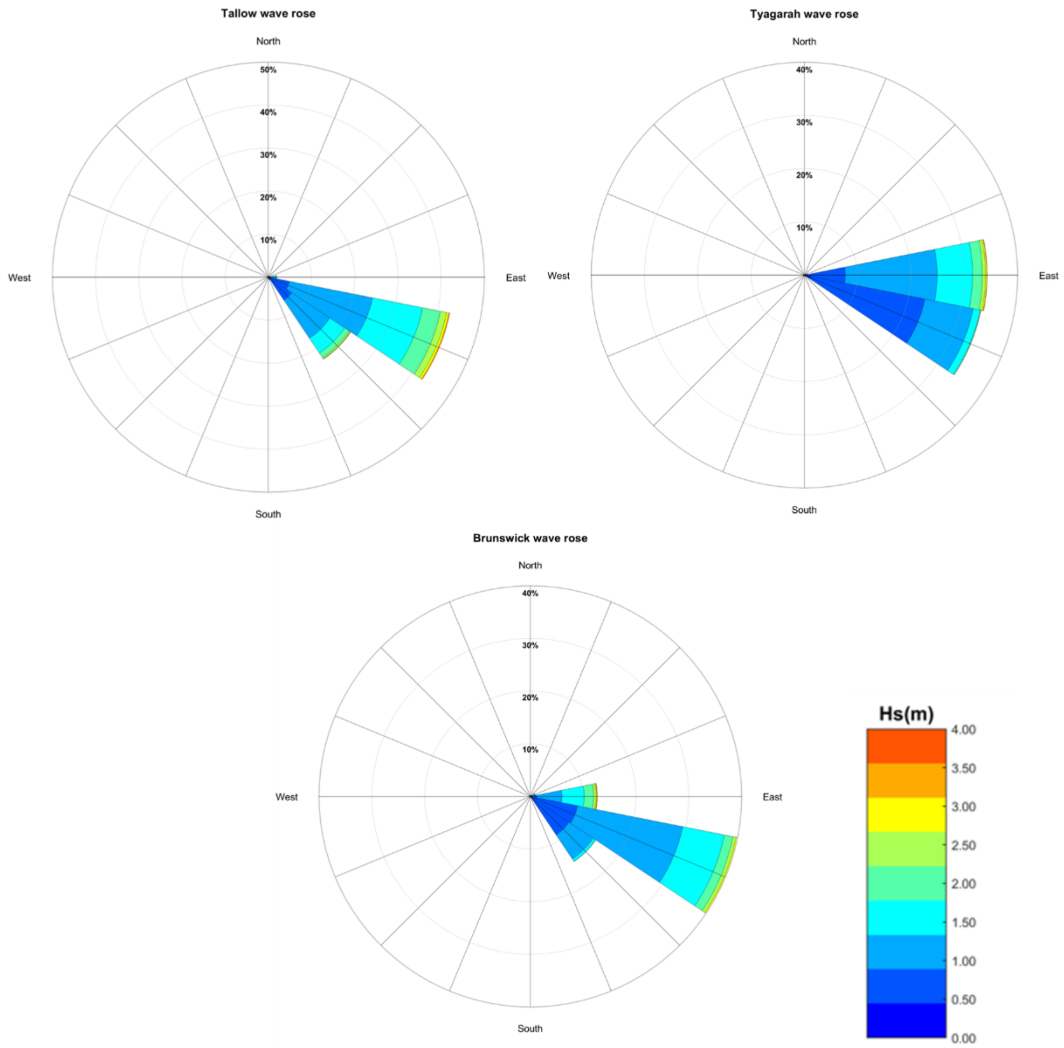

Figure 26: Total wave height and direction roses at Tallow Beach (top left), Tyagarah Beach (top right) and Brunswick Heads (bottom).

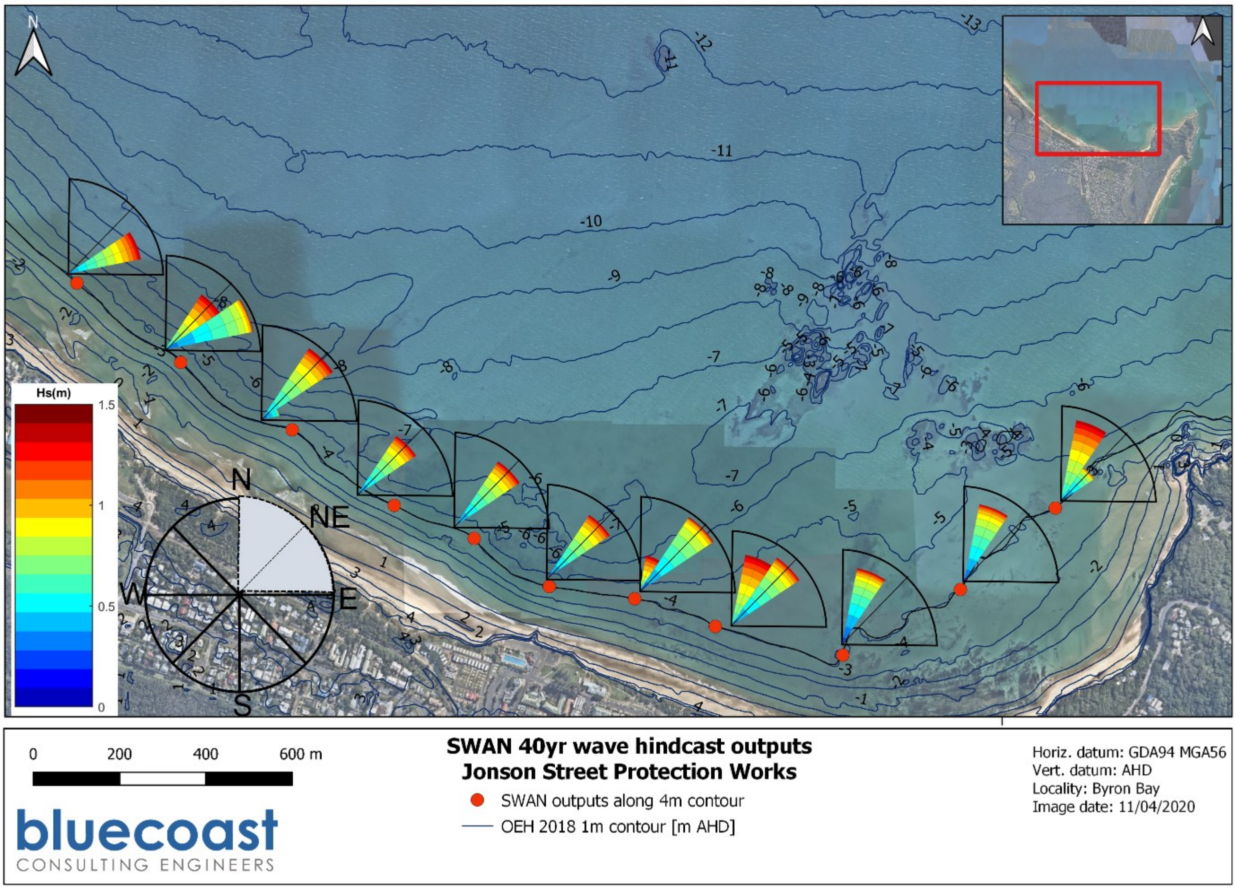

Figure 27: Nearshore wave roses along the 4m depth contour extracted from the 40-year wave hindcast results along the Byron embayment.

3.4 Wind climate

Wind measurements at the Ballina Airport AWS and Cape Byron AWS were analysed. Measured wind speeds and directions at the two sites were analysed over the period from 2010 until 2021. Seasonal wind roses are presented in Figure 28 and Figure 29 for the Ballina and Byron Bay stations, respectively. Wind measurement statistics are presented in Table 5.

The wind data shows an inclination for winds to arrive from the northern and eastern sector during spring and summer and a predominance for westerly to south-westerly winds during winter and autumn. Spring shows a more bi-modal pattern with winds generally coming from either the north-eastern or south-western sectors. Maximum wind speeds of 30m/s were recorded in Byron Bay, while the maximum wind speed in Ballina was around 20m/s.

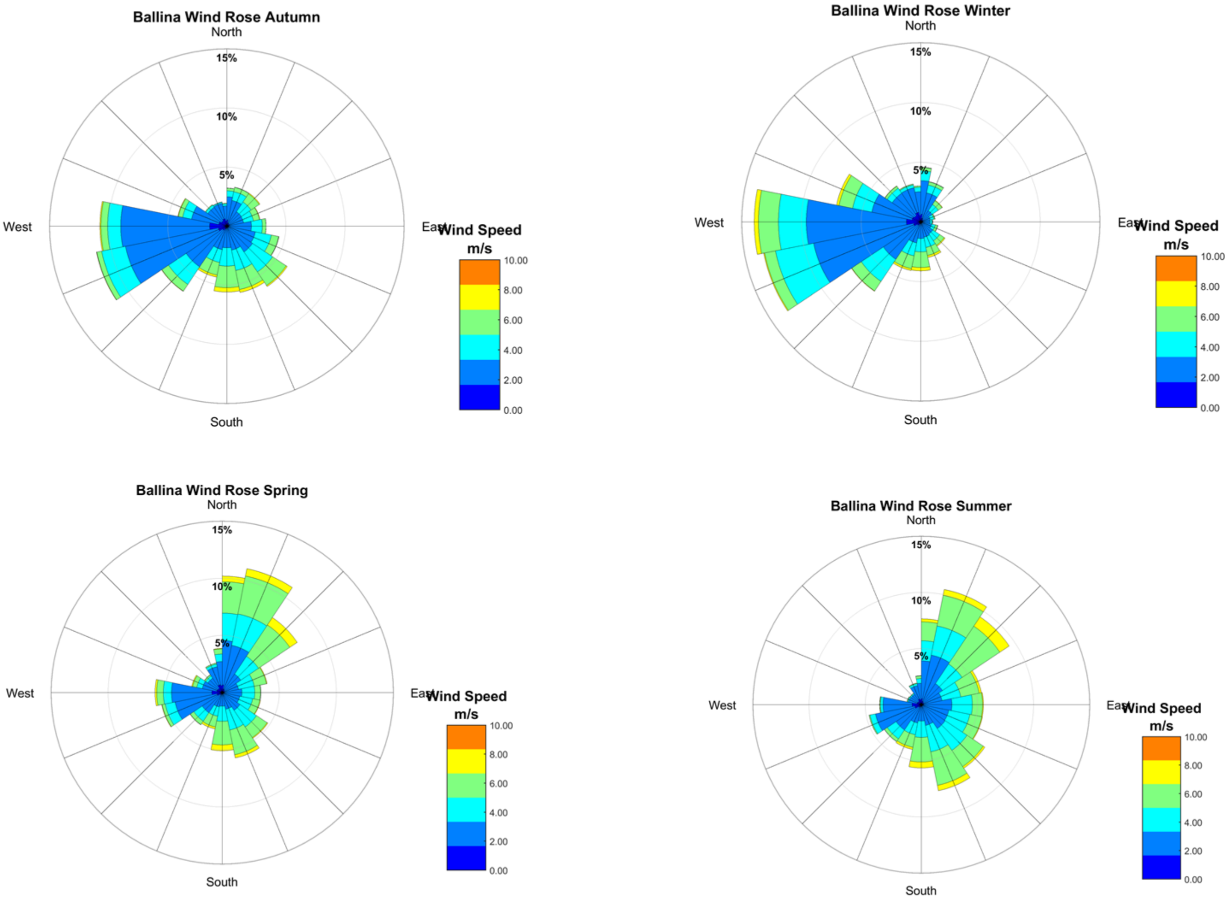

Figure 28: Wind roses of one minute data for Ballina Airport AWS from 2010 to 2021.

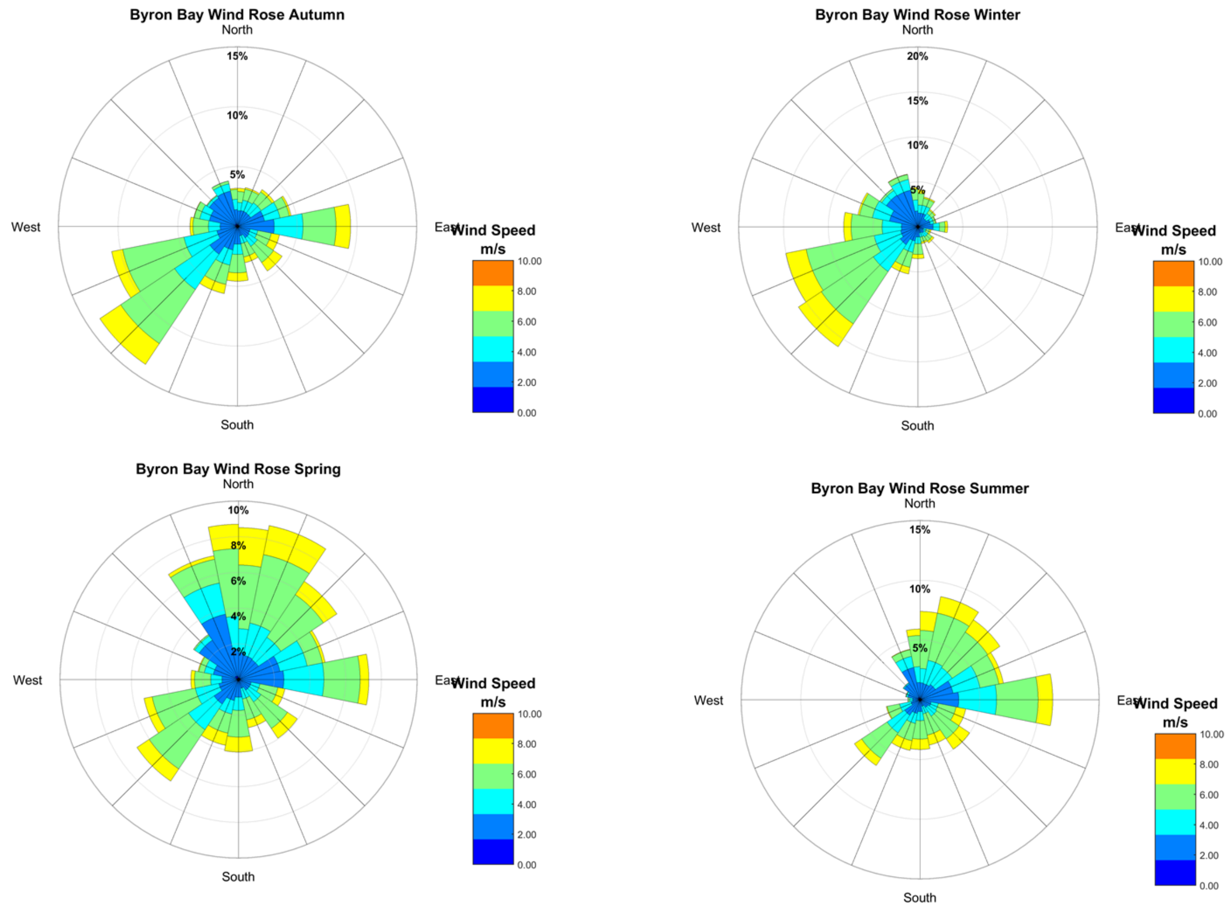

Figure 29: Wind roses of one minute data for Cape Byron AWS from 2010 to 2021.

Table 5: Wind measurement statistics for observations between 2010 to 2021.

Parameter	Statistic	Ballina Airport AWS	Cape Byron AWS
Wind speed [m/s]	Mean	4.3	6.1
	20%ile	2.5	3.5
	90%ile	7.0	9.5
	Max	20.5	30.0

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, 2023). Tidal planes for the Tweed-Byron region (ocean) and Brunswick River (estuary) tide gauges are provided in Table 6 and Table 7, respectively. A water level exceedance curve based on measurements at the Brunswick River tide gauge is presented in Figure 30

Table 6: Ocean tidal planes for Tweed-Byron region (MHL, 2023).

Tidal plane	Height (metres relative to AHD)		
	Tweed Heads	Brunswick Heads	Ballina Breakwall
High High Water Solstice Springs (HHWSS)	1.004	1.075	0.970
Mean High Water Springs (MHWS)	0.639	0.678	0.575
Mean Sea Level (MSL)	0.035	0.051	-0.015
Mean Low Water Springs (MLWS)	-0.596	-0.576	-0.605
Indian Spring Low Water (ISLW)	-0.830	-0.860	-0.887

Table 7: Tidal planes for various locations within Brunswick River estuary for 2019-2020 (MHL, 2023).

Tidal plane	Height (metres relative to AHD)		
	Brunswick River at Orana Bridge	Brunswick River at Billinudgel	Brunswick River at Mullumbimby
High High Water Solstice Springs (HHWSS)	0.912	0.658	1.096
Mean High Water Springs (MHWS)	0.606	0.448	0.738
Mean Sea Level (MSL)	0.232	0.291	0.123
Mean Low Water Springs (MLWS)	-0.142	0.134	-0.491
Indian Spring Low Water (ISLW)	-0.360	-0.016	-0.747

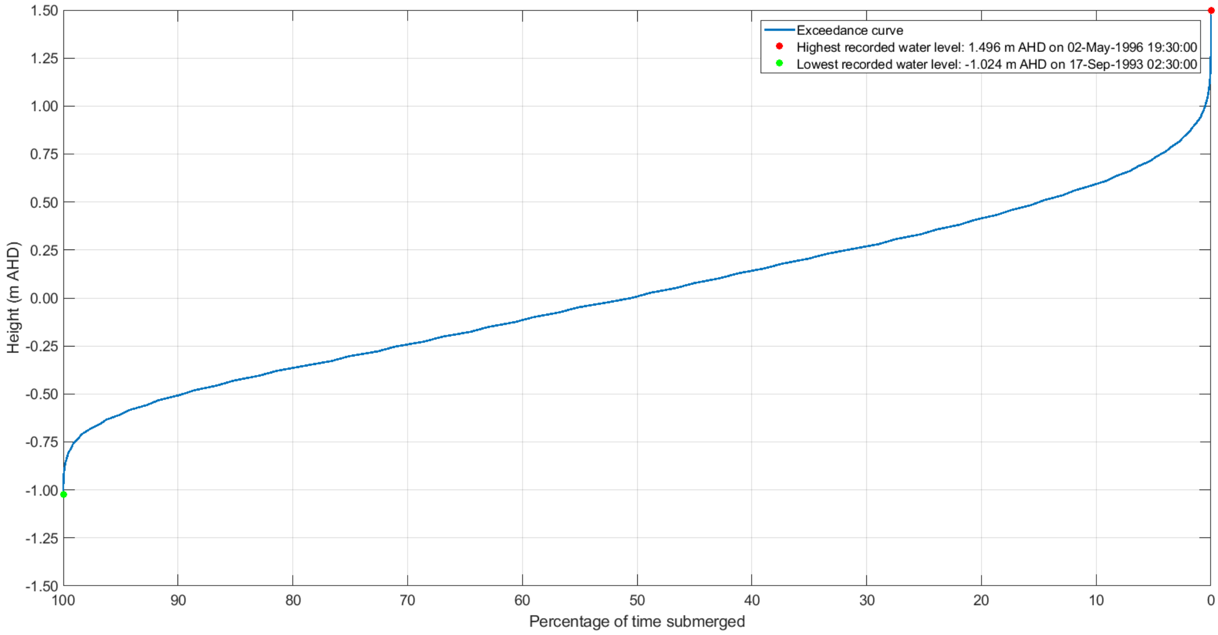

Figure 30: Water level exceedance curve for Brunswick Head tide gauge.

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 8 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 8: 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)

[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.

ARI	Water level (m AHD)
100 years *(low confidence due to short data record)*	1.46 (1.39 to 1.52)

3.6 Sea level rise

The latest advice from IPCC (AR6) on sea level rise (SLR) assesses the climate response to five illustrative 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 Yamba[2], NSW for the 'likely' mean SLR ranges (17th to 83rd percentiles) by 2100 are (refer to Figure 31):

- 0.26-0.59m under the very low greenhouse gas (GHG) emissions scenario (SSP1-1.9[3])
- 0.31-0.65m under the low GHG emissions scenario (SSP1-2.6)
- 0.43-0.80m under the intermediate GHG emissions scenario (SSP2-4.5)
- 0.55-0.97m under the high GHG emissions scenario (SSP3-7.0)
- 0.63-1.10m under the very high GHG emissions scenario (SSP5-8.5).

The adopted SLR values for the coastal hazard assessment based on the IPCC AR6 projections are presented in Table 9. The adopted values were derived from the 'medium confidence' range for SSP1-2.6 to SSP5-8.5 to consider a wide range of projections published by IPCC's AR6 report. IPCC's 'low confidence' range was not considered due to the stated uncertainty. Further analysis and extrapolation of the projected quantiles in Table 9 was undertaken as part of the probabilistic coastal erosion and recession assessment (see Section 5.3.5).

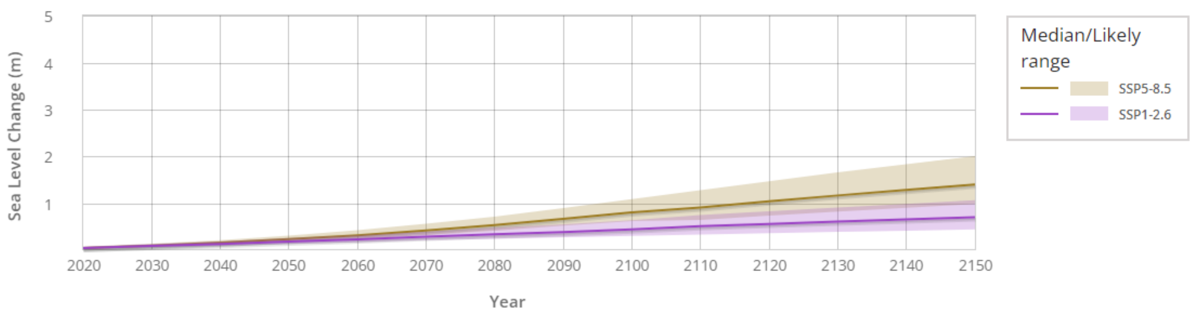

Figure 31: IPCC AR6 sea level rise projections (for Yamba, NSW) relative to 1995 - 2014 baseline for the low and very high future greenhouse gas emission scenarios (Garner et al., 2021).

Note: Shaded range represents the respective 17th to 83rd percentile ranges which IPCC refers to the 'likely' range.

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[2] Yamba, NSW was the closes data point available to this study at the time of writing.
[3] Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies.

Table 9: Sea level rise projections in metres relative to 1995 – 2014 baseline adopted for the hazard assessment.

Quantile	2050	2100	2120	Comment
5th percentile	0.11	0.23	0.28	SSP1-2.6
17th percentile	0.14	0.31	0.37	SSP1-2.6
50th percentile	0.23	0.70	0.93	Mid-value between above (17th %ile) and below (83rd %ile) values
83rd percentile	0.32	1.10	1.48	SSP5-8.5
95th percentile	0.39	1.35	1.82	SSP5-8.5

3.7 Regional 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 except in shallow and wave-sheltered areas (i.e., lagoons). On the subaerial beach, strong winds can transport sand along the beach face and to the dunes (i.e., aeolian sand transport).

Further offshore, the current regime of the outer margin of the NSW continental shelf is dominated by the East Australian Current (EAC) and its eddy field. This current runs southward from the Great Barrier Reef where it draws its waters from the pile up of water caused by trade winds. It is the strongest in the area off Cape Byron, then the current flows along the edge of the continental shelf, veering out to sea between approximately Seal Rocks and Jervis Bay, where it begins to break up into a series of anticyclonic eddies.

Off Cape Byron, the shoreface drops rapidly to depths of around 40-50m, where the EAC is typically most pronounced. At times, this proximity of the southward flowing EAC interferes with the net northerly littoral sand transport pathway around Cape Byron, partially diverting sand transport to offshore areas (namely the Cape Byron sand lobe; PWD, 1978; BMT WBM, 2013).

The EAC jet is typically stronger in summer and brings warm tropical water and associated species to the region which has contributed significantly to the ecology of the Cape Byron Marine Park (Patterson Britton and Partners, 2006).

3.8 Rainfall

The mean annual rainfall observed at Myocum between 1986 and 2021 was of 1,390mm (i.e., about 20% higher compared to Sydney). Figure 32 illustrates the mean monthly precipitation observed at Myocum. 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 1986 and 2021 ranged from a minimum of 44mm in September to a maximum of 202mm in February.

Rainfall varies significantly from one year to another as shown in Figure 33. For example, over the 36-year record period, a low of 226mm was recorded in 1987 and a high of 2,519mm was measured in 1999. Much of the variability in precipitation is due to large-scale climate variations, with El Niño – Southern Oscillation playing a considerable role.

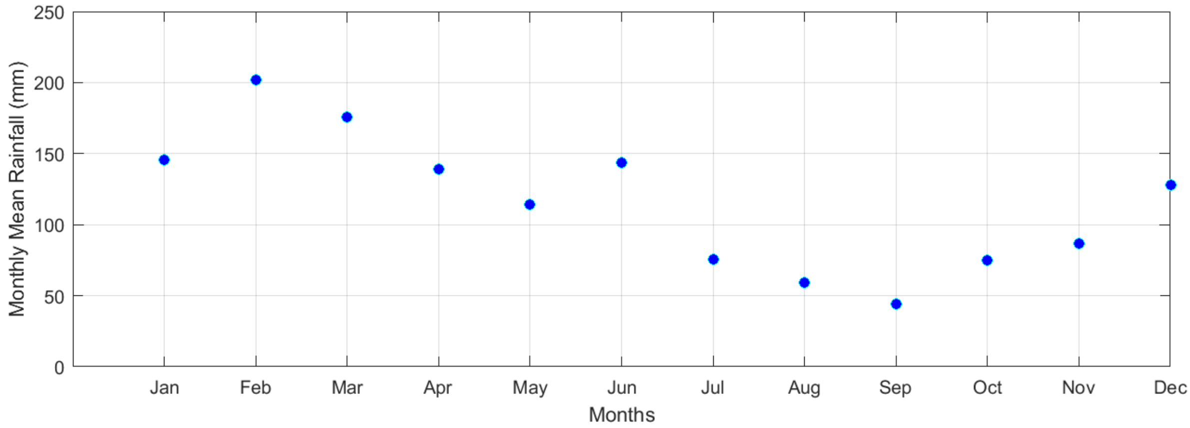

Figure 32: Mean monthly rainfall observed at Myocum (1986 – 2021).

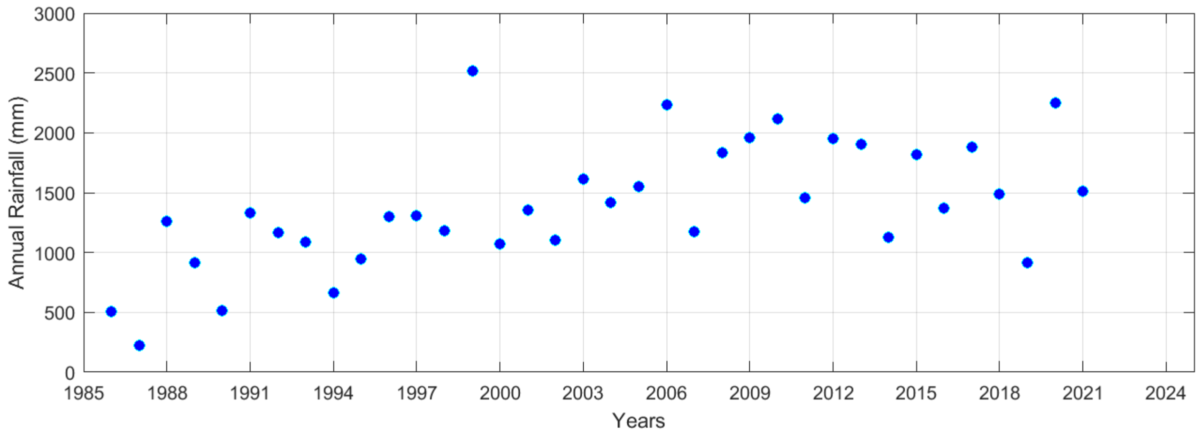

Figure 33: Annual rainfall at Myocum (1986 – 2021).

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 Inter-decadal 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). 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, 2016; Goodwin et al 2005). A timeseries of historical occurrence of El Niño and La Niña periods is shown in Figure 34.

A notable component of the climate variability on decadal scales is found to be related to IPO. Helman (2007; 2008) reported that major energy periods in the storm history of the east coast can be correlated with the negative (La Nina-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 low pressure systems, higher rainfall and associated flood activity (Rakich et al., 2008; Verdon et al., 2004).

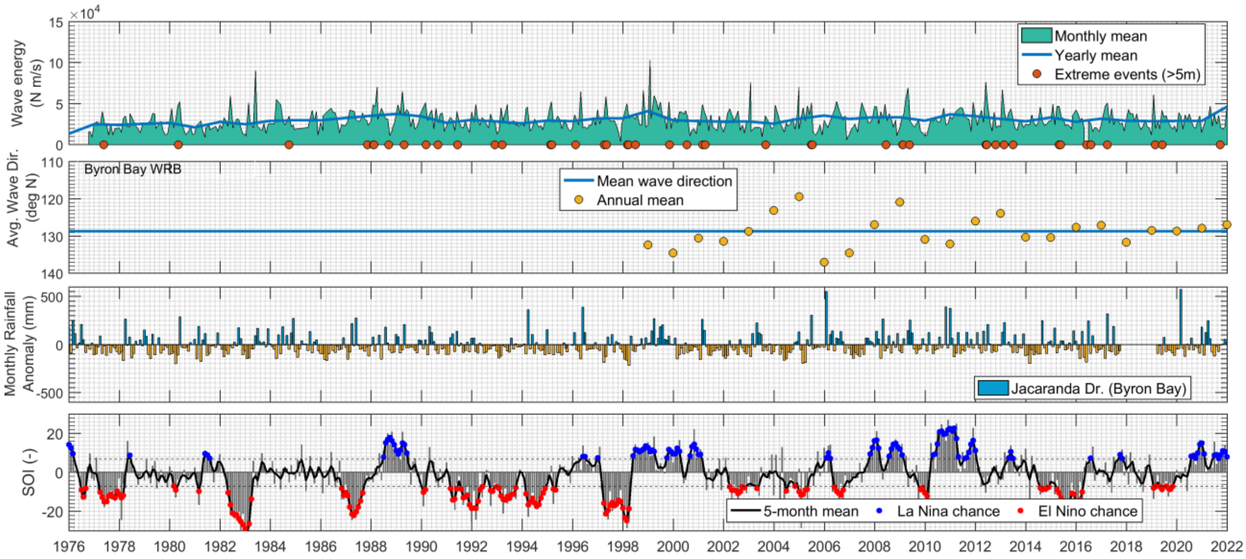

Figure 34: Timeseries of southern oscillation index (SOI) indicating periods of El Niño (red) and La Niña (blue) conditions along with wave conditions (top two panels) and rainfall (3rd panel).

4. Byron 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 Byron 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.

Analysis to determine the Byron Shire coastal sand budget involved mapping historical sand volume changes in 64 sediment cells across the study area's coastal profile using survey data from 1883 to present day. These 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 4.2.4). 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, satellite-derived bathymetry and photogrammetry) presented in **Appendix B** and **Appendix C**.

4.2 Observed changes

4.2.1 Sediment compartments adopted in this study

An assessment of the change in the sand volumes within the project region, from the southern to northern extent of the Byron Shire LGA (from Seven Mile Beach to New Brighton Beach) was undertaken adopting the 64 analysis cells shown in Figure 35 (and in more detail in **Appendix A**). 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 2.3). 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 extends from approximately shoreline (or approximate zero-meter AHD contour) to back beach area.
- Upper shoreface[4]: is the zone where under average conditions waves break and most wave energy is dissipated, commonly called the surfzone. 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.
    - Along the southern beaches (Tallow, Kings, Brays, Whites and Seven Mile beaches) and northern beaches (Tyagarah and New Brighton beaches) the upper shoreface was given *2* as the cross-shore identifier. The upper shoreface for these beaches comprises all depths less than around 12m.
    - Within the Byron embayment the upper shoreface was divided into two sub-cells. The cross-shore identifier *2* denotes depths less than around 4m AHD and *3* denotes the sub-cell with depths between around 4m and 10m. These sub-cells are labelled as the surfzone (*2*) and upper shoreface (*3*) in the analysis results presented in Section 4.2.2.
- 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 responding to longer-term, annual-decade-millennium time scale changes in wave climate and sea level. The lower shoreface was denoted by *LS*.

Changes in sand volumes relative to the 2018 survey were calculated for each cell and for all available surveys where survey extents allowed. All surveys were adjusted to be relative to AHD. The 1883 survey was conducted by Staff Commander Frederick Howard RN and comprised 7,090 lead line sounding reduced to Low Water Ordinary Spring (LWOS) and plotted with 1 foot accuracy. This survey was reconciled to AHD by adding 0.852m to all soundings following the procedure set out in Goodwin et al. (2013). An error or uncertainty analysis specific to the volume analysis reported herein has not been completed. Goodwin et al. (2013), who used the same 1883, 2002 and 2011 surveys reported volume uncertainties of between 20% and 120% and generally adopted ±20% for transport rates. To capture the uncertainty in the derived volumes from survey analysis this typical uncertainty range of ±20% for transport rates has been adopted herein.

[4] 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.

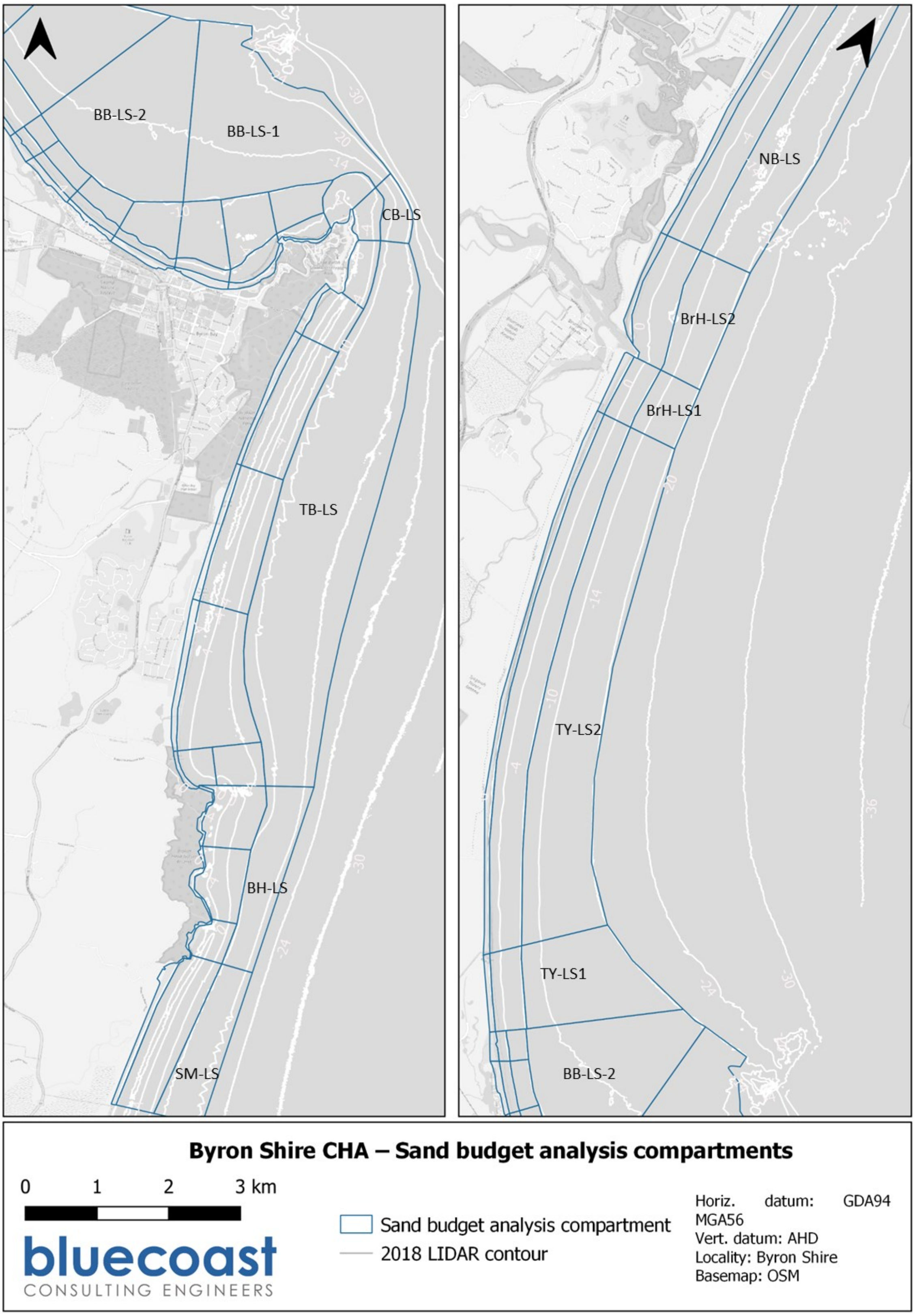

Figure 35: Sand budget analysis cell from Seven Mile Beach to Wooyung.

4.2.2 Analysis results

Table 10 provides a summary of the sand volume changes between the available surveys. As shown in Table 10, some zones were not surveyed, for example the 1883 survey was only completed within the extent of the southern and northern embayment (Little Wategos to Belongil Creek). The sand volume changes for all cells are provided in **Appendix A**. Example maps of the recent high resolution 2018 and 2011 surveys are shown in Figure 36 and Figure 37, respectively.

Changes in surveyed levels relative to 2018 for the selected 2022 (subaerial beach only), 2011, 2002 and 1883 surveys are shown from Figure 38 to Figure 42. A description of the observed changes is provided in Section 4.2.4 and Section 4.2.5. Recent (short term) changes linked to the headland bypassing event that occurred between 2018 and 2022 are described in Section 4.4.4.

Table 10: Summary of surveyed sand volume changes in Byron Bay region.

Zone (beach cell)	Volume (m^3) change relative to 2018 baseline			
	1883	2002	2011	2018
Seven Mile Beach (within Byron Shire LGA)				
Subaerial beach (crest of dune to 0m AHD)	-	-	75,000	0
Upper shoreface (0 to -12m AHD)	-	-	-440,000	0
Lower shoreface (-12 to -22m AHD)	-	-	-490,000	0
Sub-total	**-**	**-**	**-855,000**	**0**
Beaches of Broken Head Nature Reserve				
Subaerial beach (crest of dune to 0m AHD)	-	-	45,000	0
Upper shoreface (0 to -12m AHD)	-	-	-775,000	0
Lower shoreface (-12 to -22m AHD)	-	-	-640,000	0
Sub-total	**-**	**-**	**-1,370,000**	**0**
Tallow Beach				
Southern 4.2km				
Subaerial beach (crest of dune to 0m AHD)	-	-	205,000	0
Upper shoreface (0 to -12m AHD)	-	818,000	1,658,000	0
Northern 2.8km				
Subaerial beach (crest of dune to 0m AHD)	-	-	-10,000	0
Upper shoreface (0 to -12m AHD)	-	-788,000	-605,000	0
Full length 7km				
Lower shoreface (-12 to -22m AHD)	-	248,000	-1,970,000	0
Sub-total	**-**	**278,000**	**-722,000**	**0**
Cape Byron				
Subaerial beach (crest of dune to 0m AHD)	-	-	-	-
Upper shoreface (0 to -12m AHD)	-	-340,000	-980,000	0

Zone (beach cell)	Volume (m^3) change relative to 2018 baseline			
	1883	2002	2011	2018
Lower shoreface (to 22m water depth)	-	-90,000	-115,000	0
Sub-total	**-**	**-430,000**	**-1,095,000**	**0**
Southern embayment (Little Wategos to JSPW)				
Subaerial beach (crest of dune to 0m AHD)	65,000	-30,000	95,000	0
Surfzone (0m to -4m AHD)	290,000	80,000	470,000	0
Upper shoreface (-4 to -10m AHD)	1,285,000	-65,000	135,000	0
Lower shoreface (-10 to -15m AHD)	2,690,000	42,000	120,000	0
Sub-total	**4,330,000**	**27,000**	**820,000**	**0**
Northern embayment (JSPW to Belongil Creek)				
Subaerial beach (crest of dune to 0m AHD)	540,000	-	-200,000	0
Surfzone (0m to -4m AHD)	980,000	-345,000	-70,000	0
Upper shoreface (-4 to -10m AHD)	850,000	15,000	-110,000	0
Lower shoreface (-10 to -15m AHD)	1,350,000	100,000	75,000	0
Sub-total	**3,725,000**	**-230,000**	**-305,000**	**0**
Tyagarah Beach				
Subaerial beach (crest of dune to 0m AHD)	-	-	-480,000	0
Upper shoreface (0 to -10m AHD)	-	-	380,000	0
Lower shoreface (-10 to -20m AHD)	-	-	-1,830,000	0
Sub-total	**-**	**-**	**-1,930,000**	**0**
Brunswick Heads				
Subaerial beach (crest of dune to 0m AHD)	-	-	-12,000	0
Upper shoreface (0 to -10m AHD)	-	-	11,000	0
Lower shoreface (-10 to -20m AHD)	-	-	-260,000	0
Sub-total	-	-	**-261,000**	0
New Brighton Beach				
Subaerial beach (crest of dune to 0m AHD)	-	-	6,000	0
Upper shoreface (0 to -10m AHD)	-	-	580,000	0
Lower shoreface (-10 to -20m AHD)	-	-	80,000	0
Sub-total	**-**	**-**	**666,000**	**0**

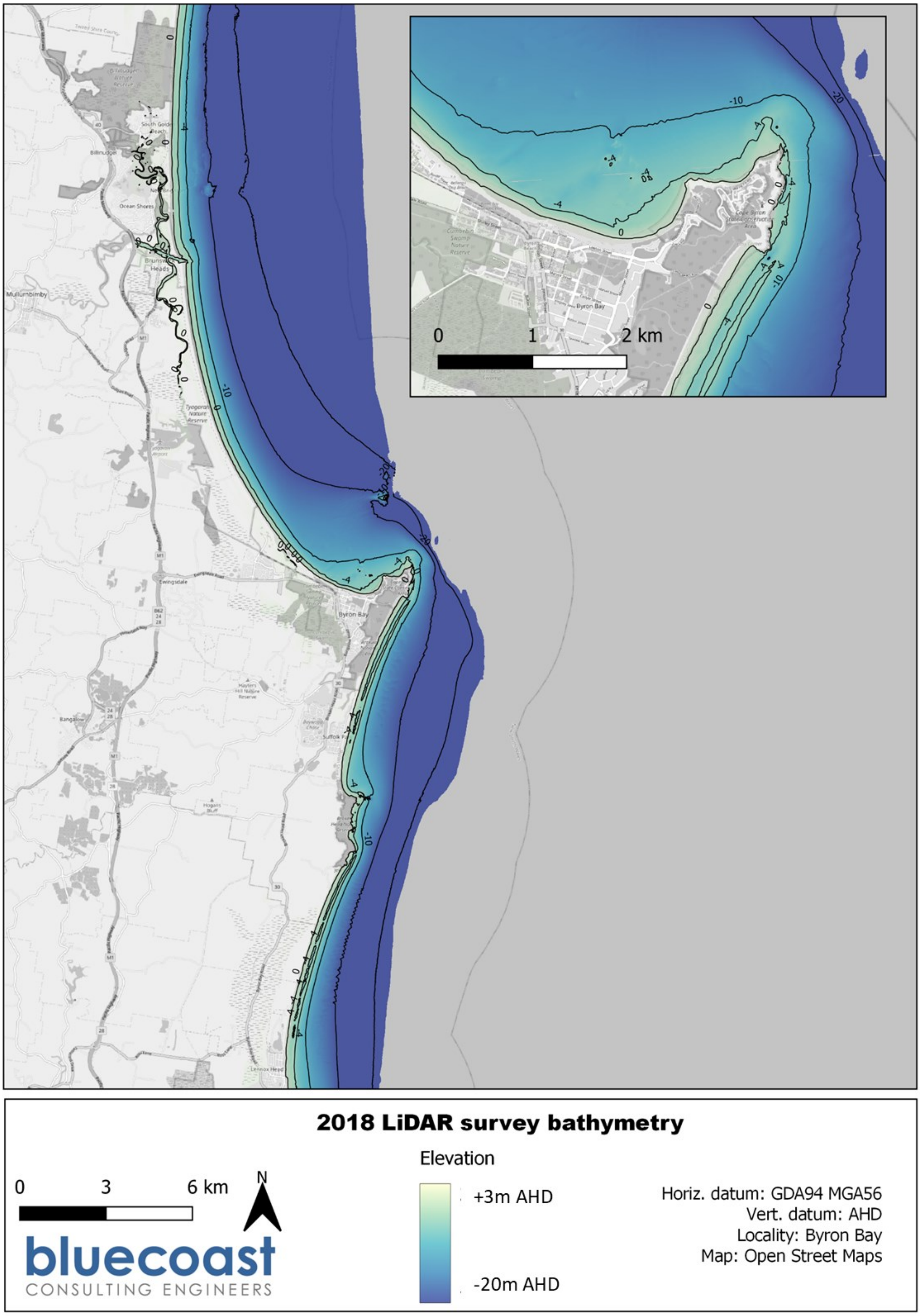

Figure 36: 2018 bathymetric and topographic LiDAR survey.

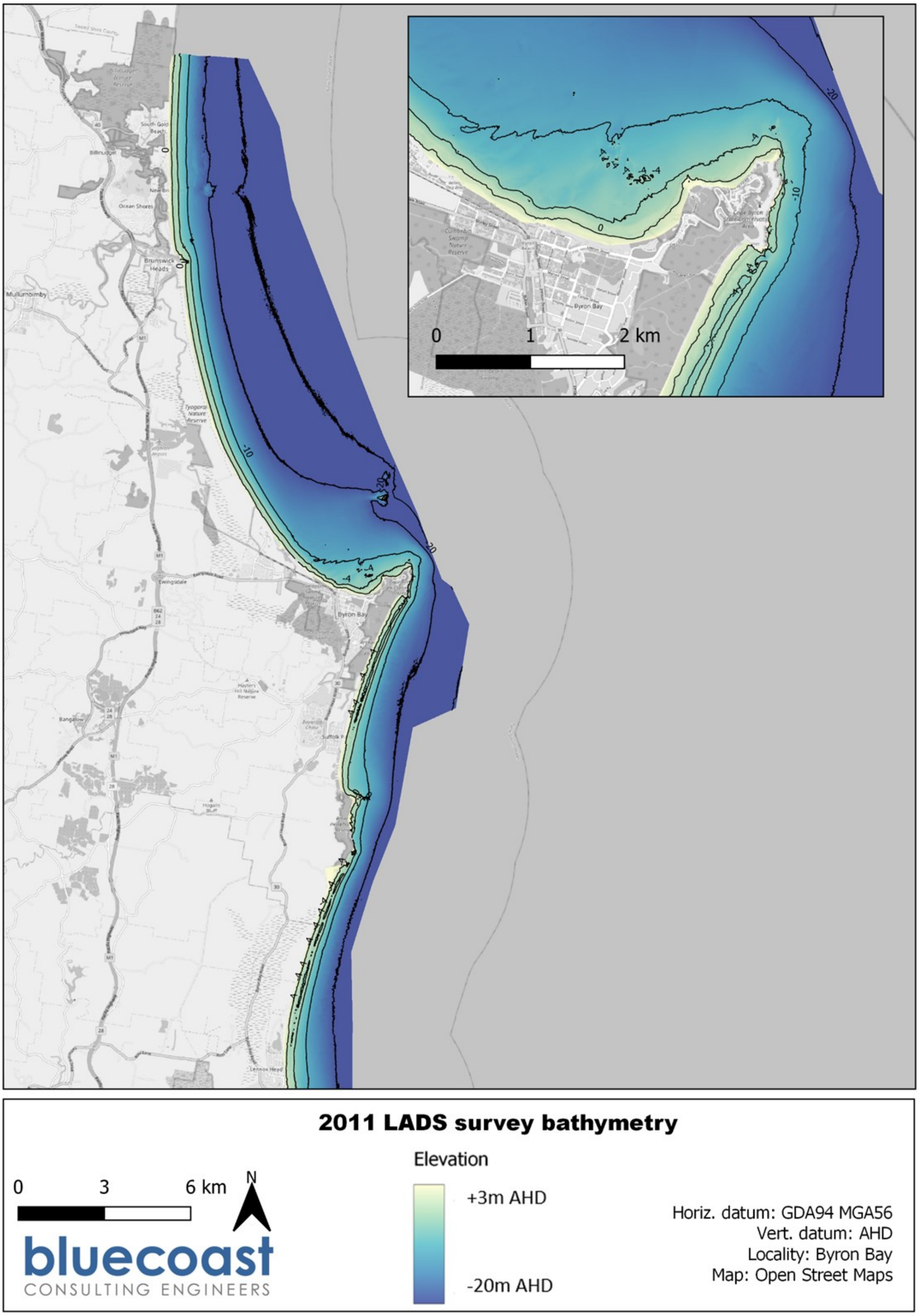

Figure 37: 2011 bathymetric and topographic LiDAR survey.

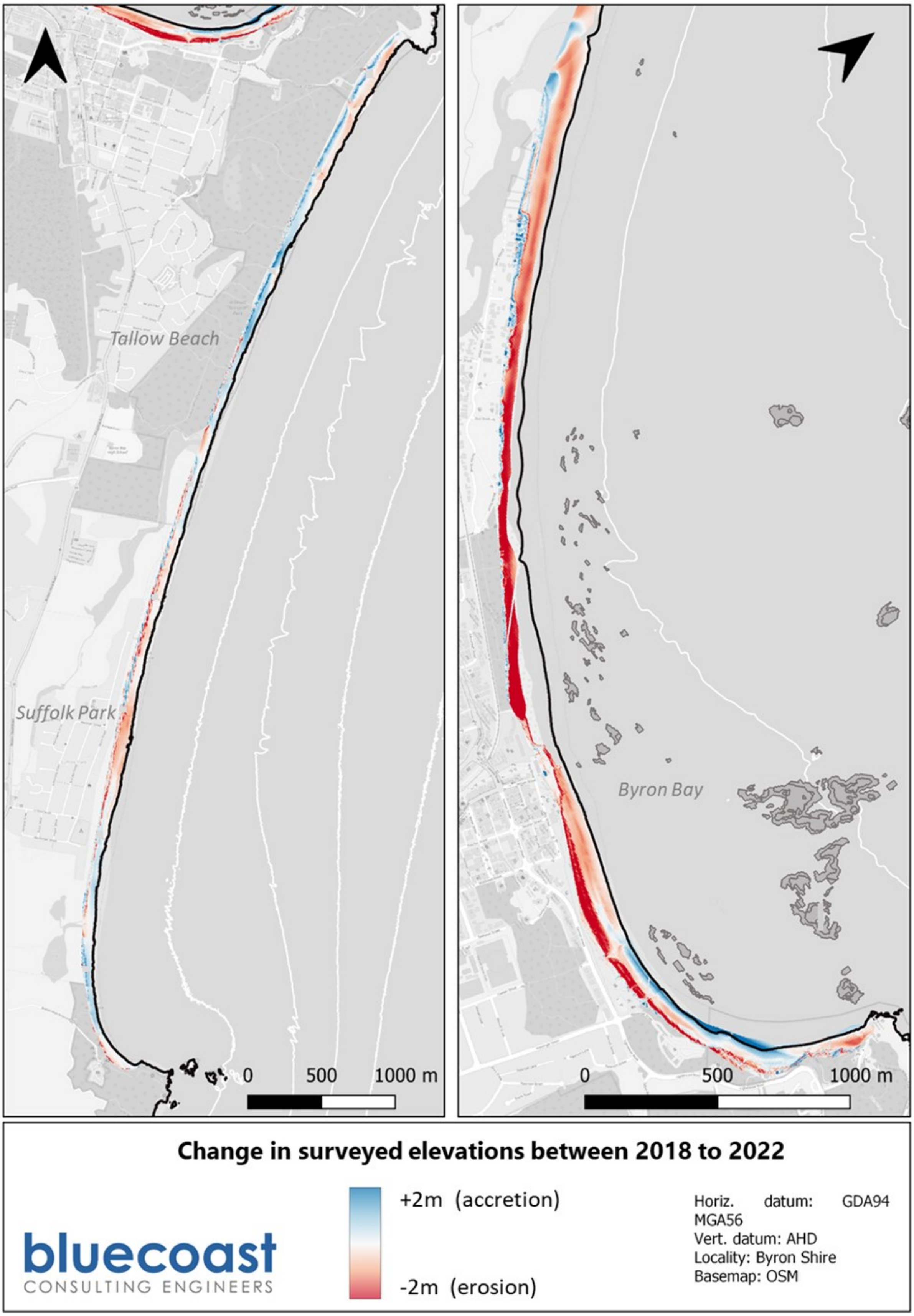

Figure 38: Map of surveyed elevation difference between 2018 and 2022 (red colours show erosion).

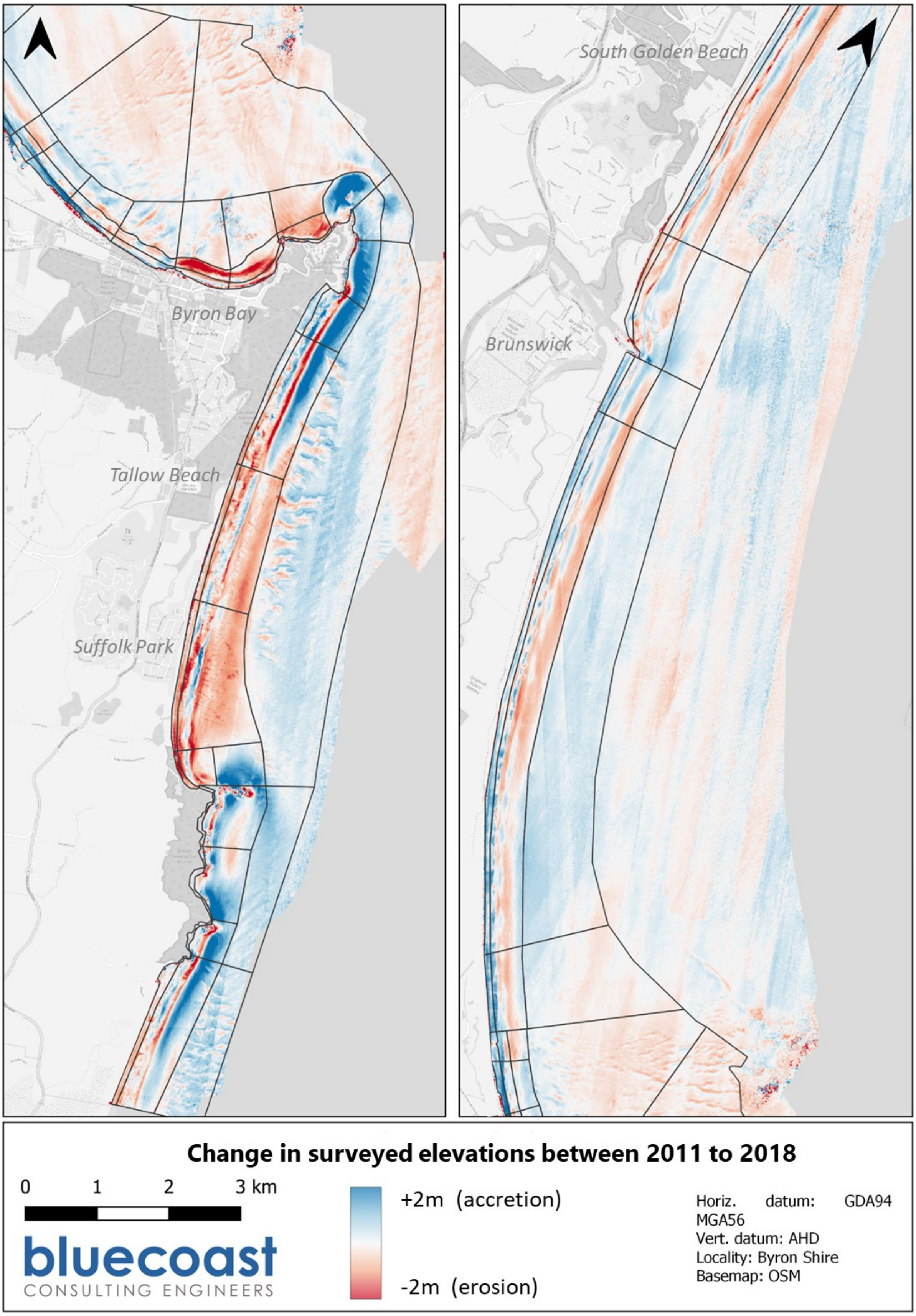

Figure 39: Map of surveyed elevation difference between 2018 and 2011 (red colours show erosion).

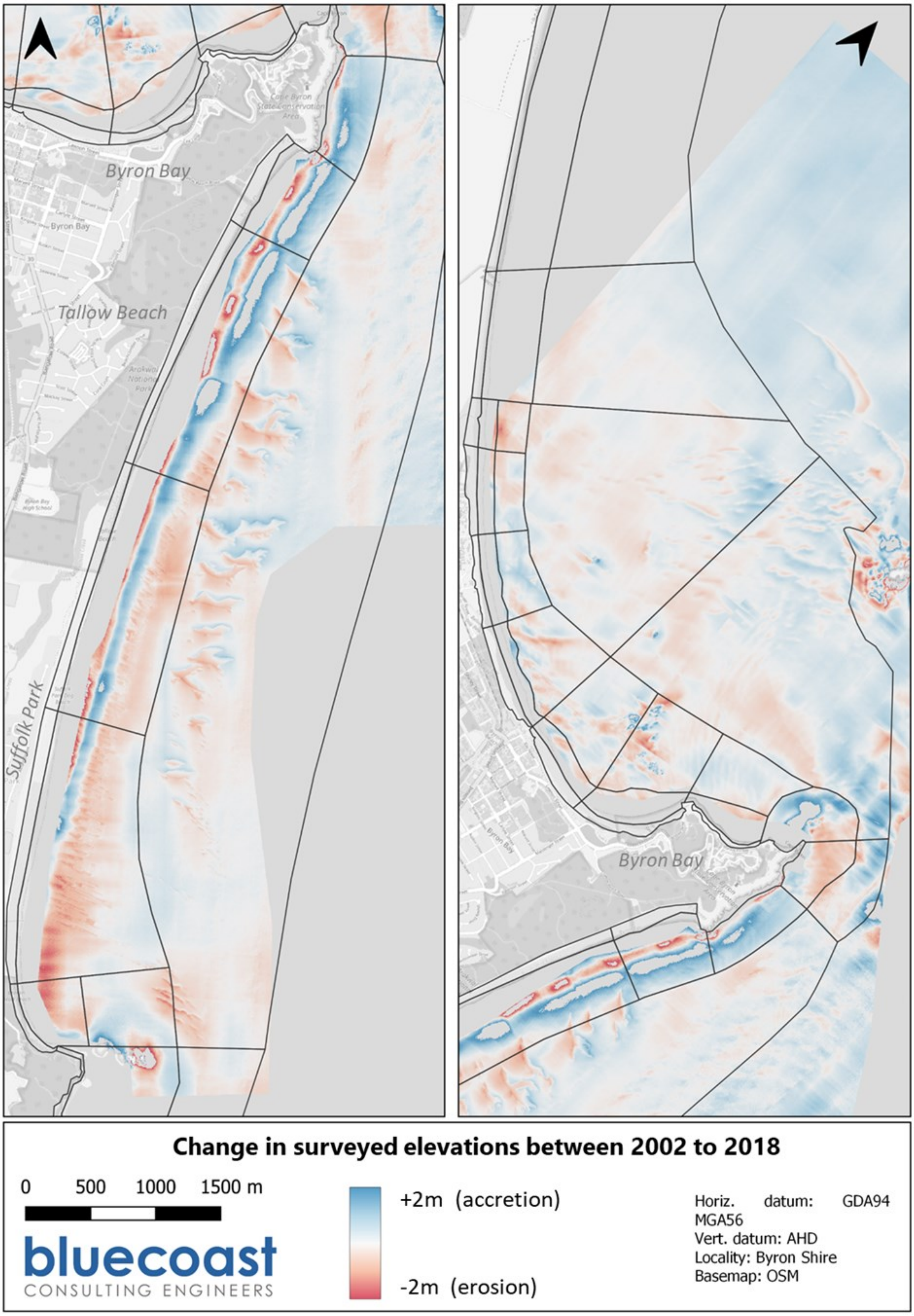

Figure 40: Map of surveyed elevation difference between 2018 and 2002 (red colours show erosion).

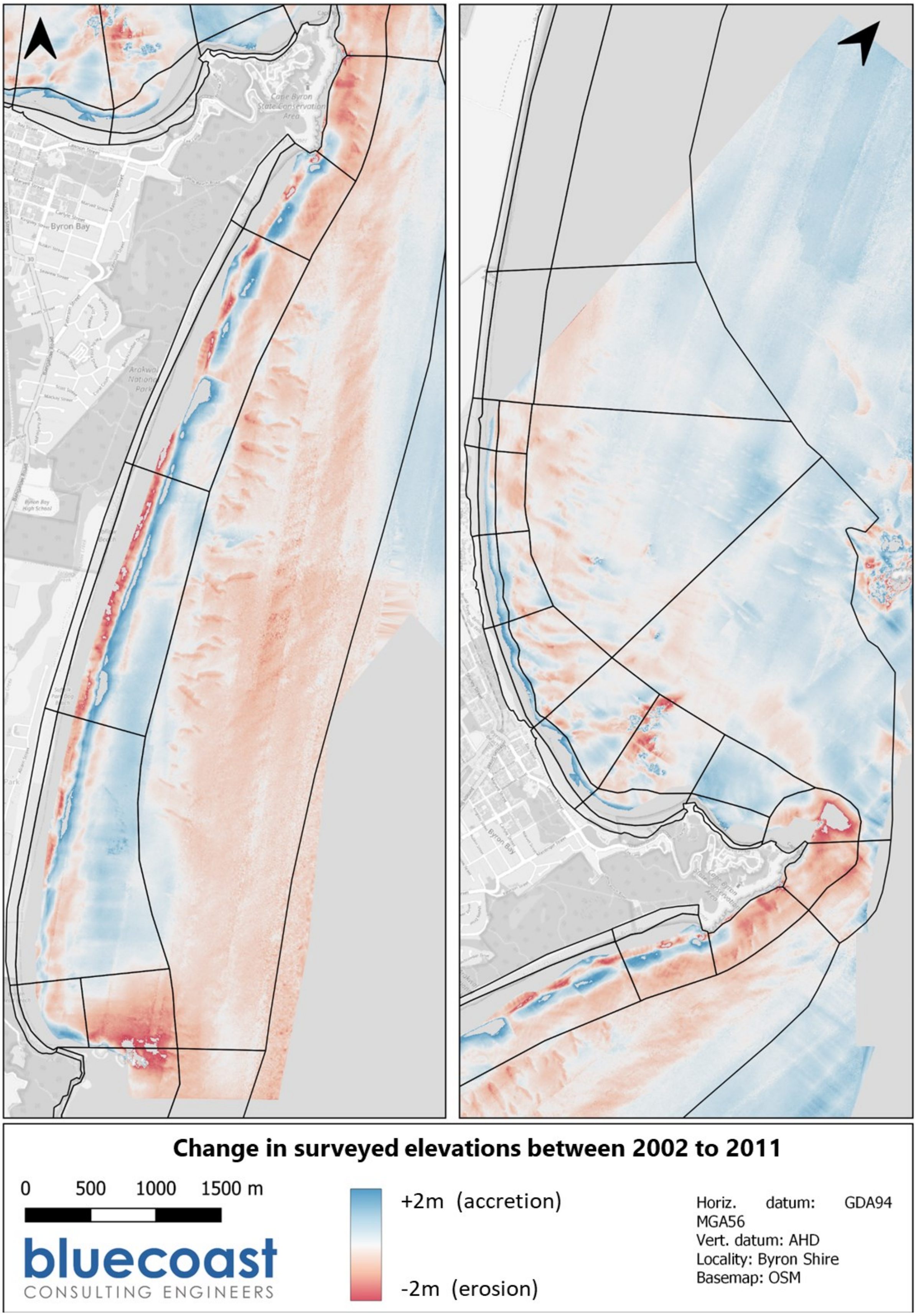

Figure 41: Map of surveyed elevation difference between 2002 and 2011 (red colours show erosion).

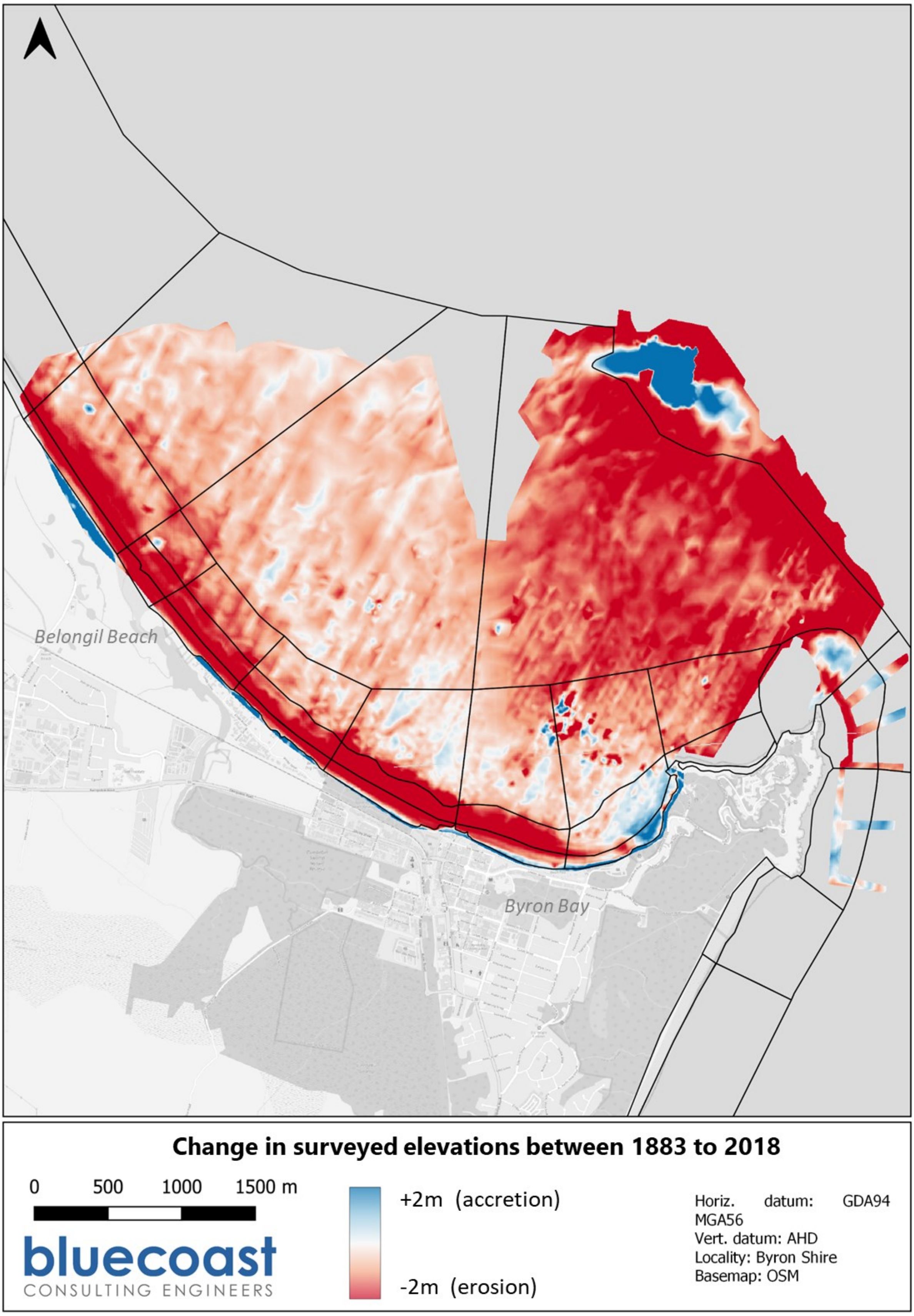

Figure 42: Map of surveyed elevation difference between 2018 and 1883 (red colours show erosion).

4.2.3 Time scales for change

The beaches along the Byron Shire coast experience change over various time scales. This is illustrated in Figure 43 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. 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. Key outcomes are described below for long term and medium-term observations.

Figure 43 and Figure 45 show the four surveys against time histories of the Interdecadal Pacific Oscillation (IPO) and Southern Oscillation Index (SOI used to track ENSO):

- 1883 survey was captured in a neutral SOI year within a multidecadal IPO La Niña like phase
- 2002 survey was captured in a neutral SOI year while the 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

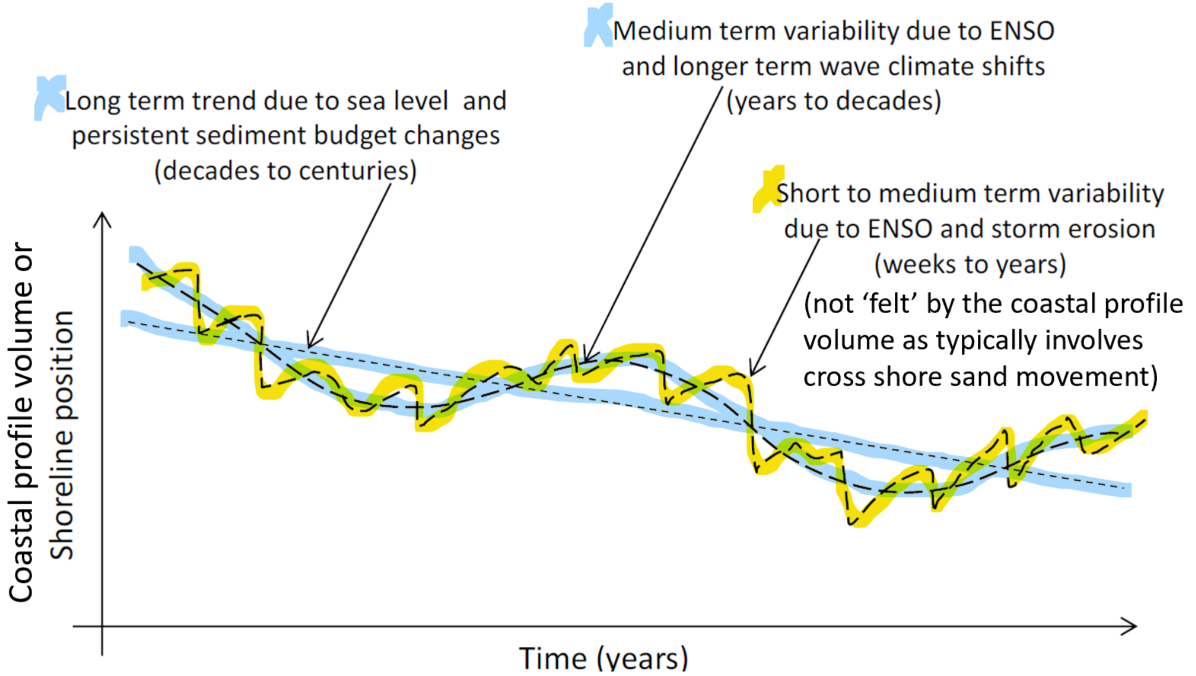

Figure 43: Conceptual illustration of time scales for beach changes (adapted from BMT BWM, 2013).

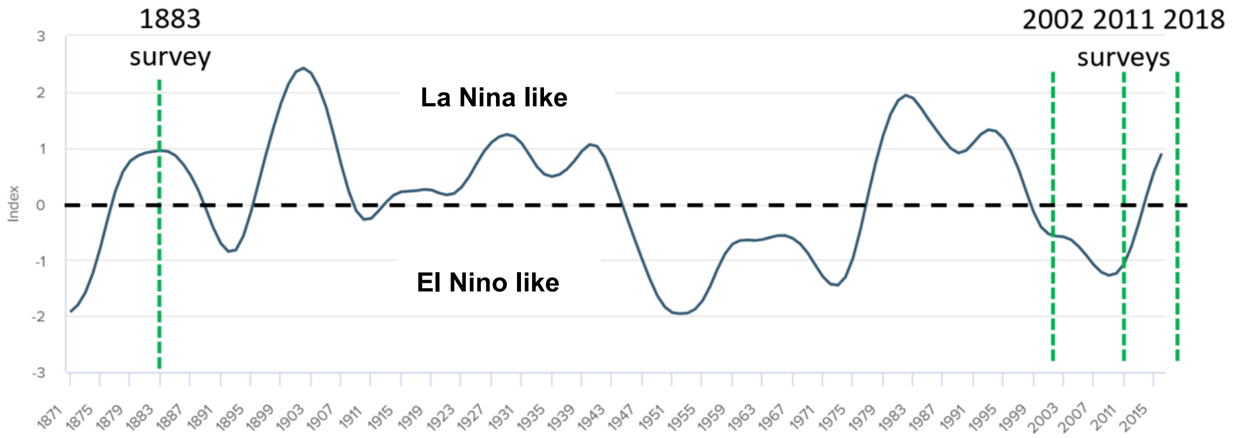

Figure 44: Annual average Interdecadal Pacific Oscillation index, 1871 to 2016 (adapted from Met Office).

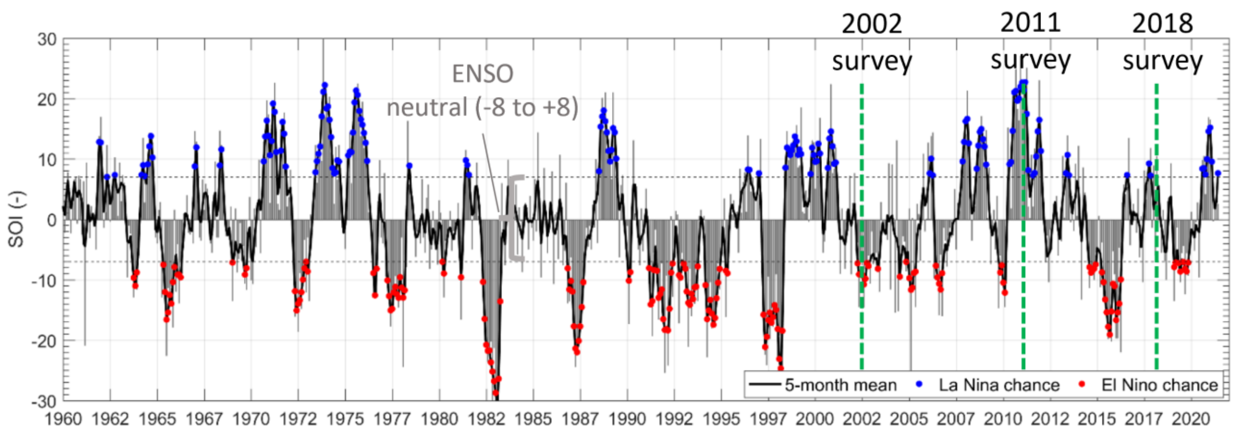

Figure 45: Monthly and annual Southern Oscillation Index (ENSO), 1960 to 2021.

4.2.4 Long term change

The historical 1883 survey has extents that allow observations of long-term change in the Byron embayment but not in other areas.

Over the 127 years from 1883 to 2018 a **net loss of sand at an approximate rate of 62,000m^3/yr** ±20% was observed from the Byron embayment (Wategos Beach to Belongil Creek). This sand loss rate considers the coastal profile (from the top of the dune to -15m AHD) and is calculated using the volume changes between the 1883 survey and average of the 2002, 2011 and 2018 surveys using a 127-year period (i.e., around 8 million cubic metres in total surveyed sand volume change over).

A long-term net loss of sand from the embayment agrees with the previous studies. The reported magnitudes of the loss rates are:

- PWD (1978) estimated an embayment sand loss rate of 65,000m^3/yr based on gradients in their calculated longshore transport rates (i.e., 15,000m^3/yr into the embayment by headland bypassing and 80,000m^3/yr out to the north as longshore transport). The PWD (1978) estimates did not specifically consider the sand losses from the lower shoreface.
- BMT WBM (2013) used photogrammetry data (i.e., subaerial beach above 0m AHD) to estimate an embayment sand loss rate of approximately 50,000m^3/yr. A factor of 2.2 was assumed to extend subaerial volume changes to cover the full coastal profile. Calculating a coastal profile volume change by multiplying subaerial beach volume changes by a factor is difficult because of

the variability in this ratio (subaerial beach : subaqueous beach). Based on profiles from the Byron embayment the observed average factor would be 4.3 times the subaerial beach volume (this does not include the lower shoreface).

- Goodwin (2013) used a similar survey analysis method as reported herein and obtained a long-term sand loss rate of 30,000m^3/y from the embayment. Despite the similar methods employed the difference in the magnitude is likely due to (i) different analysis extents (Goodwin did not include the subaerial beach in the 1883 survey and had slightly different longshore extents) and (ii) Goodwin excluded any seabed changes less than or equal to the vertical survey uncertainty.

About half (49%) of the embayment's long-term sand loss has occurred from the lower shoreface (between 10 - 15m water depth). There are significant further sand losses that appear below -15m AHD. Considering the area between the 15m and 20m depth contours a further 4.9Mm^3 of sand loss is observed since 1883, or an additional 39,000m^3/yr (see volume changes **Appendix A**). These volumes are not considered in the loss rate of 62,000m^3/yr.

Most of this lower shoreface sand loss comes from the southern part of the embayment (BB-LS-1). In the 1883 survey this area was shallower than in contemporary surveys. It is reasoned that in the 1883 era the lower shoreface of the Byron embayment was more generously supplied with littoral sand bypassing the Cape under SOI neutral wave direction and significantly higher mean wave heights (Goodwin, 2013). Since 1883, reduced supply and a continuation of the slow onshore migration of sand across the embayment has seen this area deepen by an average of 1.5m. A further 1.3Mm^3 (or 16%) of the sand lost from the embayment's lower shoreface has occurred from the northern area (BB-LS-2).

Table 11 presents annualised sand loss rates from various zones in the Byron embayment. It is reasoned that the losses from the lower shoreface, particularly in the southern embayment, have been supplying the embayment's upper shoreface, beach face and longshore sand transport. It is therefore difficult to relate the sand loss rates to observed shoreline recession rates. The shoreline change and embayment sand loss comparisons are also influenced by the JSPW and other coastal structures along Belongil Beach. However, it is noted in the most recent analysis, shoreline recession is present along the northern embayment (see Section 5 and **Appendix B**).

The sand loss rate from the upper profile (above -10m AHD) is 31,500m^3/yr ±20%, which is about half the long-term sand loss occurring above -15m AHD.

Table 11: Annual sand loss rates from various zones in the Byron embayment.

Profile zone	Annualised sand loss rates (1883 to contemporary) [m^3/yr]	
	Southern embayment (% of sand loss rate)	Northern embayment (% of sand loss rate)
Upper profile, above 10m (beach, surfzone and lower surfzone)	11,000 (18%*)	20,500 (33%*)
Lower shoreface (10m to 15m)	20,500 (33%*)	10,000 (16%*)

* The percentage contribution from each zone is calculated as the proportion of the embayment's total sand loss rate or 62,500m^3/yr ±20%.

4.2.5 Medium term change over contemporary period (2002 to 2018)

Survey coverage permitting, this section describes medium term coastal change over the contemporary period from 2002 to 2018. The 2011 and 2018 surveys extend across the entire study area and allow Shire-wide observations of coastal change. The 2002 survey covers Tallow Beach and the Byron embayment. The 2002 survey only extends inshore to around 2-4m water depth, so it does not cover the full surfzone or the beach. Further analysis of recent observations since 2018 are discussed in Section 4.4.4.

Figure 34 in Section 3.9 provides a timeseries showing the monthly mean wave energy (and extreme events with wave heights greater than 5m), annual mean wave direction and SOI (i.e., ENSO) conditions encountered over this period.

Northern Seven Mile Beach and Broken Head Nature Reserve

Comparing the 2011 and 2018 surveys, the 2018 survey shows a higher profile and more sand in this area. Collectively these areas are part of the headland bypassing pathway for Broken Head. When viewed across the bypassing pathway the surveys show:

- Subaerial beaches: there was 170,000m^3 less sand in 2018 than in 2011 with a 0.74m lower beach on average.
- Upper shoreface: there was 1,455,000m^3 more sand in 2018 than in 2011 with a 0.55m higher profile on average.
- Lower shoreface: there was 1,130,000m^3 more sand in 2018 than in 2011 with a 0.55m higher profile on average.

Overall, there was 2.4Mm^3 of extra sand in this sand bypassing pathway in 2018 than in 2011.

Tallow Beach

Comparing the 2011 and 2018 surveys, Tallow Beach shows a distinct pattern of erosion in the south and accretion in north. Across the subaerial beach and upper shoreface:

- Southern beach: there was 1.85Mm^3 less sand in 2018 compared to 2011, with a profile that was on average 0.56m lower.
- Northern beach: there was 0.60Mm^3 more sand in 2018 compared to 2011, with a profile that was on average 0.35m higher.

Between 2011 and 2018 the lower shoreface along the Tallow's embayment accreted on average by 0.23m, adding almost 2Mm^3 of sand to this deeper zone. Like the below comments regarding the lower shoreface changes at Tyagarah Beach, survey error means the sand volume change has greater uncertainty.

Byron embayment

Between 2002 and 2018, the observed amount of sand within the upper shoreface and subaerial beach of the Byron embayment shows considerable variation (see Figure 46). Sand volume changes were most pronounced in the southern embayment's upper profile (i.e., between upper shoreface and subaerial beach), for example in 2018:

- the southern embayment contained similar amounts of sand than in 2002 (slightly more - around 13,500m^3 when the beach face volume missing from the 2002 survey extents is estimated from photogrammetry)
- the southern embayment contained approximately 700,000m^3 less sand than in 2011 (average elevation 0.55m lower).

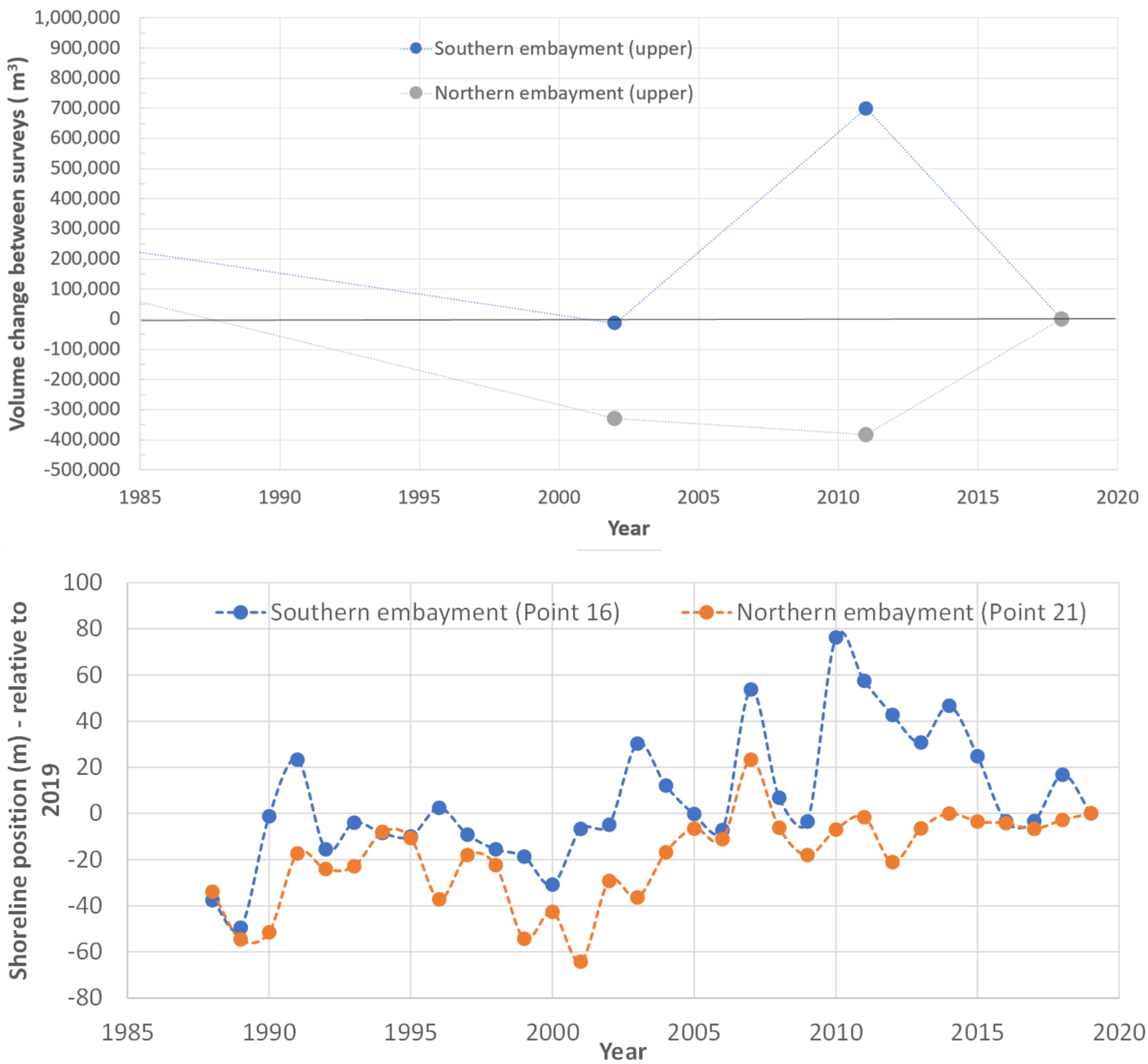

Figure 46: Contemporary Byron embayment sand volumes (top) and relative shoreline positions (bottom).

The surveys represent snapshots in time, and indicate that the amount of sand stored in the southern embayment's upper profile (above the 10m depth contour) can vary by at least 0.7Mm^3. As discussed below, this is a result of the high variability in the headland bypassing supply.

Between 2002 and 2018, the northern Byron embayment experienced smaller changes in sand volume:

- The upper profiles (i.e., between upper shoreface and subaerial beach) in 2018 had higher sand volumes compared to 2002 and 2011, these were 325,000m^3 and 375,000m^3 respectively (0.20m and 0.35m higher average elevation)
- In 2018 there was 305,000m^3 less sand volume in the lower shoreface than in 2011.

As shown in Figure 46, the subaerial beach and upper shoreface sand volumes along the northern embayment are less variable (relative to the southern embayment), ranging by up to 400,000m^3 across the contemporary surveys. This lower observed variability demonstrates the reduced impact of the variable Cape bypassing on the northern embayment. This is reasoned to be due to the ability of the southern embayment to provide a more consistent supply of sand to this northern zone (i.e., the southern embayment acts to buffer the northern parts of the embayment from the variable Cape bypassing supply).

This effect can be further inferred by the increase in sand volume in the northern embayment between 2011 and 2018 with a corresponding decrease in the sand volume over the same period in the southern embayment. Longshore transport rates out of the southern embayment are higher when the compartment is full of sand, with sand covering the various nearshore reefs and the shoreline is accreted (see Figure 39) allowing uninterrupted bypassing of the JSPW. The effect of the JSPW on longshore sand transport during lower embayment sand volumes is further discussed in Section 4.4.8.

Despite the considerable variation the contemporary sand volume changes show a stabilisation or volume increase in the case of the northern embayment.

Tyagarah Beach

The survey coverage of Tyagarah Beach, to the north of the Byron embayment, is limited to 2011 and 2018. Comparing these surveys, the following observations are made:

- The subaerial beach had some 480,000m^3 additional sand in 2018 than in 2011, raising the average elevation by 0.75m. The upper shoreface had some 380,000m^3 <u>less</u> sand than in 2011. Given the magnitude of these volumes are similar it is likely that these are reflective of short term cross shore movement of sand (i.e. surveys are snapshots of different beach conditions). When the active profile (i.e., subaerial beach and upper shoreface) is considered there was little sand volume change along Tyagarah Beach between 2011 and 2018.
- Lower shoreface (-10 to -20m AHD): in 2018 there was 1,830,000m^3 <u>more</u> sand than in 2011. The average elevation change was only 0.27m but large area of these analysis cells results in a significant volume change. Small relative survey errors at these deeper depths, rather than sand movement, may also explain the volume difference.

Brunswick Heads

Comparing 2011 and 2018 surveys there is a minimal difference in sand volume on the upper shoreface. Whereas on the lower shoreface there was 260,000m^3 more sand in 2018 than in 2011.

New Brighton Beach

At New Brighton Beach, there was no significant change in subaerial beach volumes but there was a notable difference on the shoreface (upper and lower), see Figure 47. Inshore of the reef system there was a notable lowering (up to 1.6m but more typically 0.5 to 0.8m) of the seabed between -4m and the inshore edge of the reef (around -12m). The net volume eroded from the shoreface since 2011 was around 640,000m^3. It is further noted that the surveyed level over the rocky reef were almost identical, promoting confidence in the survey accuracy at these depths.

The lowering of the shoreface between 2011 and 2018 along this section contrasts accretionary observations from the lower shoreface of Seven Mile Beach, Tallow Beach and neighbouring Tyagarah Beach. This may be related to onshore supply (from areas deeper than -20m/-22m) having been significant over this period but at New Brighton the reef system restricted this onshore supply pathway, resulting in the inshore lowering of the shoreface. Alternatively, it may be related to storm cross-shore responses in the upper profile being influenced by the presence of the reef system (i.e., sand moving offshore prior to the 2011 survey was interrupted). Additional high accuracy and resolution surveys in the future would enable greater insight.

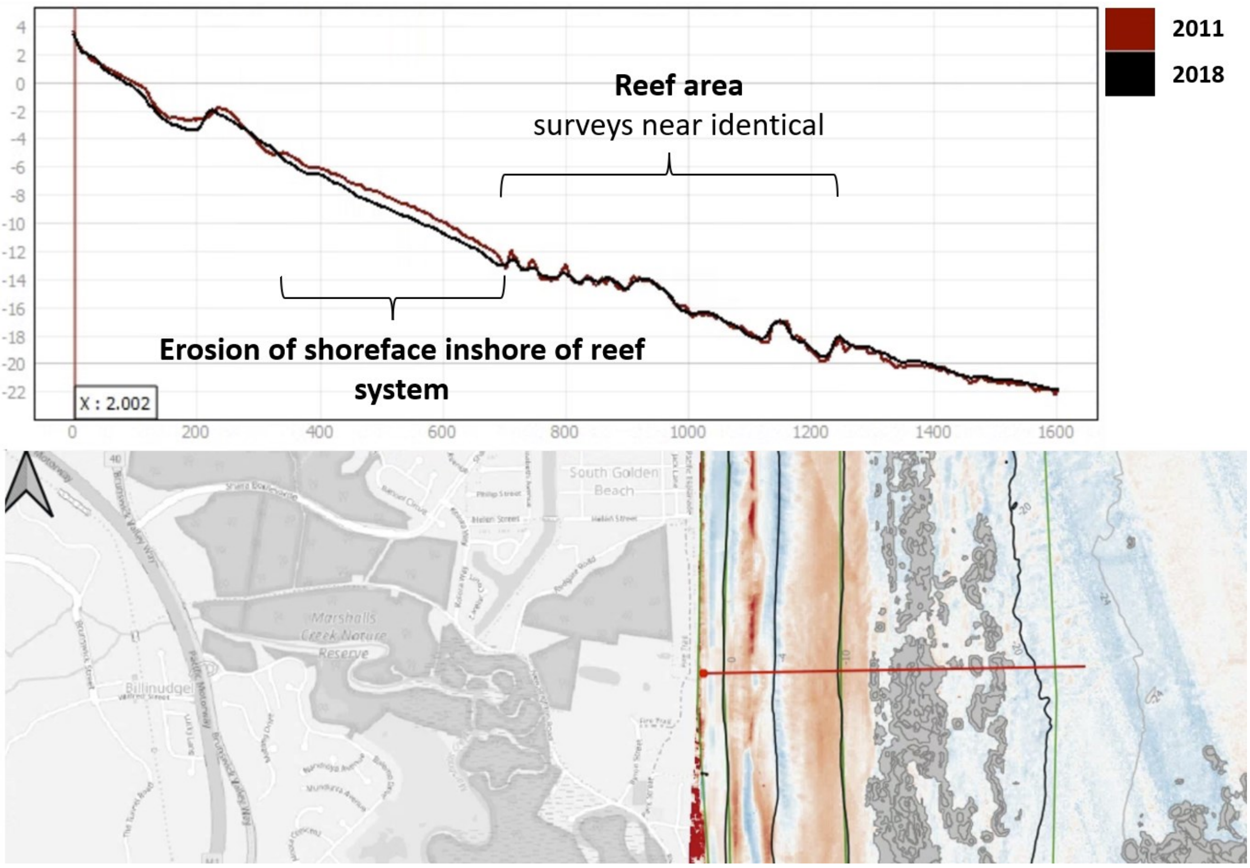

Figure 47: 2011 and 2018 coastal profile (top) and morphology pattern of change along New Brighton Beach inshore of the reef system.

4.3 Quantified conceptual sand movement model

Figure 48 provides a graphical overview of the quantified conceptual model of sand movements (quantified model) across the study area and then focused on the Byron embayment, respectively. This quantified model is based on the regional sand budget and the assessment of each of the sand movement pathways, sources and sinks presented below in Section 4.4.

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:

- **Geology and modern geomorphic structure:** The geology of the Byron region has a significant impact on the movement and accumulation of sand in the coastal zone. The study area is characterised by drift-aligned, long sandy coastal barriers which were shaped as post-glacial sea level rise migrated marine sand onshore from the continental shelf before reaching present-day sea levels approximately 6,500 years ago, followed by ongoing longshore sand transport. Today, the geology of the Byron Shire coast comprises a series of bedrock embayments filled with late Quaternary marine sand and other estuarine and fluvial sediments. The headlands at Cape Byron and Broken Head are significant features, as is the natural rocky outcrops at Brunswick Heads. As the geology and modern geomorphic structure has already been described in Section 3, it will not be discussed further below. However, details of the geomorphic structure of the Byron embayment, including bedrock and coffee rock reefs and outcrops which influence wave propagation, sand movements, shoreline dynamics and surfzone morphology are discussed.

- Rate of **net longshore sand transport** (LST) and gradients in longshore transport rates.
- Variable embayment sand supply via **headland bypassing** around Cape Byron and its effect of the quantities of sand in the southern embayment (from Little Wategos Beach to Main Beach) and the embayment's shorelines. Likewise for Broken Head and Broken Head Beach.
- **Sand movement pathways within the embayment** including the proportion that moves via the littoral pathway and the proportion that follows the cross-embayment pathway.
- 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.

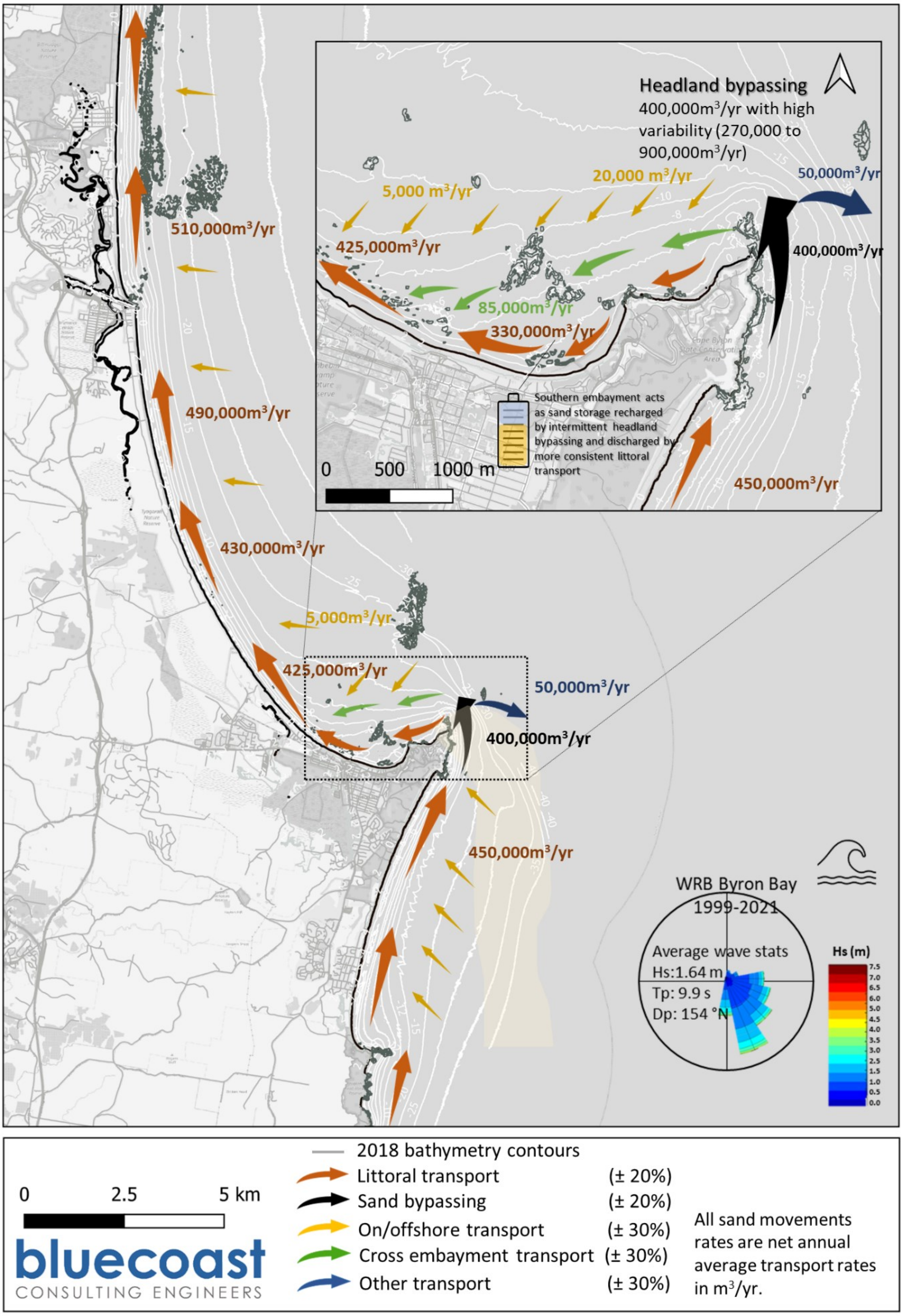

Figure 48: Quantified conceptual model of sand movements through Byron Shire.

4.4 Sand sources, sinks and pathways

4.4.1 Net longshore sand transport

Driven by wave action, longshore sand transport (LST) occurs predominately in the mid- to outer surfzone (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 Byron 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 (BMT WBM, 2013). 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's 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/year at the Clarence River to about 550,000m^3/year 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/year (±20%).
- 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/year 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 location 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 12. Of key interest to this study is the rate of LST bypassing Cape Byron, which is highlighted above.

Table 12: Adopted annual net longshore sand transport rates.

Location	Annual net longshore sand transport rate (m^3/yr)	Uncertainty (%)	Degree of annual variability
Clarence River (south of study area)	150,000[1]	±30%	Moderate
Tallow Beach (north)	450,000[1]	±20%	Moderate
Cape Byron (headland bypassing)	400,000[4]	±20%	Extremely high
Wategos Beach [WB]	400,000[2]	±20%	Very high

Location	Annual net longshore sand transport rate (m^3/yr)	Uncertainty (%)	Degree of annual variability
Clarkes Beach [CB]	405,000[2]	±20%	High
Main Beach [MB]	415,000[2]	±20%	High
Belongil Beach (1) [BB-1 & BB-2]	420,000[2]	±20%	Moderate
Belongil Beach (2) [BB-3 & BB-4]	425,000[3]	±20%	Moderate
Tyagarah Beach (south)	430,000[3]	±20%	Moderate
Brunswick Heads	490,000[3]	±20%	Moderate
New Brighton Beach	510,000[3]	±20%	Moderate
Tweed River sand pumping jetty (north of study area)	560,000[1]	±25%	Moderate

Note:

1. Derived from literature, BMT WBM (2013), Patterson (2013), Goodwin et al. (2013), Bluecoast (2022) and PWD (1978).
2. Capture littoral pathway and cross-embayment pathway as derived from the contemporary sand budget analysis.
3. Derived from long term sand budget analysis.
4. As discussed in Section 4.4.4.

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 areas coast and headland bypassing around Cape Byron (da Silva, 2021a). The alignment of the beach, is therefore important when considering LST rates and how ENSO effects these. For example, along Tallow Beach high rates of LST would be expected in El Niño events being driven by a more southern wave climate. Whereas in the southern embayment 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 expected 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 Tallow Beach but could increase potential net northerly LST rates in the southern embayment.

4.4.2 Onshore sand movement

In depths of 20 to 50m a convex up coastal profile is observed offshore of Tallow Beach and Seven Mile Beach. This is due to the presence of the Cape Byron – Ballina Shelf Sand Body (SSB). This extensive lower shoreface sand body is reasoned to promote onshore supply of sand to the Broken Head to Cape

Byron beach compartment offering a stabilising effect to the shoreline and could moderate future shoreline response to sea level rise (Ribo et al., 2020).

The sand volume of the mid-Holocene SSB off Tallow Beach and Seven Mile Beach was estimated to be around 1,650Mm^3, with a maximum sand thickness of more than 30m (Ribo et al., 2020). Kinsela et al. (2016) estimated that present-day onshore sand supply from SSBs along some southeast Australian beaches could be in the order of 1-2m^3/m/year. This range of onshore sand supply correlates well with the historic accretion observed along the Broken Head to Cape Byron beach compartment. That is, onshore sand supply from the lower shoreface can result in beach accretion but may also supply sand to the longshore sand transport system. Uncertainty remains if the present rates of onshore sand supply from the lower shoreface will change with sea level rise over the next century.

4.4.3 Headland bypassing, embayment sand volumes and shoreline behaviour

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 Byron 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 (i.e., townships of Byron Bay and Broken Head).

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.

Cape Byron is the most easterly point on mainland Australia and the most prominent headland in the two adjacent sediment compartments. The Cape has a significant influence on net northward littoral sand movements. Sand moving around Cape Byron, a process referred to headland bypassing, influences the supply of sand to the embayment as well as the way sand moves through the embayment.

Recent insights into headland bypassing in the local context are provided by the work of Silva et al. (2021a) who undertook a detailed assessment of sand movements around Fingal Head. Fingal Head is 50 kilometres to the north of Cape Byron and within the ‘Tweed’ sediment compartment. 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 Byron embayment is controlled by variations in the offshore wave climate which results in intermittent headland bypassing of pulses of sand around Cape Byron. Cape Byron is a more prominent headland in comparison to Fingal Head, and while the sand leakage process/pathway may also occur here the sandbar-driven process observed by Silva et al. (2021a) can be observed at Cape Byron.

This is best demonstrated by comparing two recent high resolutions surveys:

- 2011 LiDAR survey (see Figure 37) conducted over Byron Bay region in June and July of 2011. The 2011 survey was conducted during an extreme La Niña year.

- 2018 LiDAR survey (see Figure 36) which captured the entire NSW coastline (Byron region was around July and August 2018), an ENSO neutral year. The survey was captured around 6 months before the passage of Tropical Cyclone Oma.
- The 2002 single beam hydrographic survey (no very shallow water or subaerial beach) was captured under similar wave climate conditions to the 2018 survey.

The difference between these two surveys is shown in Figure 39. The morphology captured in the 2018 survey shows a post-storm or wave energy condition. A prominent storm bar is observed along the northern end of Tallow Beach which extends north around Cape Byron. A large sand deposit is observed off Little Wategos Beach having bypassed Cape Byron. In 2011, the outer bar at Tallow Beach is much less pronounced and there is less sand on the shoreface along Cape Byron.

Headland bypassing is highly variable with the annual range of sand supply around the Cape estimated to be from around 150,000 to over 900,000m^3/year. Table 13 provides a summary of the sand volume changes, relative to 2011, around Cape Byron and northern Tallow Beach. These areas, as noted in Table 13, define the headland bypassing pathway around the Cape (see Figure 39). Relative to 2011, the 2002 and 2018 surveys captured 684,000 to 1.38Mm^3 more sand along this bypassing pathway. While it is unlikely the surveys captured the exact start and end of such bypassing events, this provides insight into the volume of the sand pulses that bypass the Cape.

When headland bypassing sand pulses arrive in the embayment following periods of low sand supply, exacerbated erosion is typically observed preceding the migrating sand wave. In addition to the already low embayment sand levels during such periods, this erosion is linked to a rip caused by the water trapped in lee of the spit (or sand wave) which flows along the beach and exits at the end of the spit. In doing so it erodes the beach. As the sand wave migrates along the beach the erosion precedes the sand wave until a point is reached where the sand wave merges with the beach, the beach widens and normal beach processes and longshore sand transport takes place.

Large scale climatic variability linked to ENSO, PDO and IPO has been shown to result in interannual to decadal differences to the frequency and magnitude of headland bypassing. Most pronounced, extended periods of La Niña dominance (several years) would be expected to result in upper beach erosion at Tallow Beach, reducing the sand availability for sand bypassing around Cape Byron. At the same time, high energy wave events during extreme La Niña periods also arrive from a more easterly wave direction, reducing/increasing the northward longshore transport potential due a reduced wave obliqueness in respect to the coastline orientation and exposure. Conversely, extended El Niño dominance results in the opposite effect.

While a reduction in headland bypassing may be triggered by a La Niña event, or series of events, the erosive effect on the embayment's shorelines may not be apparent for two to five years' time. Similarly, it takes time for sand pulses in a large bypassing event to move into the embayment and supply the beaches (e.g., Clarkes Beach and Main Beach and later still Belongil Beach) with sand.

Table 13: Sand volume changes along the Cape Byron sand bypassing pathway.

Alongshore area	Surfzone cell	Sand volume change (m^3)		
		2002 relative to 2011	2011	2018 relative to 2011
Northern Tallow Beach surfzone	TB-5-2	48,000	0	404,000
Cape Byron surfzone	CaB-1	223,000	0	414,000

Alongshore area	Surfzone cell	Sand volume change (m^3)		
		2002 relative to 2011	2011	2018 relative to 2011
	CaB-2	175,000	0	114,000
	CB-BYPASS	238,000	0	452,000
Total bypassing pulse potential volume (m^3)		**684,000**	na	**1,382,000**

In both the 2018 and 2002 survey, the southern embayment from Wategos Beach to JSPW has lower sand levels and is generally lacking in sandy nearshore morphological features (refer to Figure 36 for 2018 survey). Conversely, the 2011 survey captures a period when the southern embayment contains significant quantities of sand within the littoral transport pathway or surfzone in water depths of 4m or less. As described above (also refer Section 4.2.5), in 2011 the southern embayment contained approximately 700,000m^3 more sand than in 2018 and 2002 surveys. Given the sand levels in the embayment were lower in 2011 and 2018, rocky or other hard nearshore features such as Middle Reef were much more visible in aerial photographs, particularly for the 2018 to 2020 period which had greater coverage of high-resolution aerials with clear water (high visibility) conditions (e.g., Nearmap.com).

When coupled with the wave propagation characteristics of the embayment, the variable sand supply leads to a highly variable shoreline in the southern embayment. This is illustrated in Figure 49 which shows DEA Coastlines in the embayment. These are annual mean sea level shorelines since 1988 shown alongside ‘boxplots’ illustrating the higher degree of variability observed in the southern embayment shorelines (east of JSPW) compared to the northern embayment.

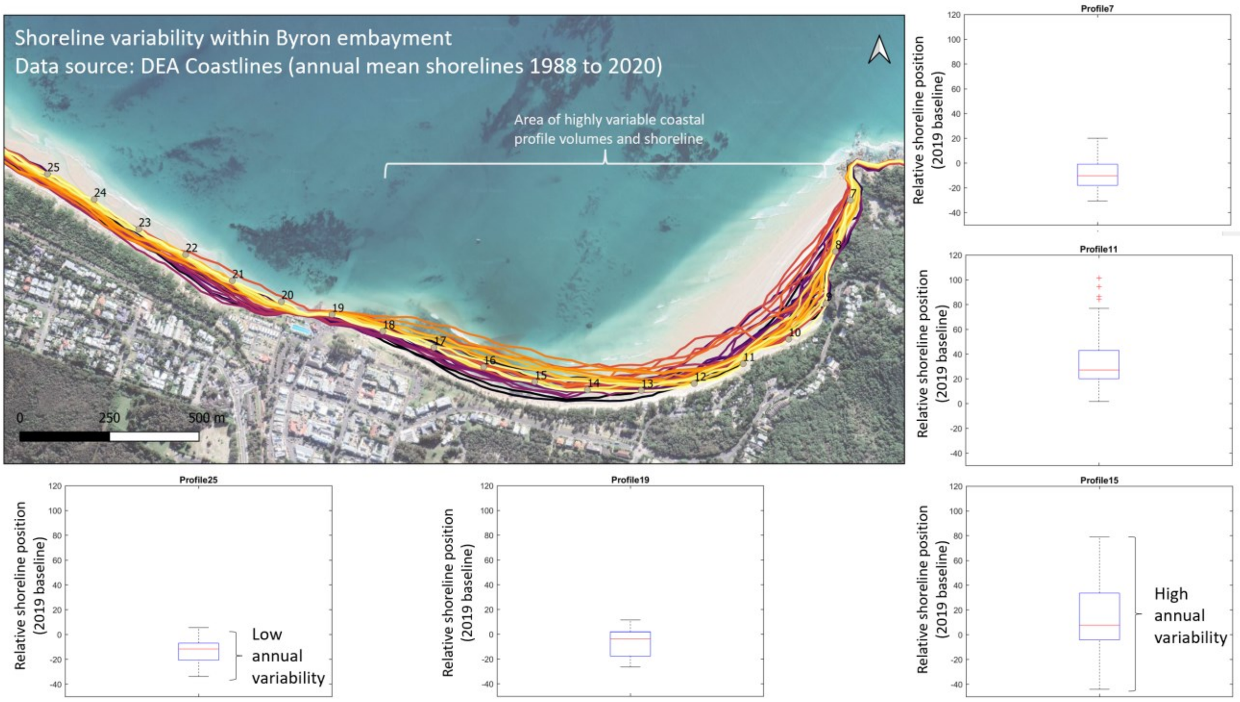

Figure 49: Byron embayment shorelines and box plots showing variability along embayment.

Note: Numbers shown on map indicate profile locations.

At times of reduced bypassing and embayment sand supply, the northward movement of sand out of the embayment persists resulting in a deficit of sand at the southern end (i.e., more sand moving north out of the southern embayment than is being supplied from the south around the Cape). This situation is more likely to occur in more easterly high energy wave conditions typical of La Niña, which reduce headland bypassing but increase littoral transport along the embayment shoreline, thus causing erosion of sand and shoreline recession in the southern embayment. Conversely, pulses of high sand supply from persistent south to southeast sector or higher than average mean wave heights associated with ENSO neutral or El Niño phases, are likely to result in increased headland bypassing. However, more southerly waves are strongly reduced in height in refracting around Cape Byron and are associated with reduced littoral zone alongshore transport along the southern embayment shoreline. This leads to a tendency for shoreline accretion there due to the surplus supply relative to the losses to the north.

The NSW Beach Profile Database provides ‘snapshots’ of the beach profile above 0m AHD since about the 1940s. These snapshots are derived from photogrammetry, LiDAR and other surveying techniques and allow insight into the shoreline and subaerial beach behaviour. In agreement with BMT WBM (2013), the review suggests that data quality issues and the influence of sand mining (mostly stopped around the late 1960s) is evident but only in the pre-1970s beach profiles. Similarly, large profile variations occurred due to storms in the late 1960, 1970’s and 1999 and may take years to recover. Therefore, the identified changes can sometimes be misleading and may not be representative of shoreline recession processes. Linear regression analysis was undertaken to derive long-term rates of subaerial beach volume change for three analysis periods, i.e.:

- 1940 to 2021 (81 years) – full data period
- 1970 to 2021 (51 years) – post sand mining and 1960 storms
- 1980 to 2021 (41 years) – post construction of the Jonson Street Protection Works (JSPW).

Figure 50 shows the rates of subaerial beach volume change along the Byron embayment for the three analysis periods. The outcomes most relevant to coastal management in the Byron Shire are:

- In agreement with the sand loss trend identified in the sand budget analysis, the embayment shows shoreline recession.
- Sand mining influences aside, the 1940 – 2021 analysis suggests that recession rates have reduced in the southern embayment but generally increased in the northern embayment.
- Comparing 1970 to 2021 and 1980 to 2021 this same trend is seen (i.e., shoreline stabilising to the west of JSPW, reducing recession rates along Belongil Beach (Block 6) and increasing recession rates downdrift of the coastal structures that terminate at the northern end of Childe Street at around chainage 5,000m).

The influence of the JSPW and other embayment coastal structure on coastal processes and shoreline behaviour is discussed further in Section 4.4.8.

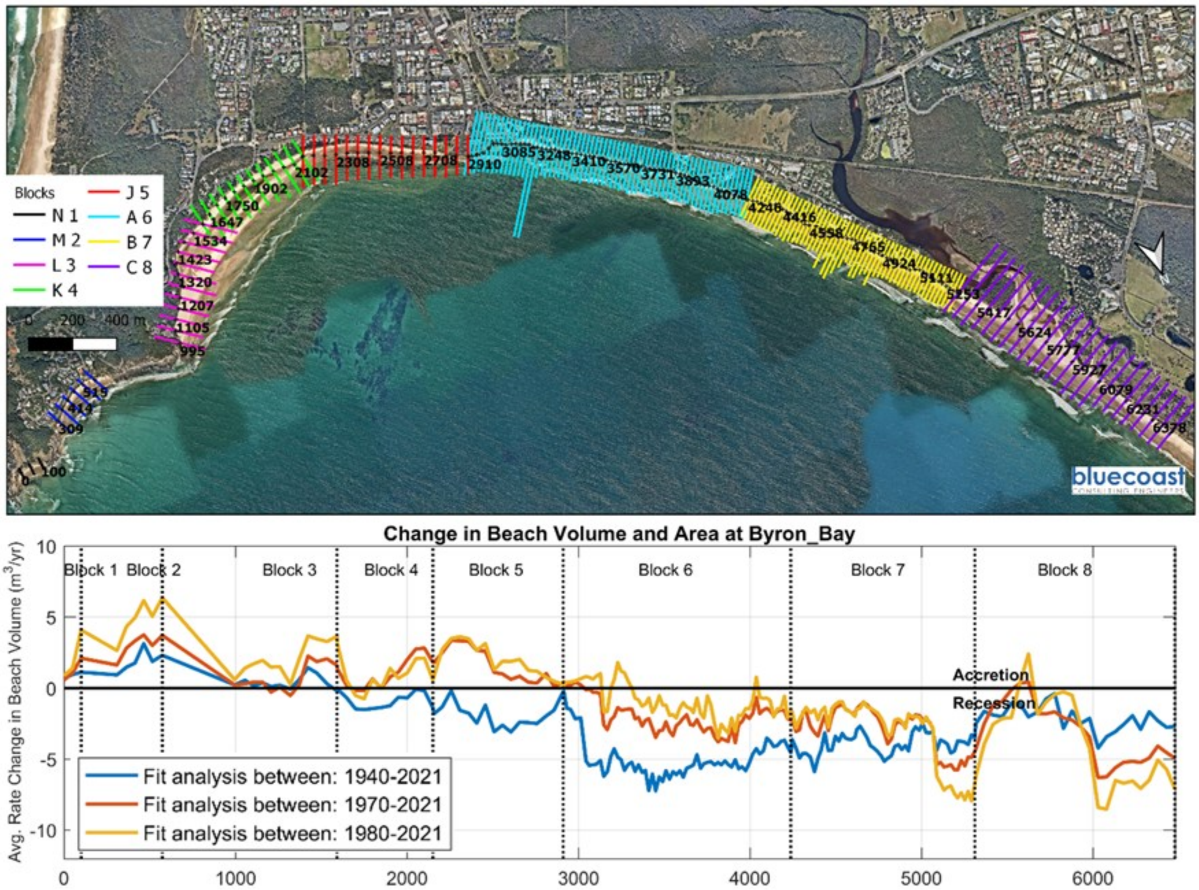

Figure 50: Subaerial beach volume changes showing areas recession/accretion rates for Byron embayment.

4.4.4 Recent headland bypassing event (2018 – 2022)

Satellite-derived bathymetry (SDB) and satellite-derived shoreline positions were used to examine a recent headland bypassing event that occurred between 2018 and 2022. The aim was to provide further insight into headland bypassing around Cape Byron and its effect on the behaviour of Byron Bay's beaches. Specifically, the analysis quantifies the volume and timing of sand movements (see Figure 51) through the embayment and outlines any implications of this for coastal monitoring and management. A summary is provided herein, with the full methodology and analysis available in **Appendix C**.

The elevation difference maps in Figure 52 show a distinct sand wave (or slug of sand) that moves around Cape Byron, from south to north, to infill The Pass (in 2021) and Main Beach (in 2022). Figure 52 also shows the corresponding aerial images. The difference maps show areas of sand loss/erosion relative to the 2018 seabed coloured red and areas of sand gain/accretion (relative to 2018) coloured blue. The observed sequence of sand movements can be described as:

- Erosive phase: By 2019 the sand levels in the southern embayment have reduced to historically low levels. The reduced sand levels in the southern embayment exposed the shorelines to increased wave action, with storms over this period resulting in 72,500m^3 of sand eroded from the Main Beach dune system, or the loss of around 30-40m of vegetated dunes over around 850m of shoreline.
- Accretion phase: Through 2021 and 2022, the sand that bypassed the Cape from 2018 to 2020, started to infill along Clarkes and Main Beach. Between 2020 and 2021, the sand volumes in the southern embayment increased by 541,000m^3. The naturally restored sand supply led to increased beach widths and refilled the surf zone creating a wider, shallower surf zone to restore

the sandy buffer. To retore the dunes along Clarkes and Main Beach, Council undertook beach scraping to move around 12,000m^3 of sand (approximately 14m^3/m over an approximately 850m length of shoreline) from the intertidal area up the profile to create an incipient dune and swale just seaward of the dune's erosion scarp.

The cycle can be visualised using DEA Coastline data (mean annual shoreline positions), see Figure 51. Like the SDB, this figure illustrates a naturally occurring lack of bypassing and sand supply between 2018 and 2020 leading to headland bypassing induced/enhanced erosion along Clarkes Beach and Main Beach (see most landward annual shoreline observed along 700m of Main Beach in 2021). Beach and shoreline recovery followed as supply was restored to Clarkes Beach in 2021 and to Main Beach in 2022.

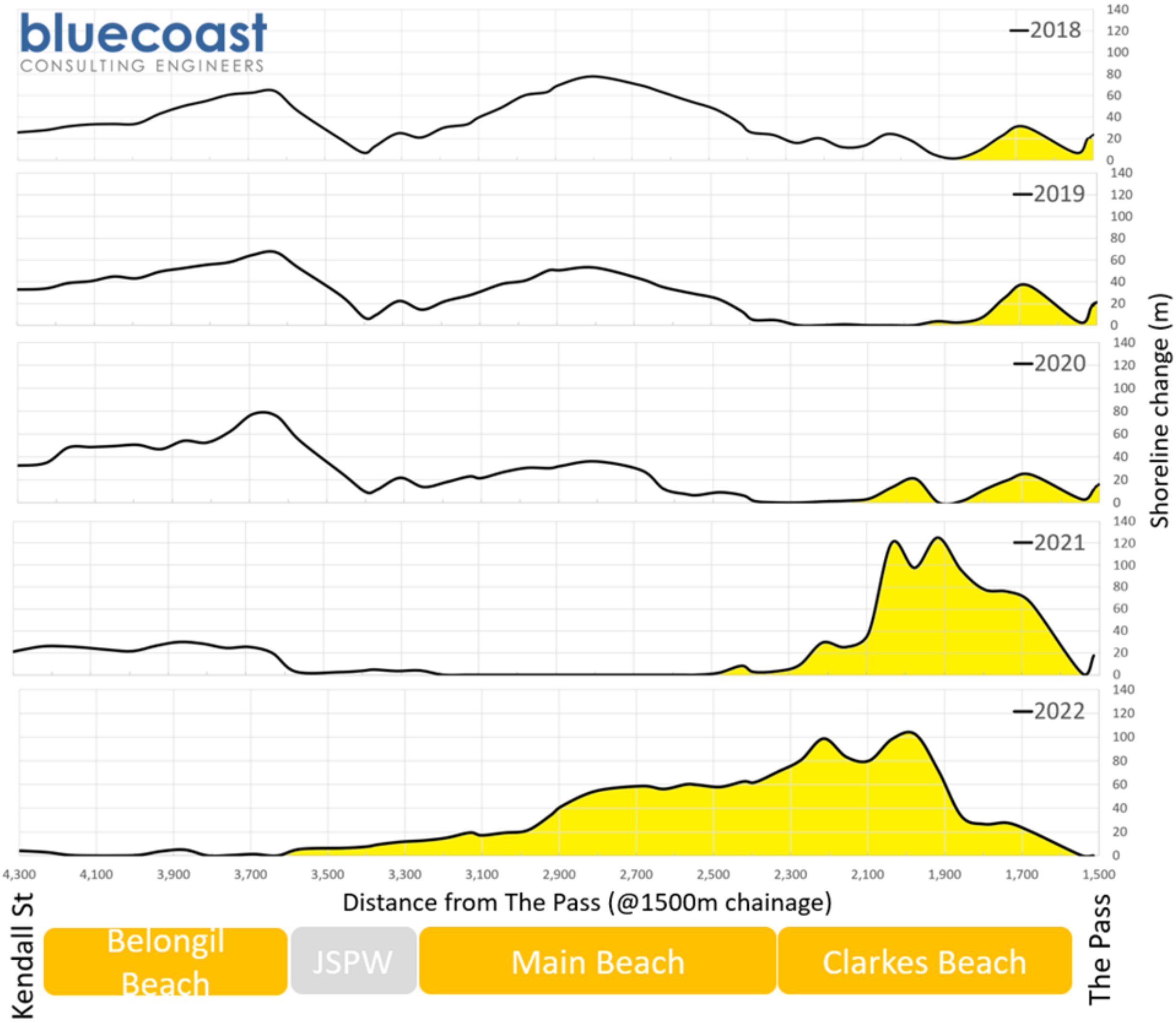

Figure 51: Time history of satellite-derived embayment shorelines from 2018 to 2022.

Note: Data is derived from the annual mean sea level shoreline from the DEA Coastlines product. All data is presented as the differences from the minimum observed position at each shoreline location at approximately 60m alongshore intervals (observation period 1988 to 2022). The accretion wave, coloured yellow, is shown for illustrative purposes. Observations: (i) minimum observed shoreline along Clarkes Beach in 2019 translating to Main Beach by 2021 and then on to Belongil Beach by 2022 and (ii) the progressive erosion (landward movement of the shoreline) along Main Beach from 2018 to 2021.

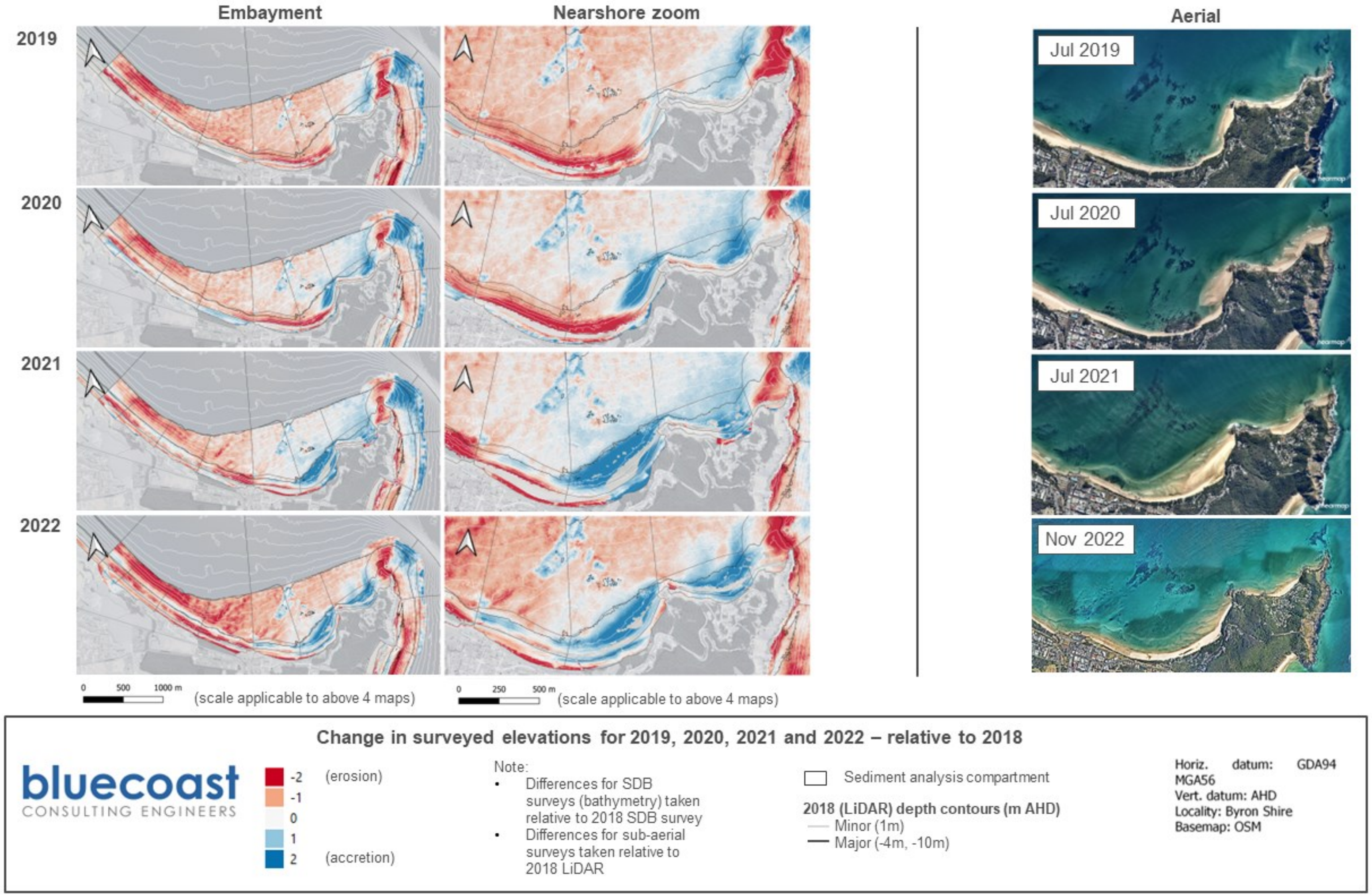

Figure 52: Difference maps for 2019, 2020, 2021 and 2022, relative to 2018.

4.4.5 Cape Byron sand lobe

The Cape Byron – Ballina Shelf Sand Body (SSB) extends approximately between the 10m and 35m depth contours offshore of Broken Head to Cape Byron and creates a convex up coastal profile offshore of Tallow Beach (Ribo et al., 2020). The northern end of this SSB has also been referred to as the ‘Cape Byron Sand Lobe’ and it is in this area the SSB interacts with littoral sand movement around the Cape and the Cape’s interference with the East Australian Current (EAC) and nearshore current.

This mid-Holocene deposit is formed from headland sand bypassing, on an oversteepened slope with a component of sand transported offshore from the littoral zone (Ribo et al., 2020). PWD (1978) reported a 49,000m^3/yr component of the longshore sand transport is lost at Cape Byron because of bifurcation of the headland bypassing caused by the shelf current. The component transport downslope by the southward flowing EAC was calculated as the volume of sand in excess to the normal offshore coastal profile in the lobe region and dividing this by the number of years (6,000) over which the sand has been theoretically depositing (Roy and Stephens, 1980). The volume of the sand deposition has been estimated as approximately 370Mm^3 (Patterson Britton and Partners, 2006). BMT WBM (2013) adopted a value of 50,000m^3/yr and included it as a loss rate in their alongshore sand movement and shoreline change modelling.

The extensive SSB and associated shoreface disequilibrium is reasoned to promote onshore supply of sand to Tallow Beach offering a stabilising or accretional effect to the shoreline. This onshore sand supply from the lower shoreface, which can be exaggerated during and following extreme storm events (Harley et al. 2022), provides sand for the longshore transport system.

4.4.6 Embayment sand movement pathways

Two distinct Byron embayment sand movement pathways have been identified in previous studies (BMT WBM, 2013 and Goodwin, 2013). These two distinct, but related pathways are defined by the different mechanisms that drive the sand transport as:

- A littoral pathway limited to the surfzone where sand movements are forced by obliquely breaking waves and the longshore currents they drive. The littoral processes are confined to depths not much greater than the wave breakpoint depths, or about 4 to 5m water depths within the embayment. Herein the littoral pathway has been defined based on the toe of steeper beach faces found in the embayment at around 4m water depth, see Figure 53.
- The cross-embayment transport which extends beyond wave breaking depth to up 15m water depth and reported to be driven by wave asymmetry, wind and wave radiation stresses (BMT WBM, 2013). As indicated in Figure 53, the cross-embayment pathway extends from the 4m water depth. Sand movements in these water depths are typically much slower.

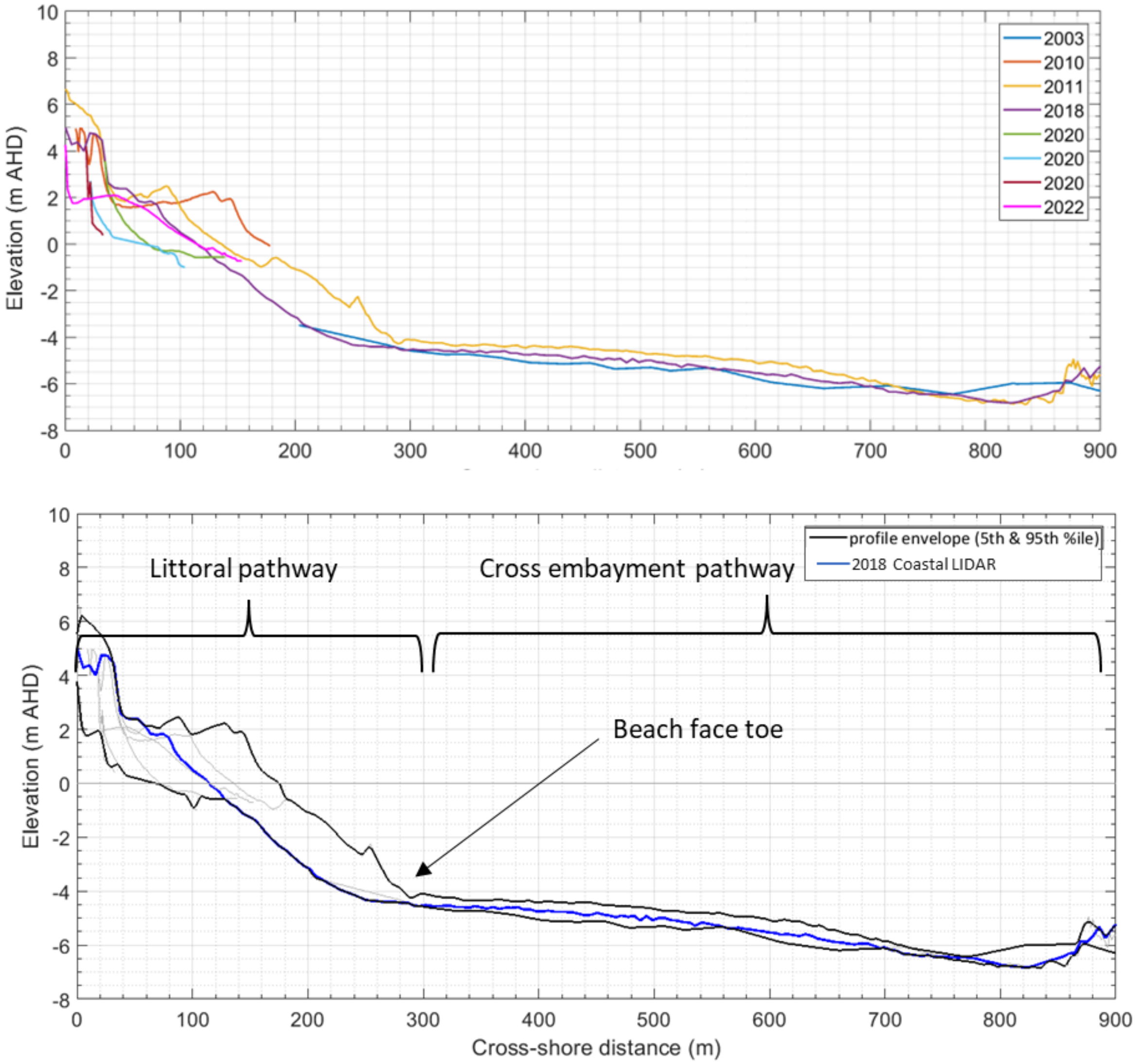

Figure 53: Coastal profile at Main Beach (top) with envelope of profile variation between 2003 and 2020 (bottom).

The proportion of sand movements that follows each pathway, as well as where along the northern shoreline the cross-embayment pathway re-joins the littoral pathway, is a relevant consideration for coastal management in the Byron Shire as it influences:

- the net longshore sediment transport rate bypassing the JSPW
- the nature of the sand supply to areas downdrift of the JSPW.

BMT WBM (2013) and Goodwin (2013) state that the relative proportions have not been quantified reliably. In BMT WBM (2013), a 50 : 50 split was based on Goodwin's results and used as an input to their shoreline model, where this assumption was found to produce good results. Based on sand volume changes determined from repeat surveys and presented in Section 4.2.2 as well as profile changes (e.g., Figure 53) the relative split between the two pathways, when averaged across the embayment, has been calculated to be 70 : 30 (littoral : cross embayment). As discussed below this split is not uniform across the embayment with sand progressively moving onshore and re-joining the littoral pathway.

Qualitatively, the dominance of the littoral pathway, is reinforced by a review of recent aerial photography, see Figure 54. Inspection of these images in the context of other data described herein revels:

- The July 2018 aerial was captured around the same time as the 2018 Coastal LiDAR survey. It shows the headland bypassing pathway loaded with sand but very little sand on Wategos Beach and a well below average amount of sand along Clarkes and Main beaches.
- By June 2019 sand bypassing the Cape appears to have moved along the cross-embayment pathway and onshore and is starting to weld to the shore to fill Wategos Beach and The Pass. Clarkes Beach has eroded as evident by the narrowing beach and nearshore reefs becoming exposed.
- By July 2020 the sand wave appears to have fully welded to the littoral pathway with Little Wategos and Wategos Beaches very wide and almost continuous having formed in front of rocky areas. A large sand spit has formed out from The Pass. However, further erosion of Clarkes Beach is evident with more reef exposed as the sand level lowers.
- By July 2021 the bulk of the bypassed sand appears to have reached Clarkes Beach with some sand in the surfzone moving all the way to JSPW. The 'bulge' shape of the surfzone pathway is seen around the western end of Main Beach.

The aerials of this bypass event indicate it took around 3-years from the time when the sand wave bypassed the Cape for the sand to start filling in the eastern end of Main Beach. More recent aerials show it took another 12-months for the sand to infill Main Beach all the way to the JSPW. While these timeframes were indicative over this period, it is important to note that the rate of sand movements through the embayment are influenced by the wave climate encountered over a given period. Large waves events, such as can be generated by tropical cyclones, and their associated storm wave direction can also result in strong pulses of alongshore sediment transport.

Further evidence in support of a higher proportion of sand movement along the littoral transport comes from current speed data collected in the Byron embayment:

- PWD 1978 reports current speeds and alongshore direction of surfzone currents (assume to be less than 4m water depth relative to AHD). Over a 4-month period in 1977 a location in the southern embayment was monitored with an average surfzone current speeds of 0.3m/s (predominately, ~90% of the time, northward flowing) and a peak speed of 0.9m/s.
- High-quality current speed measurements in approximately 6m water depth relative to AHD were made as part of the MBSP (Bluecoast, 2022). These deeper measurements, located outside the surfzone (littoral pathway) and instead within the cross-embayment pathway, show slower currents. An average speed of less than 0.1m/s and 90th percentile speed of less than 0.2m/s were recorded. It is noted that the maximum near bottom speed was 0.8m/s but that this was recorded during an extreme tropical cyclone event.

The cross-embayment pathway is likely to have a higher proportion east of The Pass (i.e., Wategos and Little Wategos Beach), but within the inner embayment the evidence suggests the littoral pathway is dominant. Fisherman's Lookout at The Pass acts as a second inner embayment headland, inside of which incoming waves approach also at right angles to the shoreline with wave crests bending by refraction and diffraction before breaking along the sand bank. This high angle of wave obliquity drives relatively high LST rates despite the lower wave heights and it is common to see recurved spits form, stretching out towards Clarkes and Main Beach with lagoons forming on the inner beach berm. Sediment transport equations like the type used in the BMT WBM (2013) modelling do not adequately resolve the transport rate on these high angle coastlines.

From the bathymetry evidence, BMT WBM (2013) concluded that the alongshore sand transport becomes exclusively 'littoral' somewhere at or north of Belongil Creek.

Figure 54: Aerial imagery showing the movement of sand through the southern embayment via the littoral pathway including the prominent sand wave and spit with a rip channel in the lee of the spit (data source: Nearmap).

4.4.7 Geomorphology, reefs and wave transformation

Geological and seabed characterisation mapping for the Byron embayment is shown in Figure 55. This map as well as historical and recent observations confirm the embayment has extensive indurated sand (or coffee rock) lenses and bedrock outcrops including Julian Rocks and Middle Reef. These hard features affect wave transformation and the movement of sand through the embayment as well as influencing shoreline dynamics. An example is provided in Figure 57 showing the 2018 less 2011 survey differences alongside a wave height map from a SWASH model simulation (Bluecoast, 2022). A wave shadow between two 'streaks' of higher waves emanating from Middle Reef is seen to coincide with an area of nearshore seabed change in the surfzone just east of the JSPW (as seen as an accumulation of sand in the 2011 survey which had move on (eroded) by the time of the 2018 survey). This suggests that the nearshore reefs influence the surfzone morphology when the southern embayment cells are full of sand. This is also evident in historic aerial imagery shown in Figure 58.

Seismic data from the 1970s suggests that bedrock lies at shallow depths beneath the seabed surface (PWD, 1978), which is validated somewhat by recent aerial images that show reefs within the embayment intermittently exposed and then covered with sand (see Figure 15). Hard substrate also reduces the volume of sand that can be stored in the southern embayment.

From the Cape to Clarkes Beach the shape of the embayment's shoreline is controlled by the greywacke bedrock that forms Cape Byron. Little Wategos, Wategos, The Pass and Clarkes Beach (east) are underlaid by bedrock as well as boulders, cobbles and gravels. Further to the west, the embayment's backbeach area becomes a Holocene beach barrier system comprised of marine sand deposits. At various locations along Main Beach and Belongil Beach coffee rock in the dunes and swash zone can be exposed at times of erosion and low sand levels.

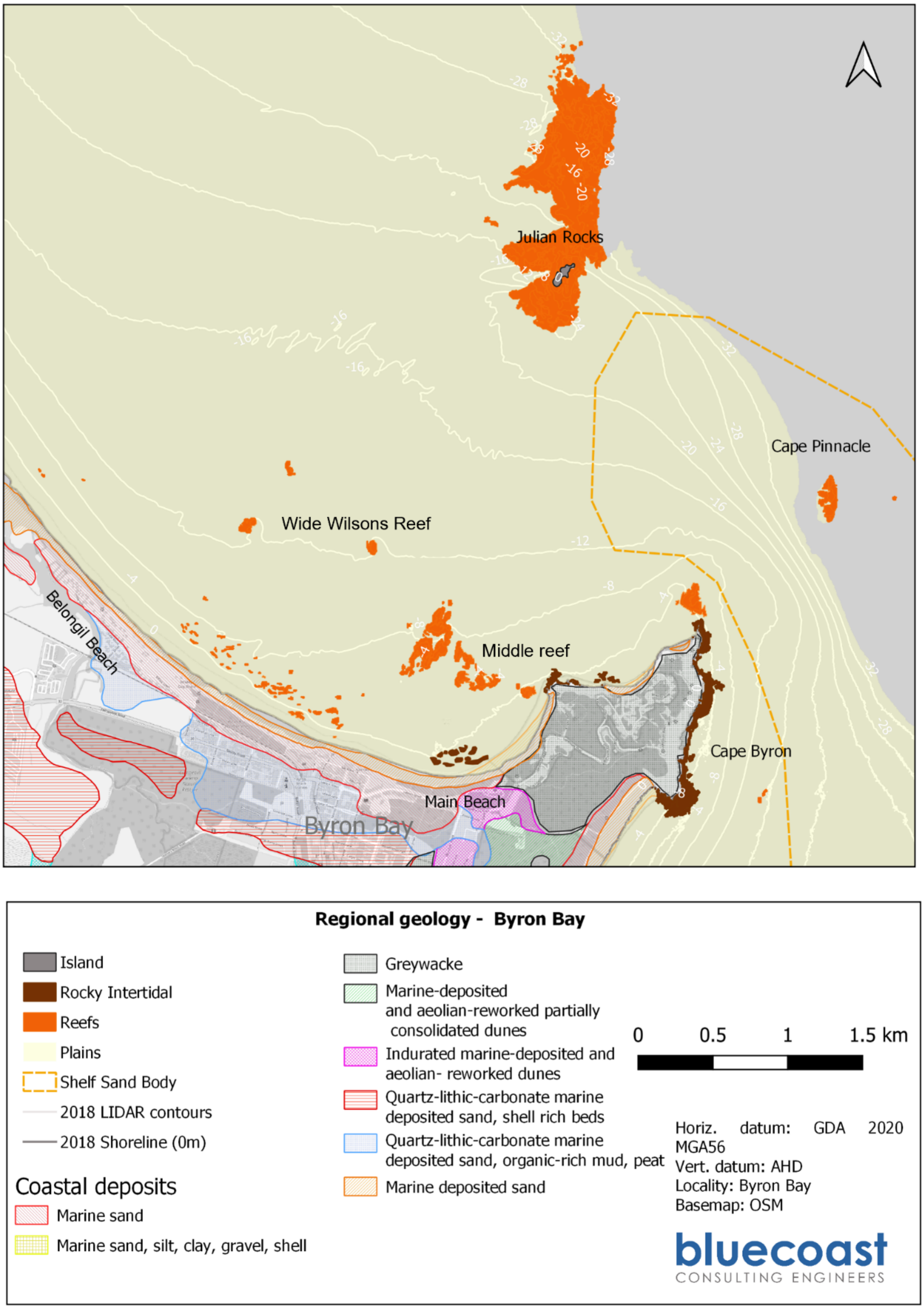

Figure 55: Byron Bay regional coastal Quaternary geology and seabed characterisation map.

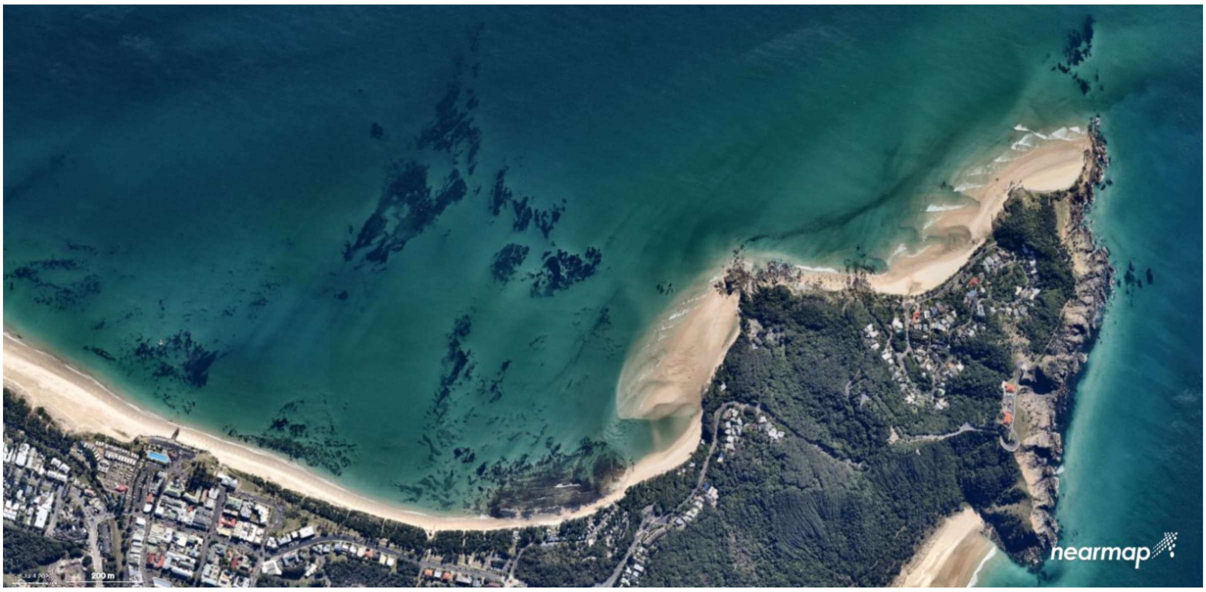

Figure 56: July 2020 aerial photography showing reefs and coffee rock outcropping (source: Nearmap).

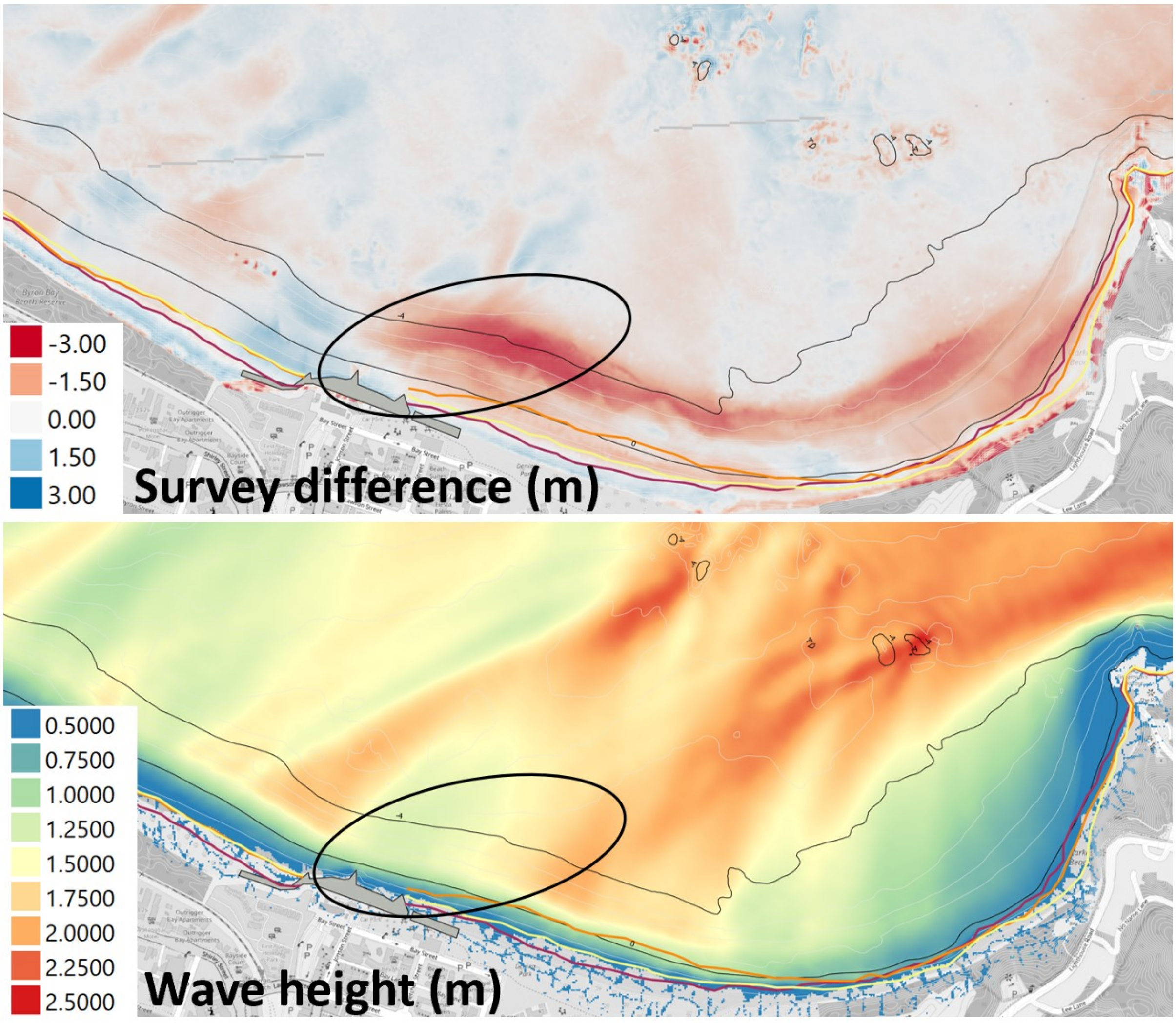

Figure 57: Survey difference 2018 less 2011 (top) and SWASH wave height map (bottom).

Figure 58: Two historical aerial images highlighting the bulge of sand in the lee of Middle Reef wave shadow and nearby JSPW.

4.4.8 Embayment coastal structures and their interactions with the embayment's shoreline

The historical timeline outlined in Section 2.2 provides details of the human modifications to the coastal barrier system in the study area. This includes the Jonson Street Protection Works (JSPW) and other coastal structures along the Byron embayment.

Jonson Street Protection Works

In the context of the contemporary coastal environment the dimensions and alignment of the JSPW are an important consideration. Figure 59 provides an elevation map of the structure from a December 2020 drone survey when beach levels were low on the eastern side of the structure. This is overlaid on the 2018 Coastal LiDAR contours. Also provided in this figure is an aerial photomosaic, combining December 2020 and July 2022 images to show the structure in an uncovered state (i.e., not buried under beach sand/vegetation).

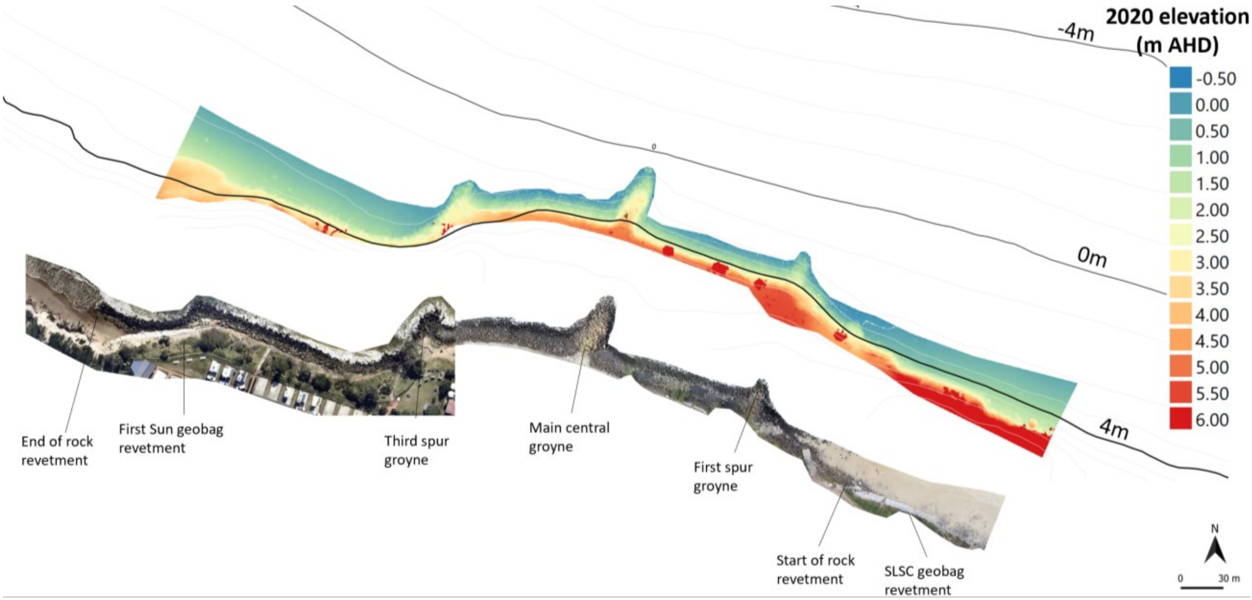

Figure 59: Elevation model (top) of JSPW taken in December 2020 along with 2018 contours and aerial mosaic combining December 2020 and July 2022 images.

The effect of the JSPW on the adjacent beach compartments has been studied extensively with much written on the subject (PWD, 1978; NSW Government, 1990; WBM Oceanics, 2000; WBM Oceanics, 2003; BMT WBM, 2010; BMT WBM, 2013; WRL, 2011 and WorleyParsons, 2013). There is consensus in the literature that:

- the JSPW[5] do influence the planform of the adjacent beaches with an initial response of accretion/stabilisation of the immediate updrift shoreline (i.e., Main Beach to the east) and additional erosion of the downdrift shoreline (i.e., Main Beach and Belongil Beach to the west)
- the wider Byron embayment was experiencing 'natural' erosion as shorelines receded due to net sand loss over the observed period.

There is no consensus in the literature on JSPW relative influence on planform changes against those of background recession nor on the cross-shore and alongshore extents of the JSPW induced erosion along Belongil Beach nor on the time scales of change. BMT WBM (2013) importantly notes that the embayment's shoreline and beach widths are largely controlled by the natural sand movement processes of headland bypassing, onshore/offshore transport, longshore transport combined with the effects of the influence of bedrock and indurated sands.

To further examine the influence of the JSPW on the embayment's shoreline, analysis of the relevant observational data is presented in Figure 60 to Figure 62. This includes recent data that was not available at the time of previous literature. Based on this further analysis the following key points are noted:

- During the early 20th century through to the 1950s beaches in the southern embayment were wide with a surplus of sand and expansive areas devoid of dune vegetation. Prior to the JSPW being

[5] Note that 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. On coastlines suffering net sand loss, seawalls with significant longshore lengths can 'lock in' sand in the dunes that would have otherwise been released to supply downdrift shorelines.

present the area at the end of Jonson Street was occupied by the original clubhouse of the Byron Bay SLSC and a boat shed. Photo records show a wide expanse of beach and a sparsely vegetated dune seaward of the original clubhouse (see Figure 60).

- Beach profile (or photogrammetry) data at Main Beach (see Figure 61, Block 5, profile 10 as representative profile) shows a sharp decline in subaerial beach volume observed between 1940's and 1970. While it is noted that sand mining may well have influenced these observations, the sharp decline in beach widths/volumes concords with the photo records from the former clubhouse.
- The alignment of the main rock revetment of the JSPW was based on the desire to protect these two public buildings (Bluecoast, 2021). The original clubhouse was present in 1946 and from the 1947 photogrammetry data it can be estimated that the clubhouse was then around 10-20m landward of the then +4m AHD contour. The main rock revetment is now some 30m seaward of an assumed 2018 'natural' +4m AHD contour. Meaning there has been some 40-50m of shoreline recession at the site of JSPW that is unrelated to the structure itself.
- In accordance with the findings in Section 4.2.4, this indicates that the southern embayment has experienced a naturally occurring net sand loss since at least the 1880's. The process driving this natural sand loss is unknown. Goodwin et al. (2013) reasoned the observed morphological change was evidence of a change in the regional wave climate indicating a shift in dominate deepwater wave direction from 120°-140° (1883) to 140°-160° (2002/2011), with a corresponding change in headland bypassing and embayment pathways. It is unclear if this sand loss trend is part of a longer-term cycle of naturally varying sand supply, which may be reversed in the future. Superimposed on the net loss is significant shorter-term cyclical variations in the embayment's sand supply. These are driven by ENSO over time scales of 2 to 7 years and IPO over longer decadal scales.

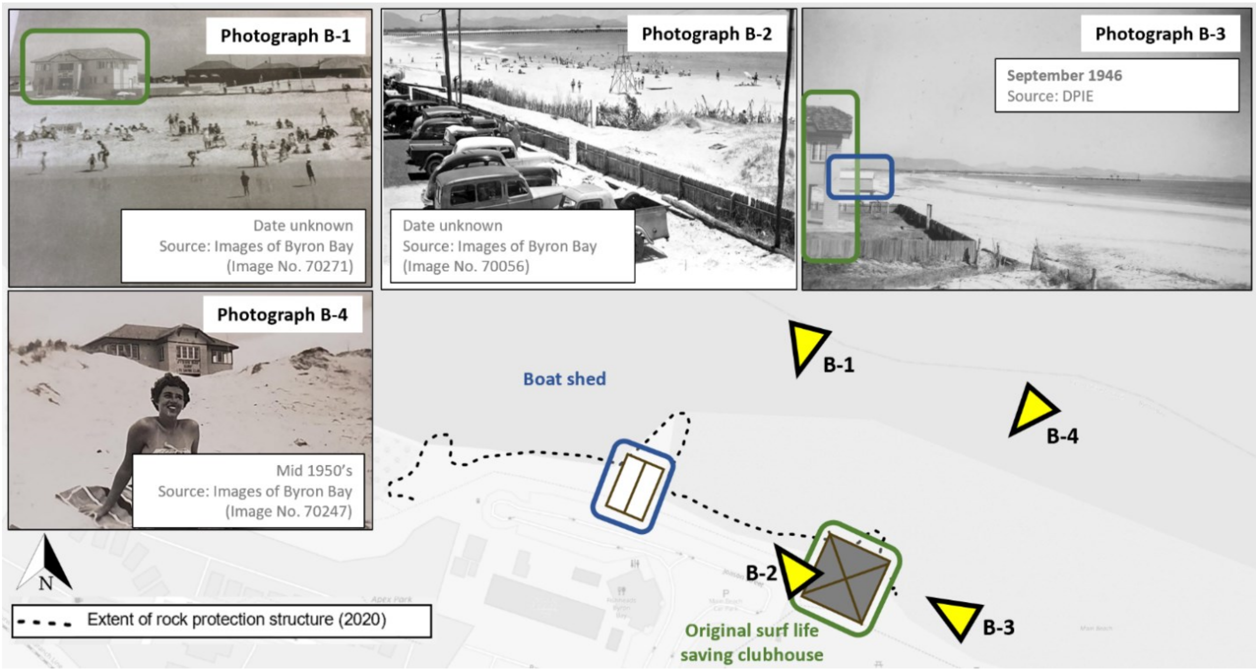

Figure 60: Photomap of the end of Jonson Street area prior to the JSPW taking shape at the site.

- Following the construction of the JSPW a relatively short period of planform realignment occurred. With reference to the photogrammetry data (see Figure 61) this manifests as:

- A sharp stabilisation (or reversal of the rapid erosion trend) updrift of JSPW (see Block 5, profile 10) along Main Beach transitioning to an accretionary trend between 1980's and 2021. The recent accretion trend observed in updrift beach profile agrees with the trend observed in DEA shorelines along Main Beach, see Figure 63.
- Continuation of a persistent erosion trend, albeit reducing in rate, along Belongil Beach immediately downdrift of the JSPW (see Block 6, Profile 14). More recently this area appears to have stabilised undergoing a slightly accreting trend between 1980 and 2021. Again, the recent accretion trend agrees with DEA shorelines trends, see Figure 63.
- Between 1km and 2km downdrift of the JSPW (see Block 6, Profile 50 and Block 7, Profile 35) the erosion trend has occurred as a more consistent rate when viewed over the 1970-2021 and 1980-2021 periods.
- North of the Belongil seawalls (see Block 7, Profile 53) the erosion trend has accelerated.

This pattern indicates that the planform adjustment to the JSPW occurred relatively quickly (i.e., within 20-years of the original construction). Downdrift erosion induced by the JSPW appears to have been reduced by the anchoring effect of the updrift Belongil seawalls. This is evidenced by the recent accretionary trend at Block 6, Profile 14 (i.e., a similar pattern to that observed earlier updrift of the JSPW). The combined effect of the JSPW and the Belongil seawalls is to translate the net sand loss to the north of the private properties along Belongil Spit (i.e., to the very northern tip of the spit, Belongil Creek and the beach north of the creek).

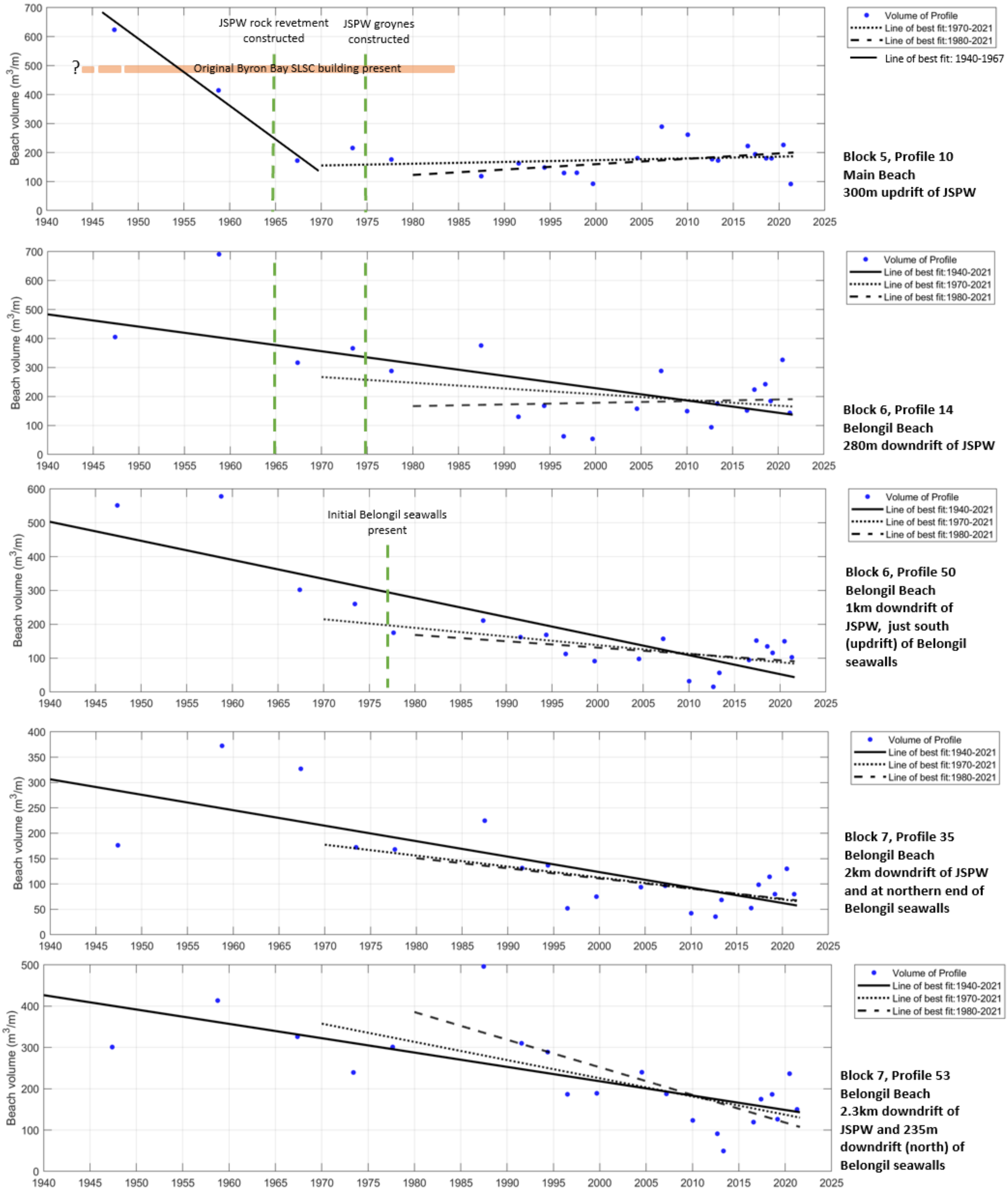

Figure 61: Timeseries of subaerial beach volumes (blue dots) from representative photogrammetry profiles at Main Beach (top) and Belongil Beach (bottom 4 panels) including lines of best fit.

Note: Lines of best fit are regression lines that show the trend in subaerial beach volume at each profile over a defined period. The steeper the line the more rapid the erosion (downward sloping) or accretion (upward sloping) observed.

- As described in Section 4.4.3, headland bypassing and the supply of sand to the southern embayment has a controlling influence on the embayment's sand volume and shoreline. Coastal profile volumes calculated from surveys in 2002, 2011 and 2018 as shown in Figure 62 provide strong evidence of this. In 2011, and because of a surplus of supply, there was just under 300,000m^3 more sand along the Main Beach compartment than in 2002. By 2018, this surplus had reduced by at least 200,000m^3 with corresponding increases in sand volumes along Belongil Beach (i.e., more sand was bypassing the JSPW then was being supplied from the south).

The fluctuations in the Main Beach shoreline since full bypassing was reached in the 1980s provides further evidence (see Figure 63). Following bypassing events, pulses of sand (or sand waves) infill Main Beach moving the shoreline and surfzone seaward to a position where sand can bypass the JSPW at all tides. This results in the structure having little to no effect on shoreline processes at these times. Between bypassing events when sand supply is low the reverse is true and structure-shoreline interactions increase.

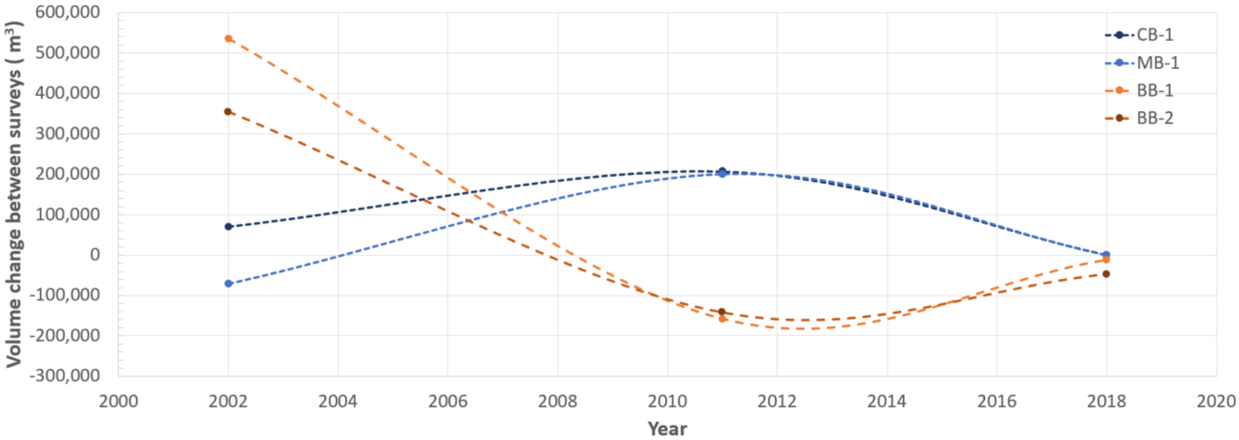

Figure 62: Full coastal profile volume change along Clarkes Beach (CB-1), Main Beach (MB-1), southern Belongil Beach (BB-1) and northern Belongil Beach (BB-2).

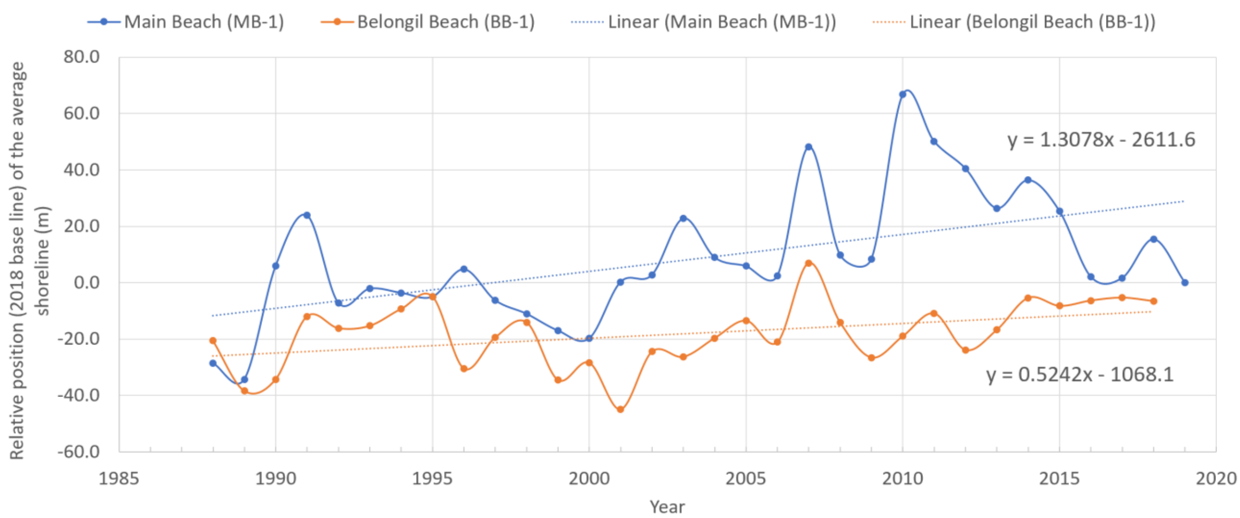

Figure 63: Average relative shoreline positions over 1km updrift (Main Beach) and 1km downdrift (Belongil Beach).

Brunswick River training walls

The twin training walls at the Brunswick River entrance were constructed by 1962. Prior to the training works, the river entrance had a nearshore rock outcrop on its northern side which influenced the longshore sand transport and shoreline alignment in this area (PWD, 1978). Once built, the training walls rapidly changed the local sand movements which resulted in significant accretion of the updrift Brunswick Head beach and erosion on the beach to the north (Doyle et al., 2019). Following re-establishment of northward sand bypassing around the structures, the beach and dunes recovered and a net sand gain was observed (Doyle et al., 2019). As described in Section 4.4.1, PWD (1978) estimated that the net longshore transport rate in the vicinity of the river entrance was 110,000 to 120,000m^3/year. This was based on the rate of updrift (southern) shoreline accretion immediately following construction of the training walls. However, estimates in other studies vary considerably, hence uncertainty remains. The sand budget analysis completed herein estimated that on average around 490,000m^3/year (±20%) of sand is moving northward along this section of coast (see Section 4.4.1).

Over more recent decades, the beach immediately updrift (south) and downdrift (north) of the river entrance has been stable or accreting with average rates of around 1m^3/m/year (shown in Figure 64; also see Section 4.2.5 and **Appendix B**). This behaviour has been observed since around late 1980s which aligns with the findings of dune volume analysis adjacent to the Brunswick River entrance presented in Doyle et al. (2019). Average accretion rates over the period between 1940s to 2021 were in the order of 0.5m^3/m/year.

The evidence available to this study indicates the section of coast has been in a long-term stable or accretionary state since data became available in late 1940s. 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 river entrance to the behaviour of adjacent beaches. As further discussed in Section 5.3.4, it is likely that the Brunswick River entrance will act as a sink for sand from adjacent beaches as the entrance morphology adjusts to raising sea levels.

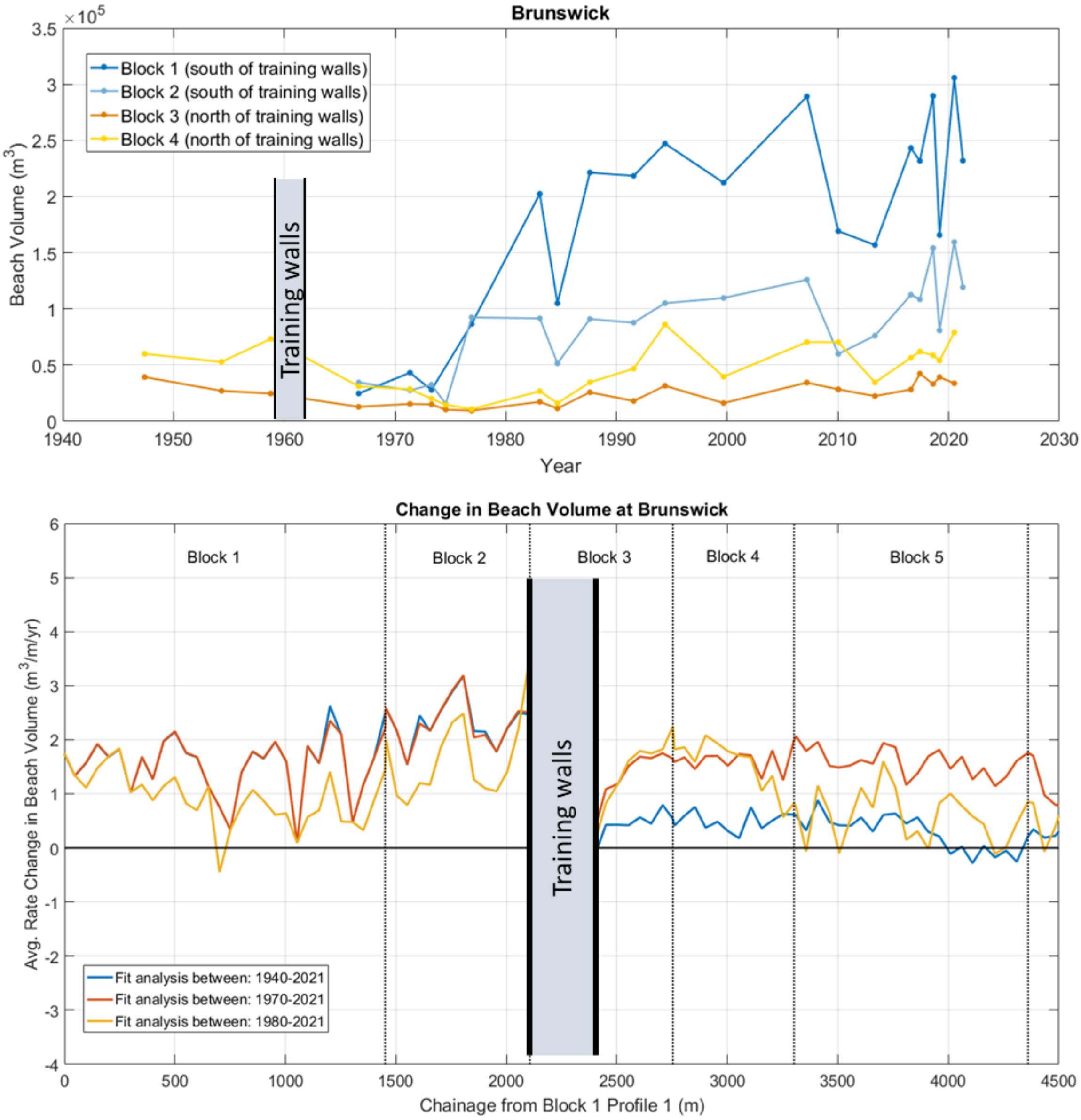

Figure 64: Beach volume change based on photogrammetry analysis of available profiles adjacent to the Brunswick River entrance.

Note: Volume change rates determined by linear regression of available data points within stated time periods.

Other coastal structures

Other coastal structures in the Byron Shire include the various seawall and emergency works along Wategos Beach, Clarkes Beach and Belongil Beach as well as several stormwater outlets that discharge onto the beach. As described above, the seawalls along Belongil Beach contribute to translating the net sand loss observed in the southern embayment to the north of the private properties along Belongil Spit. This is further discussed in Section 8.2.3.

In general, the existing stormwater outlets have little effect on the embayment-wide beach processes and do not modify the regional sand budget. During periods of high rainfall, the beach in front of the structures may lower as stormwater discharges across the beach and erodes a channel to the ocean. Depending on the cross-shore position of the outlet, this may exacerbate erosion locally on the upper beach due to reduction of the local sand buffer against storm waves. Where the stormwater outlet terminates high on the beach profile stormwater discharge may also directly erode sections of the dune. For example, the stormwater outlet at the eastern end of Clarkes Beach has resulted in localised erosion of the surrounding dune (see Figure 65). The respective sections of beach are expected to have adapted to the effects of the various existing stormwater outlets in the study area and these effects are captured in the relevant data used in this study (i.e., surveys and photogrammetry).

Figure 65: Dune erosion around stormwater outlet on upper beach at Clarkes Beach (photo taken July 2020).

4.5 Conclusion

The implications of the sand budget for coastal management in the Byron 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 headland bypassing along a coastline such at Byron Shire, would be expected to lead to better coastal management outcomes. For example, in November 2022 Council undertook beach scraping to assist in the restoration of Clarkes and Main Beach dunes that had been significantly eroded during the erosive phase of a headland bypassing cycle. This is an adaptive approach that works with the natural cycles in sand supply and avoid reactive approaches that can have adverse long-term impacts on adjacent coastlines. Potential future sand management activities, such as beach nourishment or beach scraping can be programmed with an understanding of the quantity, timing and rates of alongshore sand movement.

- Clarkes Beach and Main Beach in particularly but also Belongil Beach are vulnerable to erosion and shoreline variability due to headland bypassing. Development along this zone should be considered in the context of these natural processes as they will continue to occur, albeit not every year/decade. For example, Apex Park and the coastal dune system are an asset in accommodating these variations. Little Wategos and Wategos Beach are considered less vulnerable as it is underlaid by bedrock or boulders which provide a landward limit to shoreline movement.
- There are accessible datasets, such as Nearmap aerial photography (or other sources), DEA Coastlines and ENSO indexes, that could be used to monitor the likelihood of the commencement of a potentially damaging (to natural and built assets) bypassing cycle. Potentially damaging cycles seem to occur when (i) shoreline/sand volumes in the embayment are average or below average at the start of a cycle and (ii) a strong El Niño event precedes a period of reduced sand supply to the embayment by 1 to 4 years.
- 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).
- The sand budget outcomes were used to inform the development of probabilistic coastal erosion and recession hazard lines (see Section 5). 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:
  - Allowance for the effects of headland bypassing events for the section of beach between The Pass and Belongil Creek is required to account for the additional shoreline variability observed in these areas.
  - A net long-term sand loss from the southern embayment results in shoreline recession which requires consideration in long-term shoreline change calculations as part of the hazard assessment.
  - Onshore sand supply was reasoned to promote stable to accretionary shoreline change along some sections of Byron Shire beaches. Where uncertainty in future onshore sand supply rates exists, an allowance for variability in such rates was adopted.
  - At present, the three ICOLLs of Ti Tree Lake, Tallow Creek and Belongil Creek were not regarded as a sink or source to the Byron Shire's sand budget. With sea level rise the sand budget at the estuary entrances (including Brunswick River) may become unbalanced, which may contribute to recession of adjacent beaches.
- 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.

5. Coastal erosion and recession hazard assessment

5.1 Overview

In line with the NSW Coastal Management Manual Part B (the Manual - OEH, 2018a), a probabilistic coastal erosion and recession hazard assessment for the Byron Shire coastline was undertaken. This section provides an overview of the approach and inputs to the hazard assessment. The mapped results are presented in the map compendium at the end of this report.

The adopted approach and inputs have been determined in collaboration with the Department of Planning and Environment (DPE) and Council.

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 66. Site-specific supporting analysis of photogrammetry and shoreline position is presented in **Appendix B**.

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 Byron Shire 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 Byron Shire erosion hazard assessment include:

   - Beach erosion due to storm events, long-term beach behaviour trends due to sand budget imbalances or sea level rise, shorter-term variability in the sand budget (e.g., headland bypassing effects, storm clusters), cross embayment transport, losses to offshore sand lobe, 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, coffee rock, coastal protection structures and associated downdrift shoreline impacts.

2. <u>Calculations</u>

   The Monte Carlo simulation of coastal erosion uses one million 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 horizon. 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 slope adjustment 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 several 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 year. Note that 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 engineering design purposes and interpretation of the results should consider the following assumptions and uncertainties:

- A regional hazard assessment was completed herein using the most 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 Byron 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.

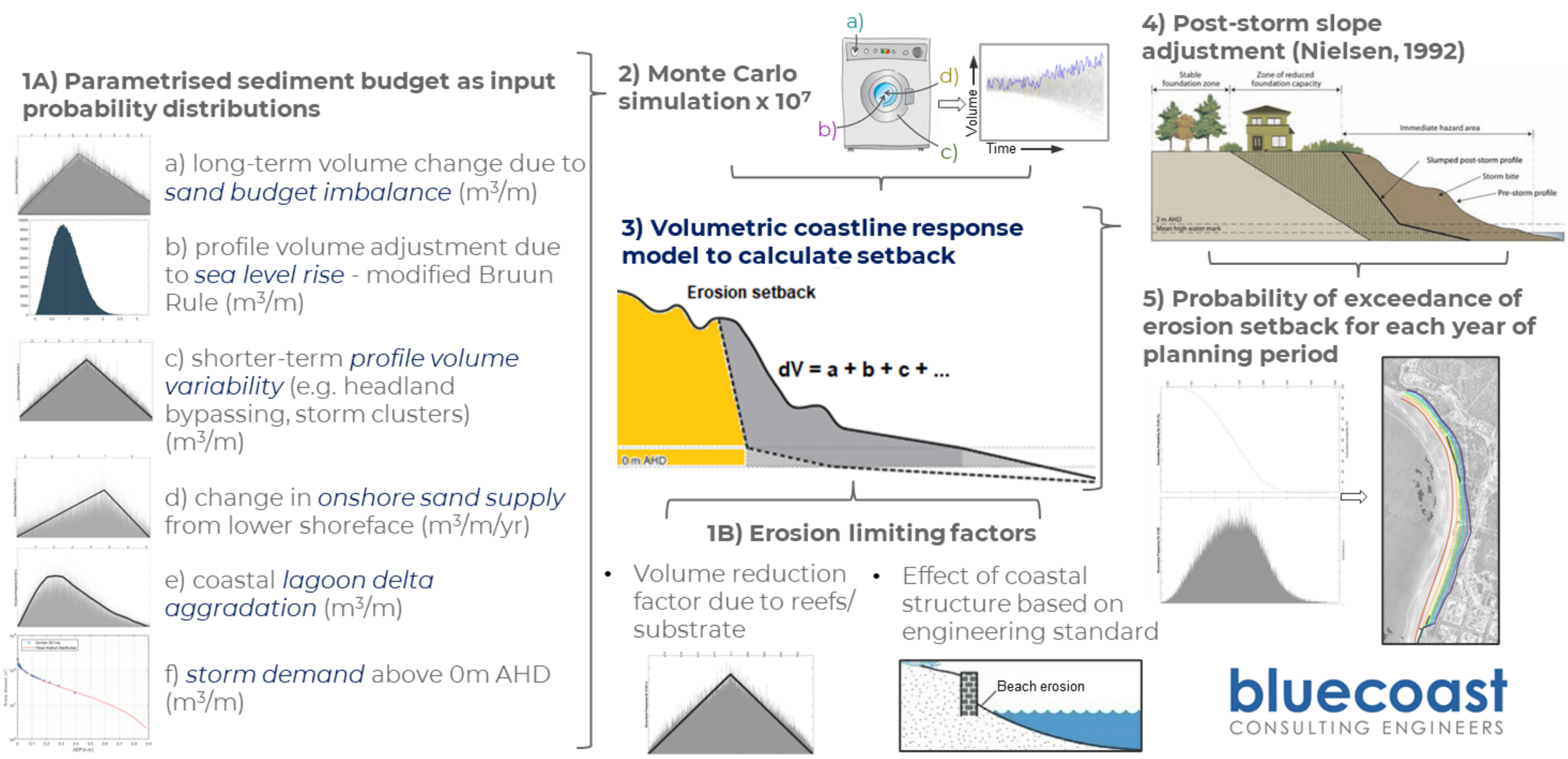

Figure 66: Overview of probabilistic coastal erosion and recession hazard model.

5.3 Adopted inputs and methodology

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

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 596 regular shore-normal profiles between Seven Mile Beach and Wooyung were adopted for the erosion and recession calculations. The profiles are at 20m to 200m 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 D**.

5.3.2 Baseline

The 2018 NSW Coastal LiDAR topographic and bathymetric 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 beach state across the Shire's coastline. The 2018 Coastal LiDAR was captured between July to October 2018 during a neutral El Niño–Southern Oscillation (ENSO) period.

More recently, beach conditions within the study area have been affected by the pre-dominant La Niña periods since 2020 and headland bypassing events (see Section 4). As described in Section 4.4.3 and Section 4.4.4, since the erosion cycle observed in the southern embayment in 2020 and 2021, headland bypassing events have resulted in sand pulses (or sand waves) moving through the Byron embayment, hence causing considerable differences in the beach states within the study area. Adopting a 'eroded' baseline profile would result in potentially overly conservative hazard predictions. The effects of headland bypassing are considered statistically using shorter-term beach volume variability as an input to the hazard model (see Section 5.3.4).

An example profile at Main Beach showing available survey data since 2003 (including 2018) is provided in Figure 67. Further comparison of the 2018 LiDAR data and other surveys is provided in Section 4.2 and **Appendix B**.

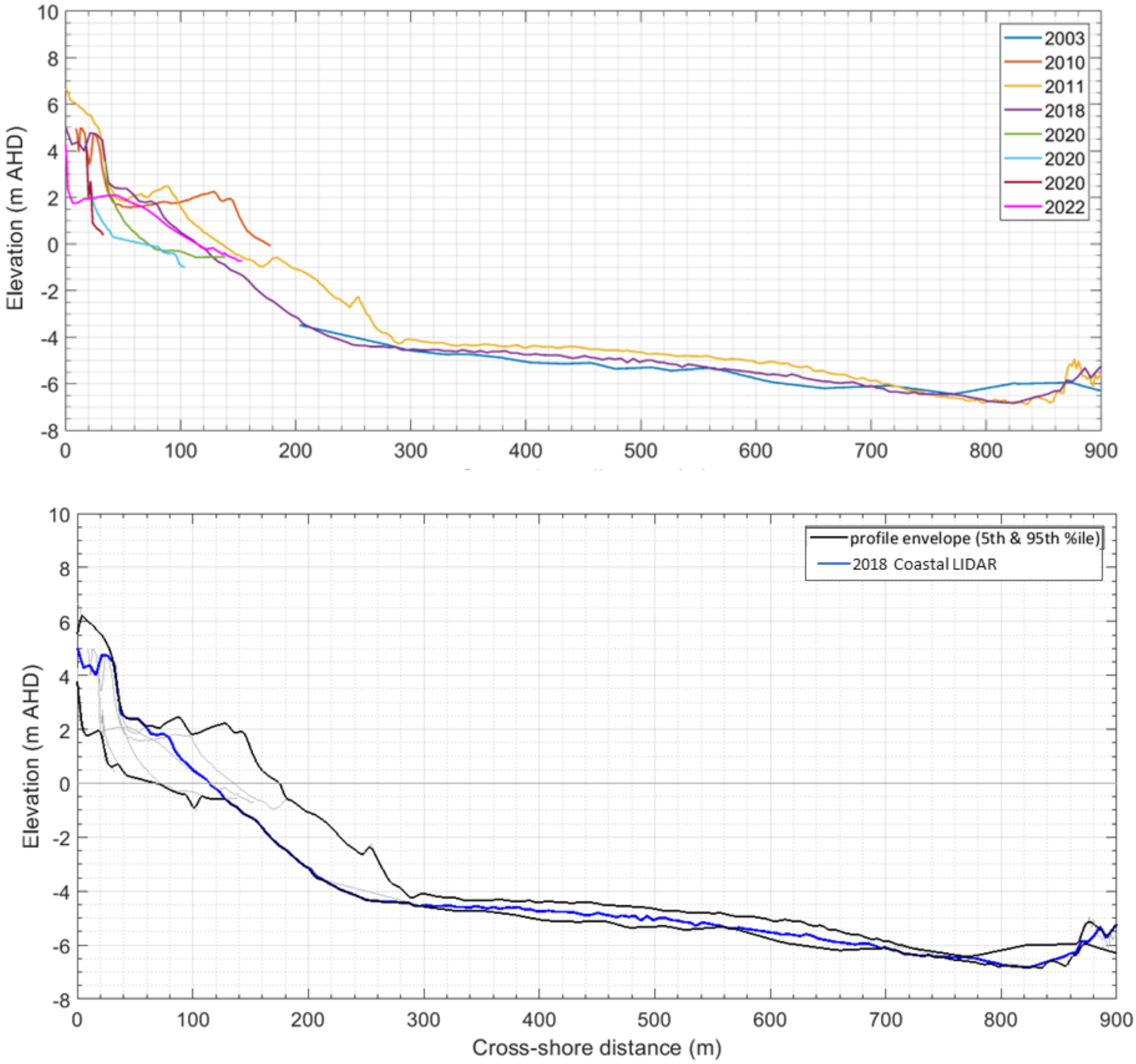

Figure 67: (top) Coastal survey profiles at Main Beach and (bottom) envelope of profile variations between 2003 and 2022.

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 300m^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 full range of storm demands in the Byron Shire with rare and frequent occurrence probabilities were estimated by curve-fitting to the commonly used distribution of storm demands in New South Wales by Gordon (1987). Figure 68 presents the relationship between storm demand and annual recurrence intervals in Gordon (1987) as well as examples of the adapted 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 Byron Shire, the probabilistic storm erosion calculations were undertaken as follows:

a. Review of observed storm demands at each section of beach (presented in **Appendix B**)

b. Selection of a representative 100-year ARI storm demand based on (a) and relative beach exposure. A triangular distribution representing a possible range was used to account for uncertainty in this value (presented in Table 14).

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 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 69). 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.

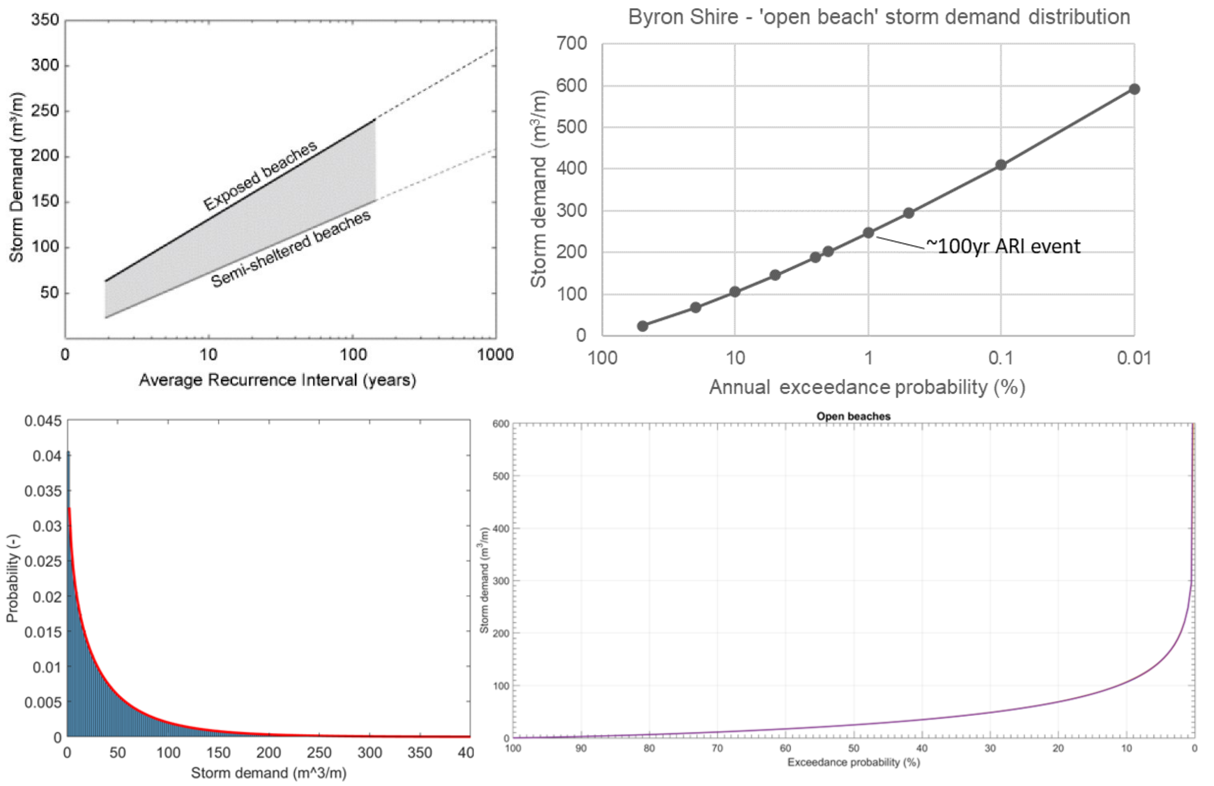

Figure 68: (top left) Storm demand distribution after Gordon (1987), (top right) example input distribution used in this study and (bottom) full probability distributions adopted for Byron Shire's open coast beaches.

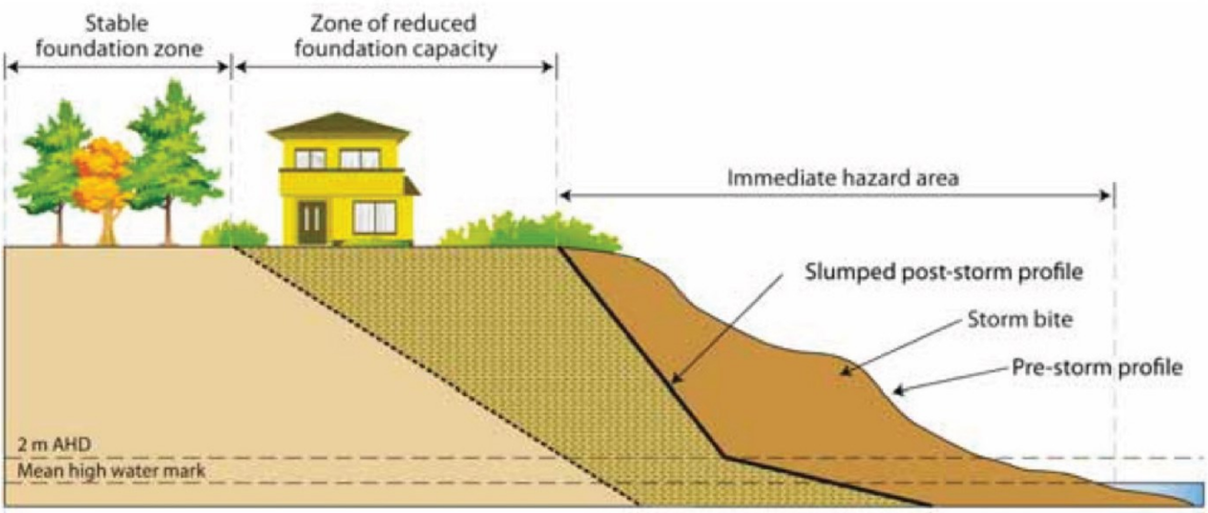

Figure 69: Wedge Failure Plane Model (NSW Coastal Risk Management Guide, 2010; after Nielsen et al., 1992).

Table 14: Adopted input ranges for a 100-year ARI storm demand in the erosion and recession hazard model.

Area	Beach	Adopted 100-yr ARI value range [min, mod, max] m^3/m	Comment
Seven Mile Beach to Broken Head	All beaches	150, **200**, 300	
Broken Head to Cape Byron	Broken Head	150, **200**, 300	Assumed 'open beach' with full wave exposure. Value ranges based on historic observed storm erosion volumes presented in **Appendix B**. Some erosion extents may be limited by presence of bed rock which is considered separately.
	Suffolk Park	150, **200**, 300	
	Tallow Beach	150, **200**, 300	
	Cosy Corner	150, **200**, 300	
Byron embayment	Wategos Beach	75, **100**, 150	Value range representative of observed storm erosion values along these beaches. Adopted 50% reduction in 'open beach values' due to wave sheltering effect by Cape Byron.
	The Pass	75, **100**, 150	
	Clarkes Beach	110, **150**, 225	25% reduction in 'open beach values' as wave sheltering effect by Cape Byron becomes less significant and beach transitions to higher wave exposure towards Main Beach. This is evident in the observed historic storm erosion volumes presented in **Appendix B**.
	Main Beach (east of JSPW)	150, **200**, 300	Assumed full wave exposure. While some wave sheltering by Cape Byron and Julian Rocks may occur during easterly to southerly wave events, full wave exposure during north-easterly storm waves. Localised shoaling and

Area	Beach	Adopted 100-yr ARI value range [min, mod, max] m³/m	Comment
			diffraction due to nearshore reefs may also increase inshore wave heights. Adopted value ranges representative of observations in photogrammetry data.
	Main Beach (west of JSPW)	150, **250**, 350	As above. Adopted increased allowance for storm erosion due to potential localised influence of the JSPW on coastal processes and observed historic storm erosion volumes presented in **Appendix B**.
	Belongil Beach	150, **200**, 300	Assumed full wave exposure. While some wave sheltering by Cape Byron and Julian Rocks may occur during easterly to southerly wave events, full wave exposure during north-easterly storm waves. Relatively lower storm erosion volumes observed compared to western section of Main Beach (see **Appendix B**).
Tyagarah to Brunswick River	Tyagarah Beach	150, **200**, 300	Observed range of historic storm erosion volumes somewhat lower compared to Main Beach and Belongil Beach. However, due to full wave exposure storm erosion volumes typical for open beaches are adopted. Some erosion extents may be limited by presence of bed rock which is considered separately.
	Brunswick Head Beach	150, **200**, 300	
Brunswick River to Wooyung	North Head	150, **200**, 300	
	New Brighton Beach	150, **200**, 300	
	South Golden Beach	150, **200**, 300	
	Wooyung Beach	150, **200**, 300	

5.3.4 Sand budget allowances

Coastal profile response to long-term trends and short-term variability in the Shire's sand budget are a key input to the coastal erosion and recession hazard assessment. Based on the findings from the sand budget analysis presented in Section 4, consideration was given to the following processes:

- Long-term shoreline recession or accretion caused by sediment budget imbalances evident in historical data.
- Shorter-term variability of the beach profile volume due to changes in headland bypassing, cross-embayment sand transport, storm clusters, offshore losses and other processes linked to climate cycles.
- Potential future changes to the rate of onshore sand supply from the lower shoreface affecting the Shire's sand budget.
- 'Loss' of marine sand from the active coastal zone due to tidal delta aggradation with sea level rise adjacent to coastal lakes and estuaries in the Byron Shire.

The adopted sand budget inputs to the coastal erosion and recession hazard assessment are further described in the following sections.

Long term beach volume trends

Long-term volumetric shoreline recession or accretion rates caused by sand budget imbalances have been determined based on the sand budget analysis (see Section 4) as well as observations in subaerial beach volumes (photogrammetry) and mean annual shoreline positions (DEA coastlines), presented in **Appendix B**.

A summary of the range of long-term shoreline recession/accretion rates adopted in the erosion and recession hazard assessment in the form of triangular probability distributions is provided in Table 15. Example input probability distributions for selected beach areas (defined in Table 15) are presented in Figure 70 to Figure 72.

Table 15: Adopted erosion and recession hazard model input for long-term subaerial volume change.

Location	Section (profile #)	Long-term subaerial volume change [min, mod, max] m^3/m/year	Comment
Seven Mile Beach to Broken Head	Seven Mile Beach (p1 – p43)	-2.3, **-1.9**, -1.5	Long-term recession observed. Adopted average observed rate in photogrammetry data over Block 7 and Block 8 (1947 – 2021) with ±20% uncertainty range.
Broken Head to Cape Byron	Broken Head (p44 – p71)	0, **+0.8**, +1.0	Accreting beach behaviour observed. Adopted average observed rate in photogrammetry data over Block 1 (1947 – 2021) with +20% upper uncertainty range. Conservative nil lower range to account for uncertainty but input range skewed towards accretionary rate.
	Suffolk Park (p72 – p113)	0, **+1.4**, +1.7	Accreting beach behaviour observed. Average observed rate in photogrammetry data over Block 2 to 7 (1973 – 2021) with +20% upper uncertainty range. Conservative nil lower range to account for uncertainty but input range heavily skewed towards accretionary rate.
	Tallow Beach (p114 – p143)	0, **+1.4**, +1.7	
	Cosy Corner (p144 – p150)	0, **+1.4**, +1.7	As above. Some higher cyclic variability in profile volumes adjacent to Cape Byron observed due to headland bypassing pulses.
Byron embayment	Wategos Beach (p151 – p159)	-0.2, **0**, +0.2	Wategos Beach and The Pass are underlaid by bedrock and boulders, cobbles and gravels which are expected to limit any long-term recession. No receding or accreting trend observed in satellite derived shorelines between 1988 and 2019 (Digital Earth Australia, 2021). Possible small accretionary trend observed in photogrammetry analysis but data heavily influenced by headland bypassing pulses. Conservative estimate with minimal range around nil adopted to account for uncertainty.
	The Pass (p160 – p169)	-0.2, **0**, +0.2	

Location	Section (profile #)	Long-term subaerial volume change [min, mod, max] m^3/m/year	Comment
	Clarkes Beach (p170 – p179)	-1.0, **0**, +1.0	Rates of beach volume change are highly sensitive to the period of analysis. This is related to the highly variable cyclic nature of this area being downdrift of a major shoreline control (Cape Byron) as well as a sharp decline in beach volume until 1970s (potentially due to sand mining) and the recovery since 1970's. A net long-term sand loss from the southern embayment was observed in the sand budget (mostly on subaqueous part of profile and further west). Adopted conservative lower and upper range based on average photogrammetry block values for 1940-2021 (net recession) and 1970-2021 (net accretion) period, respectively. The adopted wide range of negative and positive rates around a zero modal value is reflective of the remaining uncertainty in the long-term beach behaviour of this section of beach.
	Main Beach (east of JSPW) (p180 – p194)	-1.9, **0**, +1.6	Rates of beach volumes change are highly sensitive to the period of analysis. This is for the same reasons as Clarkes Beach mentioned above. Pre-1970 photogrammetry data for Main Beach is affected by sand mining activity (verified in historic aerial imagery). Adopted lower and upper range based on average photogrammetry block values for 1940-2021 (net recession) and 1970-2021 (net accretion) period, respectively. While a modal value of zero is adopted which reflects the remaining uncertainty the input range is skewed towards recession for this section of beach.
	Main Beach (west of JSPW) (p195 – p259)	-2.1, **0**, +0.2	Observed long-term beach behaviour suggests this section of beach has been receding. Rate of shoreline recession is highly sensitive to the period of analysis due to sharp decline in beach volume until 1970s and construction of JSPW in mid 1970s. Adopted modal value is Nil to reflect uncertainty and observations over the past two decades, i.e., after the shoreline has largely adjusted to the presence of the JSPW. Lower range conservatively based on photogrammetry block-averaged values for 1970-2021. Upper limit based on observations since 1990s. Adopted input range heavily skewed towards recession for this section of beach.

Location	Section (profile #)	Long-term subaerial volume change [min, mod, max] m^3/m/year	Comment
	Belongil Beach (p260 – p300)	-2.9, **0**, +0.2	As above. Rates of shoreline recession sensitive to the analysis due to sharp decline in beach volume until 1970s. Adopted modal value conservatively based on photogrammetry block-averaged values from 1970 to 2021. Lower range based on block-averaged values from 1940 to 2021. Upper limit based on observations since 1990s.
	Belongil Beach (north of protective structures) (p301 – p341)	-3.6, **0**, +0.2	As above, but lower limit increased by 25% to account for ongoing influence of coastal structures at Belongil Beach.
Tyagarah to Brunswick River	Tyagarah Beach (p342 – p409)	-0.2, **0**, 0.2	No significant receding or accreting trend observed in satellite derived shorelines between 1988 and 2019 (Digital Earth Australia, 2021). Minimal range around nil adopted to account for uncertainty.
	Brunswick Head Beach (p410 – p453)	0, **+0.2**, +0.4	Accretion of this section of beach is observed following Brunswick River training walls built in 1959-1962. Over more recent decades, rate of accretion has reduced as a beach profile may reached a new equilibrium. Future rate of accretion possible to reduce further. Average rates between updrift and downdrift beaches adopted. The lower range was conservatively set to nil to account for possible future reduction in accretion rates.
Brunswick River to Wooyung	North Head (p454 – p487)	0, **+0.5**, +0.6	Average observed rate over Block 4 (1947 – 2021, full available record) with ±20% uncertainty adopted for upper limit. The lower range was conservatively set to nil to account for possible future reduction in accretion rates.
	New Brighton Beach (p488 – p524)	0, **+0.4**, +0.5	Average observed rate over photogrammetry Block 5, 6 and 7 (1947 – 2021) with ±20% uncertainty adopted as upper limit. Repeated beach scraping occurred in this area, however influence on estimated long-term rates assumed

Location	Section (profile #)	Long-term subaerial volume change [min, mod, max] m³/m/year	Comment
			to be minimal. The lower range was conservatively set to nil to account for possible future reduction in accretion rates.
	South Golden Beach (p525 – p583)	0, **+0.4**, +0.5	Average observed rate over photogrammetry Block 8 (1947 – 2021) with ±20% uncertainty adopted as upper limit. The lower range was conservatively set to nil to account for possible future reduction in accretion rates.
	Wooyung Beach (p584 – p596)	0, **+0.3**, +0.4	Average observed rate over photogrammetry Block 1 and 2 (1947 – 2021) with ±20% uncertainty adopted as upper limit. The lower range was conservatively set to nil to account for possible future reduction in accretion rates.

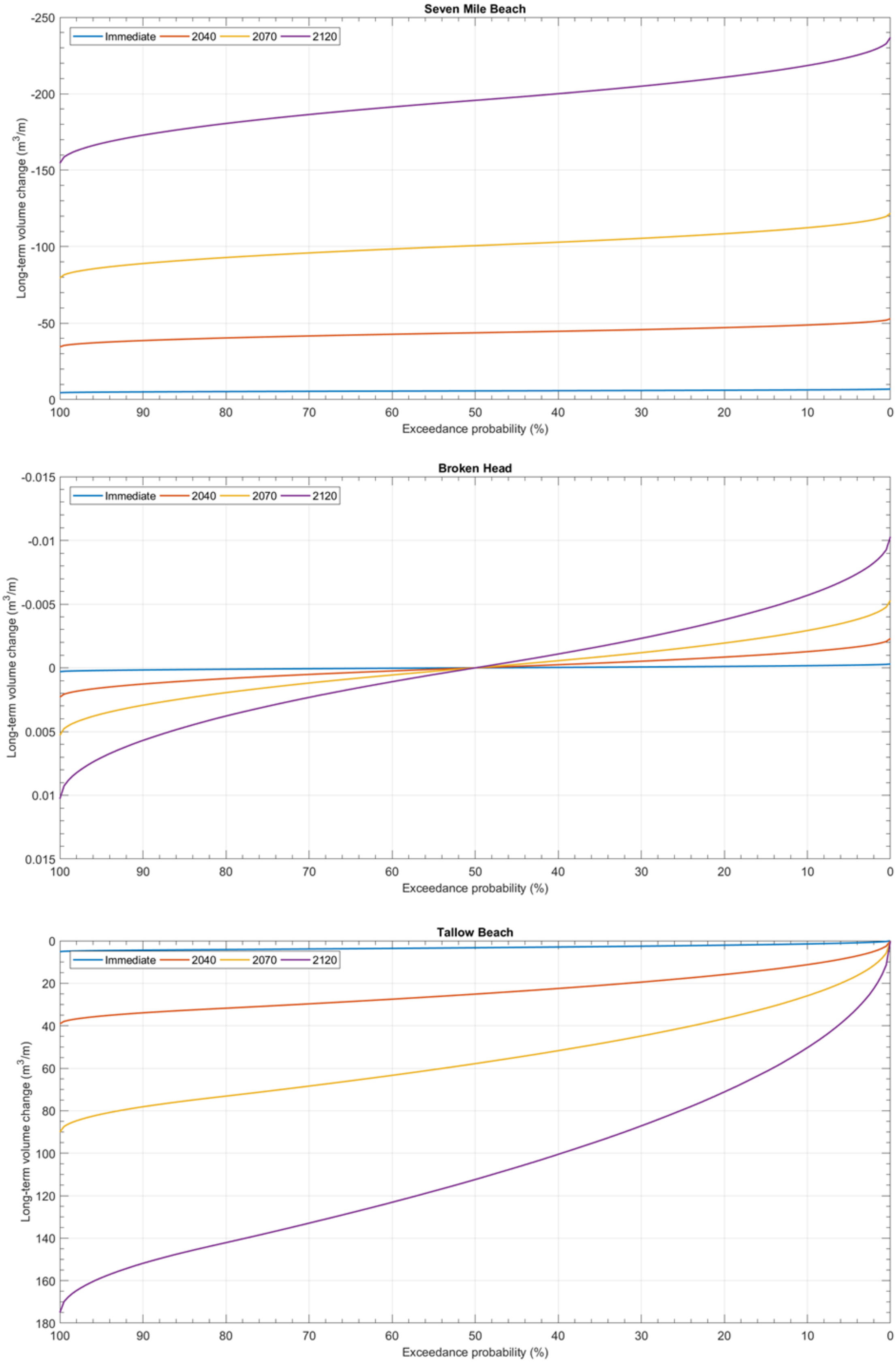

Figure 70: Example cumulative probability distributions for long-term volume change inputs – southern beaches.

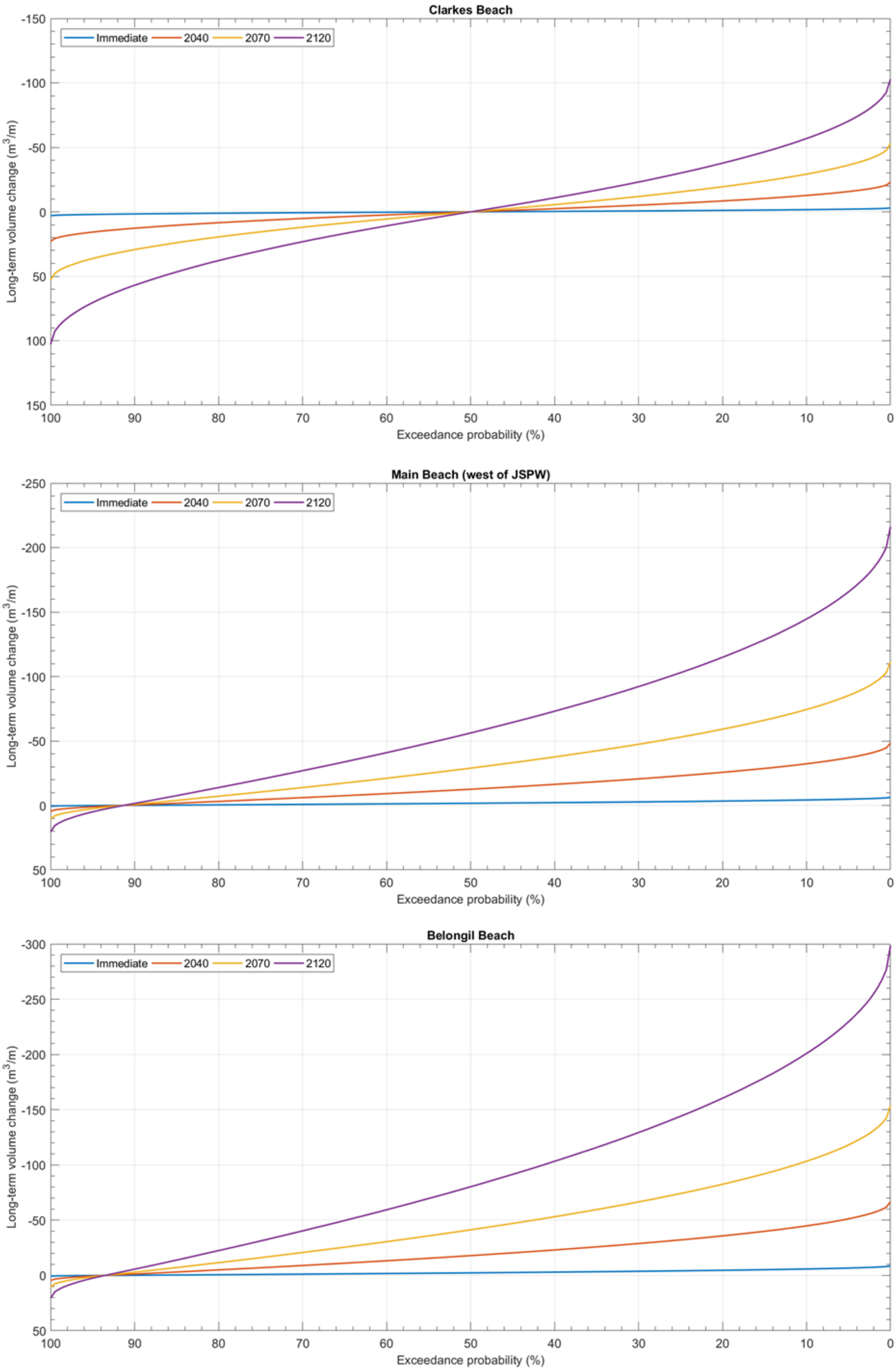

Figure 71: Example cumulative probability distributions for long-term volume change inputs – southern embayment.

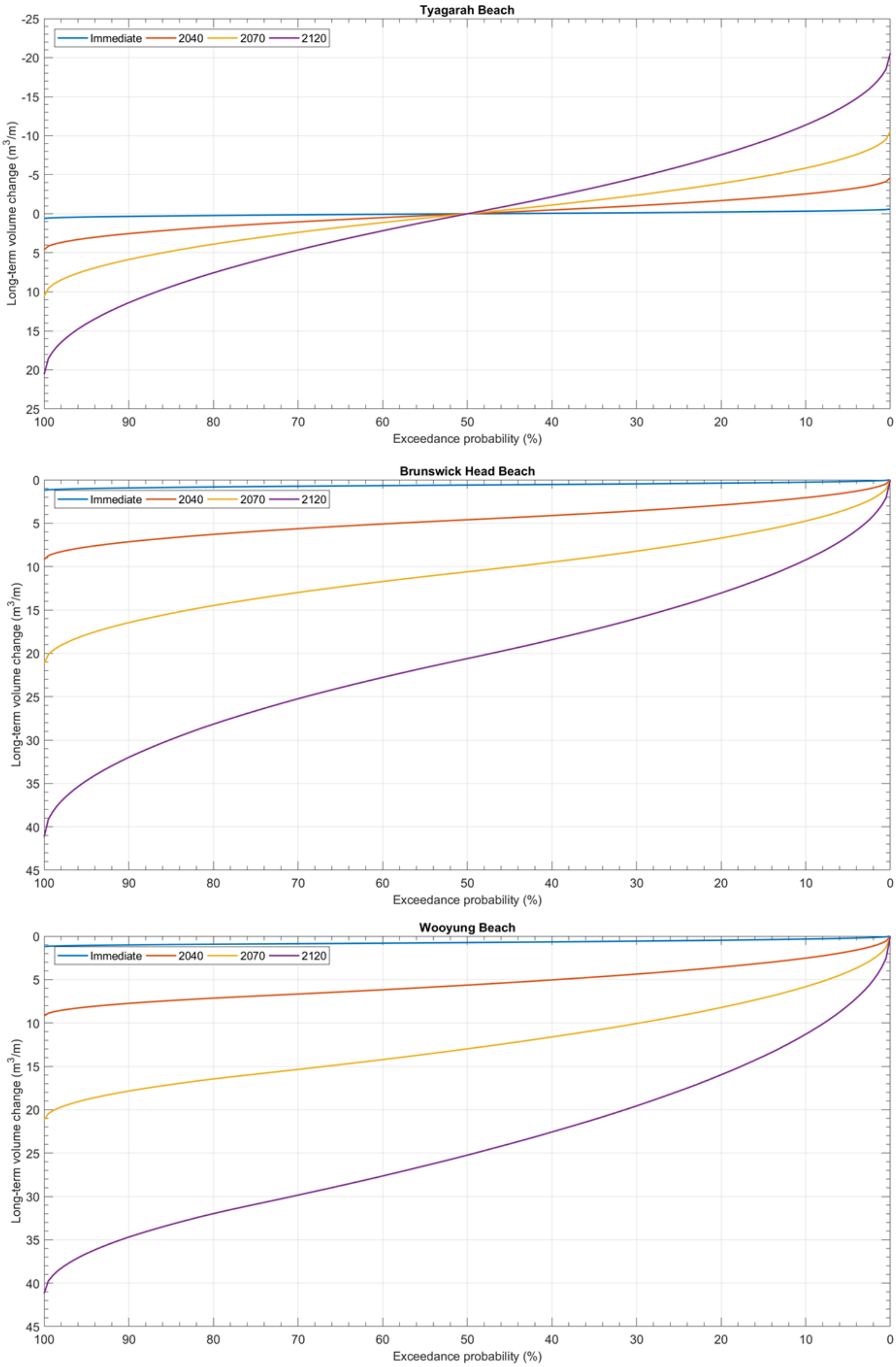

Figure 72: Example cumulative probability distributions for long-term volume change inputs – northern beaches.

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, cross-embayment sand transport, storm clusters, offshore losses and other processes linked to climate cycles. These fluctuations in beach volume are mainly observed at the southern embayment and have been taken into account in the coastal erosion and recession assessment.

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 (i.e., derived from August 2018 marine LiDAR data), see Figure 73. Two allowances for short term beach volume variability have been defined independently, i.e.:

- Headland bypassing effects – based on the observed subaerial profile volume change during the most recent bypassing event (see Section 4.4.3 and Section 4.4.4)
- Cross-embayment sand transport effects – based on the estimated additional onshore sand supply during high cross embayment sand transport events (see Section 4.4.6). The available evidence suggests that the timing and rate of such temporary increases in sand transport via the cross-embayment pathway differs to the headland bypassing sand transport via the littoral pathway and therefore the effects of these processes should be considered independently.

The erosion and recession calculations for other included hazards are then undertaken on the modified baseline profile with the randomly sampled subaerial profile volume variability. An example input probability distribution for the short term subaerial beach volume variability due to headland bypassing effects are presented in Figure 73.

It is noted that while two specific coastal processes were defined above, there could be other events that result in short term variability of the typical subaerial beach profile (e.g., storm clusters, climate cycles). It is assumed that such other processes are also well captured within the adopted short term subaerial beach profile volume variability allowances and treating such events independently would likely result in over-conservative hazard extent predictions.

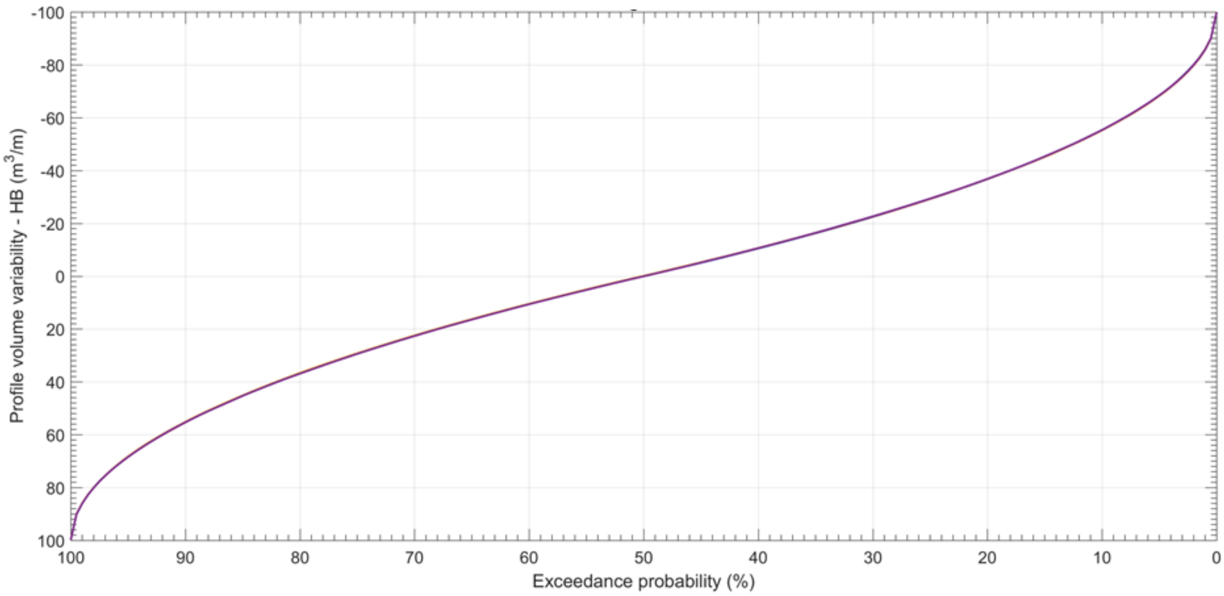

Figure 73: Example input probability distribution for short term subaerial beach profile volume variability due to headland bypassing effects.

Table 16: Adopted input ranges for triangular distribution of short term beach volume variability in the erosion and recession hazard model.

Location	Section (profile #)	Short-term variability in subaerial profile volume (m^3/m) [2] [min, mode, max]
Byron embayment	Wategos Beach	*Not included*
	The Pass	*Not included*
	Clarkes Beach (p170 – p179)	-100, **0**, +100 (headland bypassing) 0, +**40**, +60 (cross-embayment transport)
	Main Beach (east and west of JSPW) (p180 – p259)	-100, **0**, +100 (headland bypassing) 0, +**40**, +60 (cross-embayment transport)
	Belongil Beach	*Not included*

Change in onshore sand supply

As described in Section 4.4.2, at present, onshore sand supply likely occurs and is captured in historic observed beach behaviour along all beaches in the study area. For the Tallow Beach compartment (i.e., Broken Head to Cosy Corner), a relatively higher rate of onshore sand transport was estimated due to the influence of the Cape Byron - Ballina Shelf Sand Body.

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 17). This included a range of change in onshore sand supply to the subaerial beach using a triangular probability distribution as follows:

- Present – modal value set to nil as adopted historic profile volume changes already include (to some extent) onshore sand supply.
- Uncertainty range increased for later planning periods due to limited knowledge of future change to upper shoreface sand supply rate with sea level rise. Skewed toward increase in onshore sand supply with sea level rise.
- Linear interpolation between time periods presented in Table 17.

An example probability distribution as input to the probabilistic erosion and recession hazard model is presented in Figure 74.

Table 17: Adopted input ranges for triangular distribution of changes to onshore sand supply in the erosion and recession hazard model.

Location (profile #)	Section	Change in onshore sand transport rate ($m^3/m/yr$) [1] [min, mode, max]
Broken Head to Cape Byron (p44 – p150)	Broken Head Suffolk Park Tallow Beach Cosy Corner	-0.2, **0**, +0.2 (immediate) -0.5, **0**, +1.0 (2050) -1.0, **0**, +2.0 (2120)

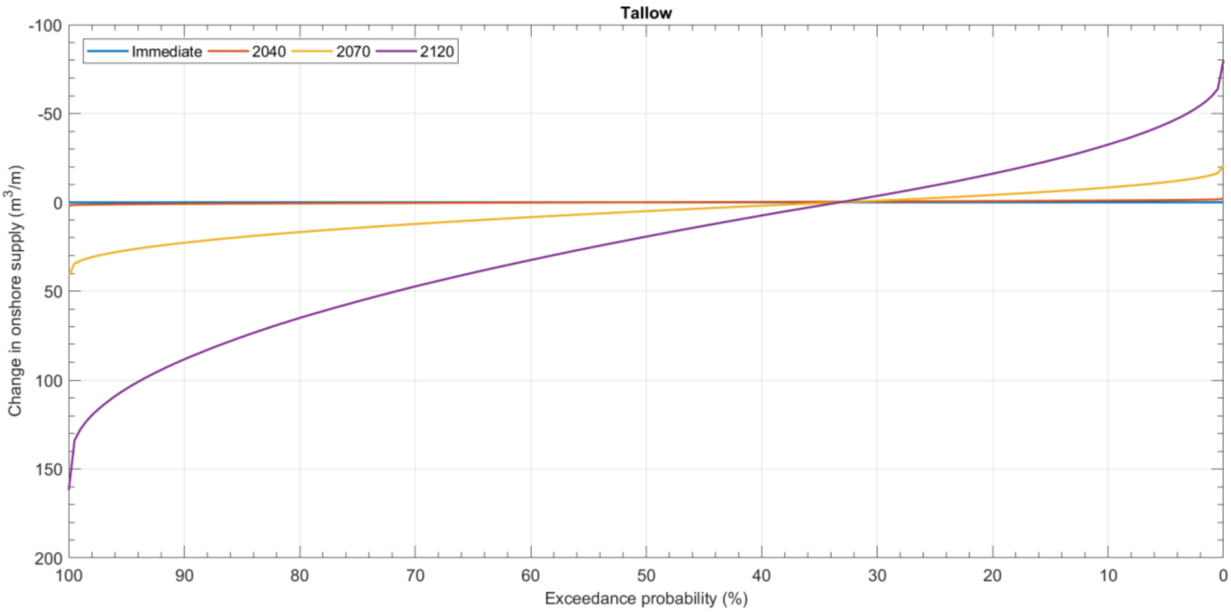

Figure 74: Cumulative probability distribution for change in onshore sand supply allowance for subaerial beach volume.

Estuaries

Flood tide delta aggradation at the estuary entrances in the Byron Shire is expected with rising sea levels (Eysink, 1990). This assumes that sea level rise will cause an 'overdepth' (or increased accommodation space) within the estuary mouth which will subsequently infill with marine sand to re-establish the previous equilibrium in water depths. This net 'loss' of marine sand from the active coastal zone 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 then applied to each of the analysis beach profiles within adjacent updrift and downdrift compartments of the estuary entrances, as specified in Table 18. This volume reduction would be expected to occur across the full active coastal profile. For the purposes of the erosion and recession hazard calculations, one third of this volume reduction is applied to the subaerial beach volume.

The adopted active submerged flood delta area for each estuary and length of affected sandy beach adjacent to estuary entrance are provided in Table 18. The approximate active flood tide delta area (including entrance berm) was estimated based on aerial imagery. Probability distributions as input to the probabilistic erosion and recession model are provided in Figure 75.

Table 18: Ranges of active flood tide delta areas in square metres (m^2).

Estuary	Min	Mode	Max	Alongshore length of affected beach (m) (profile #)	Comment
Ti Tree Lake	4,000	5,000	6,000	1,000 (p52 – p71)	Affected section of beach estimated based on observed historic entrance processes.
Tallow Creek	16,000	20,000	24,000	2,000 (p108 – p129)	
Belongil Creek	28,000	35,000	42,000	2,000 (p283 – p337)	
Brunswick River	280,000	350,000	420,000	2,000 (p433 – p474)	

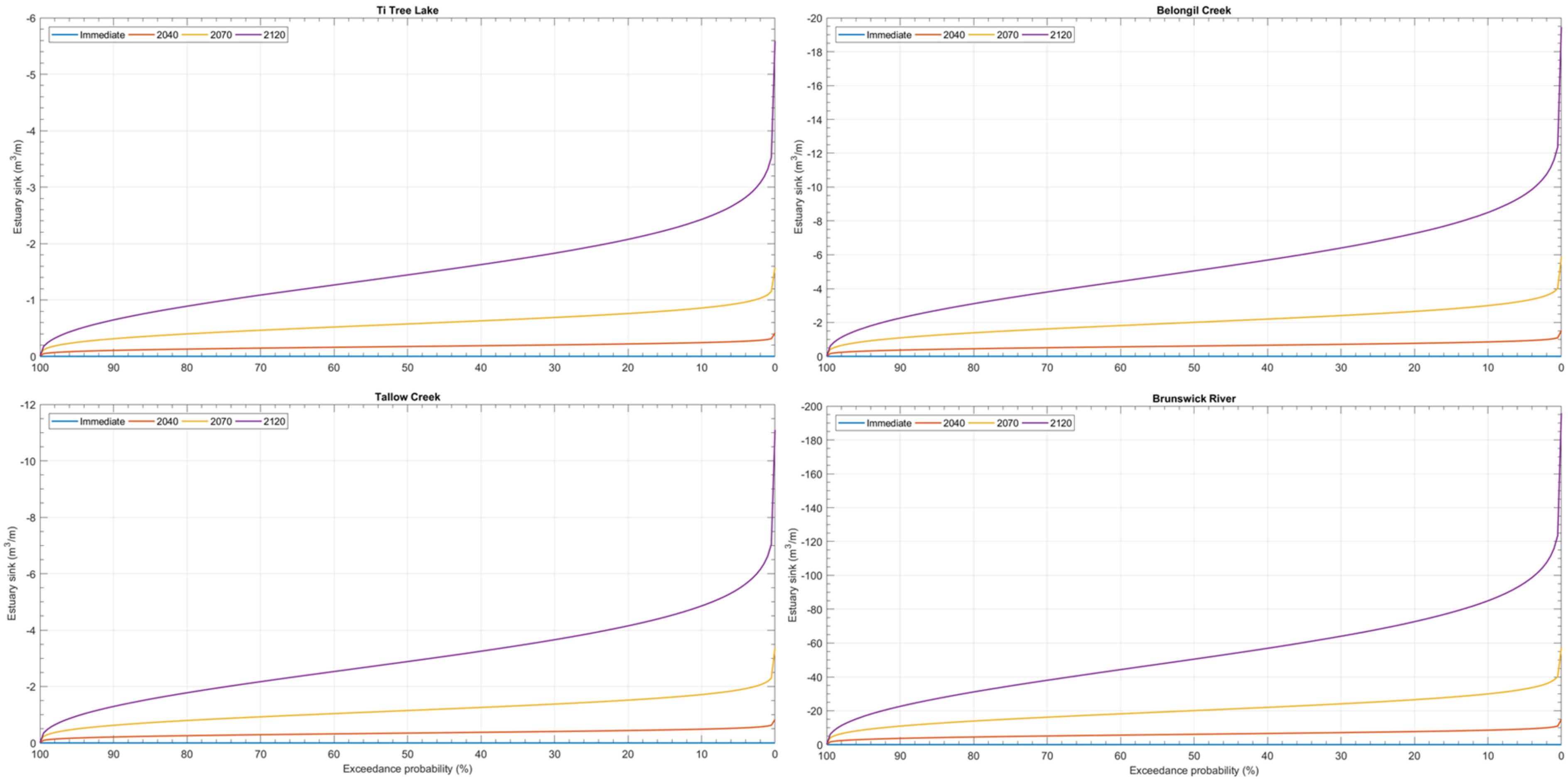

Figure 75: Cumulative probability distributions for estuary sink allowances due to sea level rise.

5.3.5 Sea level rise

Coastal profile adjustments due to sea level rise are assessed using a volumetric approach following the principles in Bruun (1962). A similar method used in Kinsela et al. (2016) was further refined for the purposes of this hazard assessment. This considers an upward and landward shift of the equilibrium profile with sea level rise. The active volume of sand that is redistributed by this process is limited to the profile part between the top of dune and the depth of closure. A conceptual diagram describing the adopted approach to estimating the profile response to sea level rise is provided in Figure 76.

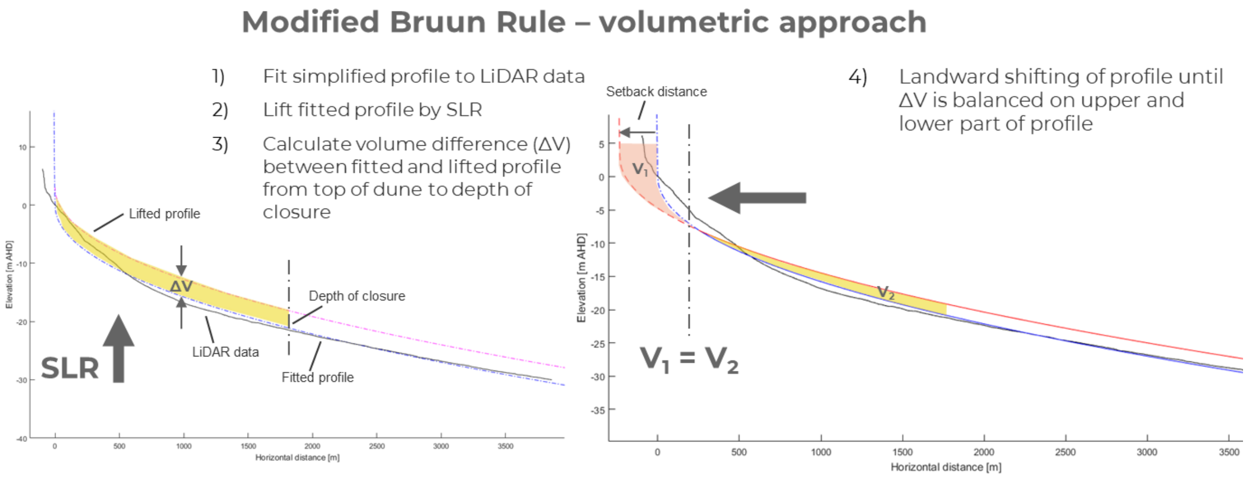

Figure 76: Diagram describing adopted sea level rise recession calculation.

For the purposes of the recession calculations, the sea level rise values and likelihoods presented in Section 3.6 (Table 9) based on the IPCC AR6 projection for Yamba (Garner et al., 2021) were considered. A full distribution of sea level rise projections for every year in the planning periods was established by fitting a Weibull distribution[6] to the quantiles (5th to 95th) in Table 9. This allows extrapolating to higher and lower quantiles that are not reported in IPCC AR6 'medium confidence' projections. The extrapolated, full probability distributions, of sea level rise projections (relative to 2020 baseline) adopted as input to the probabilistic recession calculations are provided in Figure 77.

To determine the seaward extent of the active coastal profile for the sea level rise recession calculation, the depth of closure value ranges presented in Table 19 were defined. The adopted ranges were used to generate triangular probability distributions as input to the probabilistic model. Linear interpolation of the presented depth of closure values in Table 18 was undertaken for every year in the adopted planning periods. The adopted depth of closure values were determined for the purposes of sea level rise recession calculation and consider typical closure depth along NSW beaches, relative wave exposure as well as morphology and geology of the coastal profile. Within the southern embayment, the adopted seaward end of the profile where littoral processes are observed are relatively shallow. It is noted that seabed changes in deeper water occur and are related to other sand transport processes, including cross-embayment transport and headland bypassing effects (see Section 4.4.3 and Section 4.4.6). For exposed open-beach locations in the Byron Shire, the closure depth ranges were gradually increased for later planning horizons following the reasoning in Kinsela and Cowell (2015) and Kinsela et al. (2016).

[6] Representative fitting model and parameters were determined via sensitivity analysis.

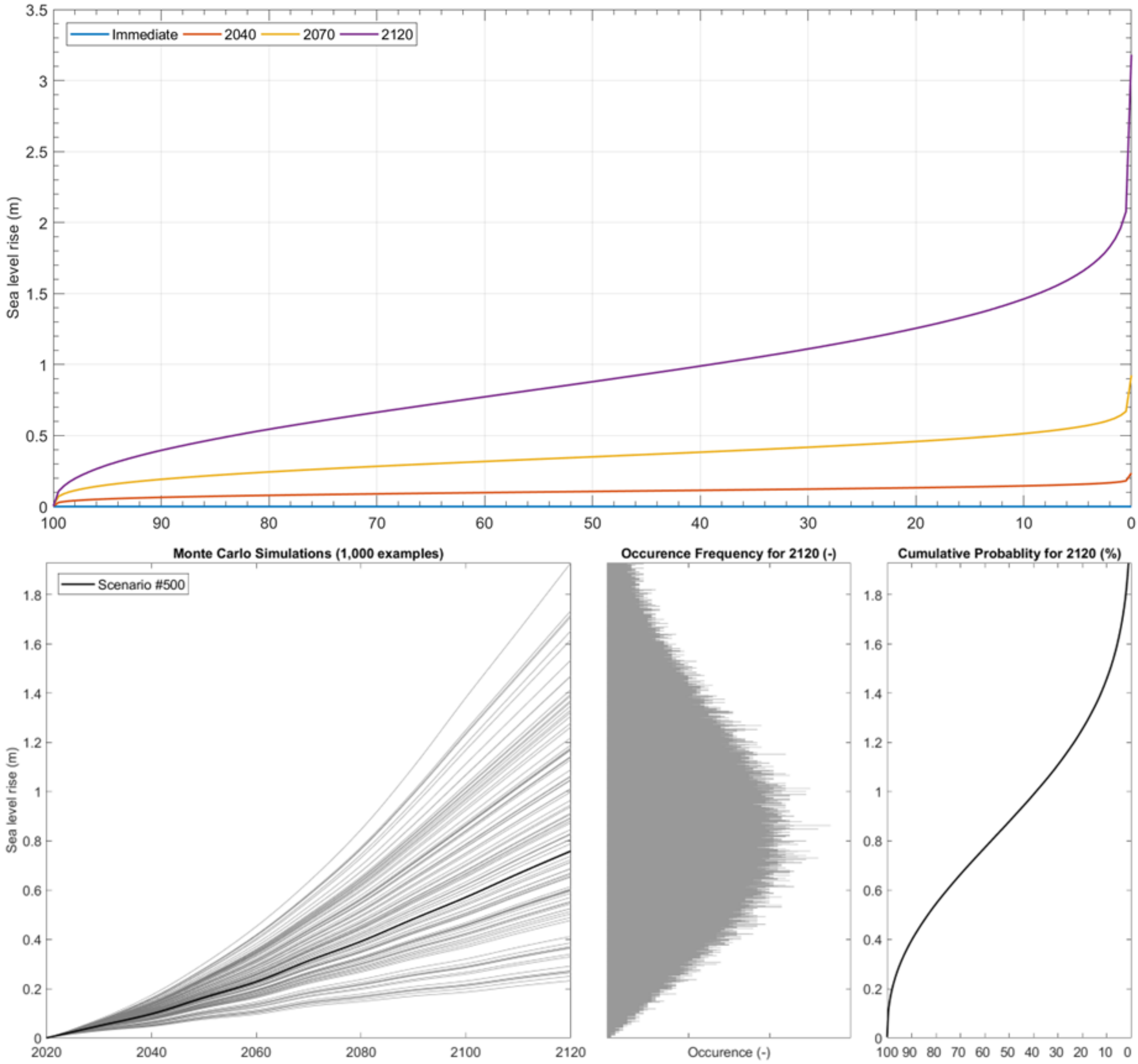

Figure 77: (top) Adopted probability distributions of sea level rise projections for key planning horizons and (bottom) example results from Monte Carlo simulation.

Table 19: Adopted depth of closure ranges over time.

Location		Until 2050	2100	2120	Comment
Open beaches^	Minimum	10	13	14	Current values (until 2050) derived from repeat bathymetry survey. 2120 value range based on 'slope factors' adopted in BMT WBM (2013). 2100 value range interpolated between 2050, 2100 values.
	Mode	14	20	22	
	Maximum	20	25	27	

Location		Until 2050	2100	2120	Comment
Wategos Beach to Clarkes Beach	Minimum	4	4	4	Values derived from repeat bathymetry survey, interpretation of profile slopes and geology. Depth of active littoral zone influenced by presence of reef platforms and embayment planform (see Section 4.4.6). No increase in closure depth for future periods due limiting factors described above.
	Mode	5	5	5	
	Maximum	8	8	8	
Main Beach	Minimum	5	5	5	
	Mode	6	6	6	
	Maximum	9	9	9	
Belongil Beach	Minimum	6	6	6	
	Mode	8	8	8	
	Maximum	10	10	10	

Note: ^Open beaches include Seven Mile Beach to Cosy Corner and Tyagarah to Wooyung.

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, revetments and other informal coastal protection structures exist along the Byron Shire coastline. The structure locations are shown on the coastal erosion and recession hazard maps in the map compendium at the end of this report. The legal status, condition and expected performance in limiting coastal erosion during extreme events varies considerably across these structures. At Belongil, some form of seawall or revetment exist near-continuously between Border Street and the northern end of Childe Street protecting private properties and public road reserves (i.e., some seawalls are privately owned/maintained, and others are publicly owned). Council has provided an April 2018 summary of information pertaining to these seawalls based on the development applications from six properties where the residents were seeking repair of these seawalls (Byron Shire Council, 2018). The summary states that the pre-repair/renewal level of erosion resistance of most of the structures (5 out of 6) was equivalent or less than that of a 1-year Annual Recurrence Interval (ARI) erosion event. Further, this information states that for some (2 out of 6) of the rock seawalls the proposed repairs would increase the performance of the subject structures to withstand a 10-year ARI event. For the purpose of this hazard assessment, and in the absence of a consistent, detailed and current engineering condition assessment across each of the rock seawalls, it has been assumed that all existing private and public rock seawalls between Border Street and Childe Street have an equivalent engineering design standard of a 10-year ARI event.

It was assumed that all structures are retained and maintained in their existing footprints over the assessment period. The critical levels of structural damage and related erosion event probability proposed for the erosion hazard assessment are presented in Table 20. The adopted structural damage/ failure thresholds are informed by WorleyParsons (2013), Byron Shire Council (2018), past observations and engineering judgement. If the damage threshold is exceeded, it was assumed that the structure will provide a 50 per cent reduction in erosion landward of its position. If the failure threshold is exceeded, no reduction in erosion is assumed. For example, all maintained rock structures at Belongil would be considered to:

- Fully limit the landward erosion extent up to a 10-year ARI erosion event (i.e., repaired structure's proposed design event; see Byron Shire Council, 2018)
- Provide a 50 per cent reduction in erosion for areas landward of the structure for events between 10-year ARI and 20-year ARI (i.e., assumed failure threshold)
- Provide no reduction in erosion for areas landward of the structure for erosion events greater than 20-year ARI (full failure of structure)

It was assumed that all structures would be adequately maintained to be effective in limiting long-term shoreline recession due to sand budget imbalances and/or sea level rise (i.e., structures would be rebuilt and upgraded as required to maintain their current position and performance). A 25 per cent increase in the historically observed shoreline recession rates was adopted for the area downdrift (west) of the Belongil seawalls up to the northern end of Belongil spit. This is to account for their effect on coastal processes as the adjacent shoreline recedes and the structures protrude further on the active beach, as estimated in BMT WBM (2013). No increase in the recession rates downdrift (west) of the Jonson Street protection works was adopted as this (Jonson Street) structure already protrudes on the active beach. However, a higher storm demand has been adopted for the area immediately west of the Jonson Street protection works due to possible structure interaction that may exacerbate storm erosion in this area during extreme events.

Table 20: Existing coastal protection structures and their considered level of erosion protection performance.

ID	Description	Threshold for landward erosion	Threshold for full failure	Comment
S1	Elements Resort (Belongil Beach) geotextile revetment	Fully erodible	Fully erodible	Assumed not designed to withstand direct wave attack.
S2	Belongil geotextile revetments (public)	1-year ARI	20-year ARI	Damage threshold derived from WorleyParsons (2013). Full failure threshold assumed based on structural performance to date and engineering judgement.
S3	Rock revetment in front of private properties and public road reserves at Belongil Beach	10-year ARI	20-year ARI	Based on 10-year ARI design standard for proposed structure repairs in Byron Shire Council (2018).

ID	Description	Threshold for landward erosion	Threshold for full failure	Comment
S4	Jonson Street Protection Works	Non erodible	Non erodible	Assumed to be maintained/ upgraded to required engineering standard to withstand all erosion events.
S5	Byron SLSC geotextile revetment	1-year ARI	20-year ARI	Damage threshold derived from WorleyParsons (2013). Full failure threshold assumed based on structural performance to date and engineering judgement.
S6	Clarkes Beach geotextile revetment	Fully erodible	Fully erodible	Temporary and low crested structure not expected to provide long-term protection. Not included in hazard assessment.
S7	Wategos Beach rock revetment	Full erodible	Fully erodible	Low crested rock revetment between Marine Parade and the beach. Design standard unknown and not expected to provide long-term protection. Not included in hazard assessment.

5.3.7 Substrate effects

The presence of indurated sand (or coffee rock) lenses and shallow/ outcropping bedrock within the coastal profile is evident along much of the Byron Shire coast (see Section 3.1). Such consolidated or hard substrata can provide a level of erosion resistance. While the level of erosion resistance of coffee rock lenses depends on many variables, it is commonly accepted that some resistance is provided during storm erosion events (OEH, 2016; Kinsela et al., 2016). The effect of substrate was considered in determining the erosion extents on sandy coastlines along the Byron Shire coast.

Where coffee rock lenses and/or shallow or outcropping bedrock are known to be present within the dune face, upper beach or inner nearshore a reduction in the storm erosion volumes has been applied in the probabilistic model. The range of scaling factors was adopted from OEH's (2016) assessment into coastal hazards at Lake Cathie, NSW. In the absence of relevant data, OEH (2016) determined this range through an expert panel. Given the uncertainty in the level of erosion resistance, a triangular distribution for a range of reduction 'factors' was used based on the values presented in Table 21. The erosion limiting factors were considered as follows:

- Scaling of storm erosion volumes was applied to all beach profiles within areas where there is evidence for the presence of coffee rock based on regional geology data, previous reports, site observations and review of aerial imagery (see Figure 79). No scaling of long-term recession calculations was undertaken for areas with known coffee rock presence due to the low resistance of this substrate to weathering and erosion once it has been exposed.
- Where there is evidence of nearshore reefs, this was accounted for in the sea level rise profile adjustments (see Section 0). Similar to the scaling of the storm erosion volumes, the reduction factors in Table 21 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 large nearshore reefs based on aerial imagery and NSW seabed landforms dataset derived from marine lidar data (shown in Figure 79).

- Where outcropping bedrock is evident on the upper beach, the landward extent of erosion hazard was limited to the seaward edge of the known bedrock location/level.

Table 21: Adopted coastal response scaling factors for coffee rock lenses and nearshore reefs.

Probability distribution parameter	Volume reduction factor (-)
Minimum	0.6
Mode	0.7
Maximum	0.8

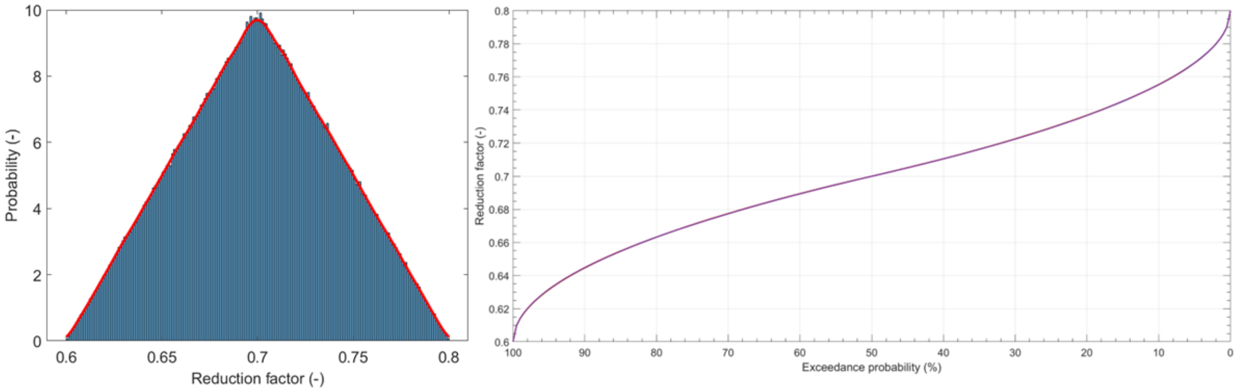

Figure 78: Input (left) triangular probability distribution and (right) cumulative distribution for adopted range of volume reduction factors for storm demand and sea level rise profile adjustments.

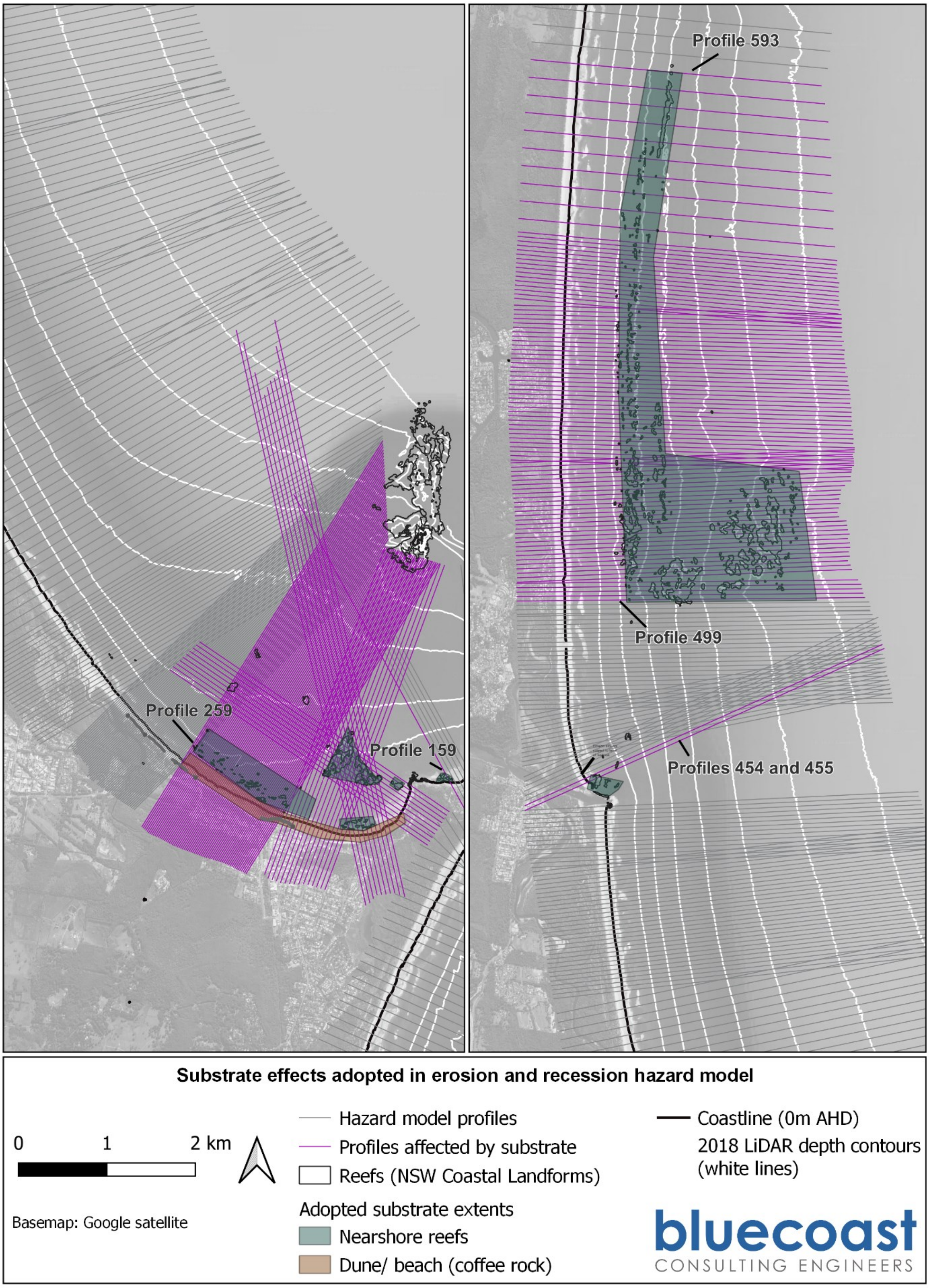

Figure 79: Adopted extents of coffee rock substrate and reefs in the erosion and recession hazard model.

5.3.8 Summary of inputs

A summary of the adopted inputs for the probabilistic coastal erosion and recession hazard assessment is provided in Table 22.

Table 22: Summary of adopted inputs for the erosion and recession hazard assessment.

Location	Section (profile #)	Long-term subaerial volume change m³/m/year	100-yr ARI storm erosion volume range m³/m	Depth of closure range m	Change in onshore transport rate m³/m/yr	Short-term variability in profile volume m³/m	Substrate scaling factors (type) -	Estuary sink – active delta area/ length of beach section (profile #) m² /m
Seven Mile Beach to Broken Head	Seven Mile Beach (p1 – p43)	-2.3, -1.9, -1.5	150, 200, 300	10, 14, 20 (up to 2050) 13, 20, 25 (2100) 14, 22, 27 (2120)	-	-	-	-
Broken Head to Cape Byron	Broken Head (p44 – p71)	0, 0, 0	150, 200, 300	10, 14, 20 (up to 2050) 13, 20, 25 (2100) 14, 22, 27 (2120)	-0.2, 0, +0.2 (immediate) -0.5, 0, +1.0 (2050) -1.0, 0, +2.0 (2120)	-	-	4, 5, 6 (p52 – p71)
	Suffolk Park (p72 – p113)	0, +1.4, +1.7				-	-	8, 10, 12 (p108 – p113)
	Tallow Beach (p114 – p143)	0, +1.4, +1.7				-	-	8, 10, 12 (p114 – p129)
	Cosy Corner (p144 – p150)	0, +1.4, +1.7				-	-	-

Location	Section (profile #)	Long-term subaerial volume change	100-yr ARI storm erosion volume range	Depth of closure range	Change in onshore transport rate	Short-term variability in profile volume	Substrate scaling factors (type)	Estuary sink – active delta area/ length of beach section (profile #)
		m^3/m/year	m^3/m	m	m^3/m/yr	m^3/m	-	m^2 /m
	Wategos Beach (p151 – p159)	-0.2, 0, +0.2	75, 100, 150	4, 5, 8 (all years)	-	-	-	-
	The Pass (p160 – p169)	-0.2, 0, +0.2	75, 100, 150	4, 5, 8 (all years)	-	-		-
	Clarkes Beach (p170 – p179)	-1.0, 0, +1.0	110, 150, 225	4, 5, 8 (all years)	-	-100, 0, +100 (headland bypassing) 0, +40, +60 (cross-embayment transport)	0.6, 0.7, 0.8 (coffee rock) 0.6, 0.7, 0.8 (reefs)	-
Byron embayment	Main Beach (east of JSPW: p180 – p194) (west of JSPW: p195 – p259)	-1.9, 0, +1.6 (east of JSPW) -2.1, 0, +0.2 (west of JSPW)	150, 200, 300 (east of JSPW) 150, 250, 350 (west of JSPW)	5, 6, 9 (all years)	-			-
	Belongil Beach (up to north end of seawalls: p260 – p300) (north of seawalls: p301 – p341)	-2.9, 0, +0.2 (up to north end of seawalls) -3.6, 0, +0.2 (north of seawalls)	150, 200, 300	6, 8, 10 (all years)	-	-	-	14, 17.5, 21 (p283 – p337)
	Tyagarah Beach (p342 – p409)	-0.2, 0, +0.2	150, 200, 300	10, 14, 20 (up to 2050)	-	-	-	-

Location	Section (profile #)	Long-term subaerial volume change m³/m/year	100-yr ARI storm erosion volume range m³/m	Depth of closure range m	Change in onshore transport rate m³/m/yr	Short-term variability in profile volume m³/m	Substrate scaling factors (type) -	Estuary sink – active delta area/ length of beach section (profile #) m² /m
Tyagarah to Brunswick River	Brunswick Head Beach (p410 – p453)	0, +0.2, +0.4		13, 20, 25 (2100) 14, 22, 27 (2120)	-	-	-	140, 175, 210 (p433 – p453)
Brunswick River to Wooyung	North Head (p454 – p487)	0, +0.5, +0.6	150, 200, 300	10, 14, 20 (up to 2050) 13, 20, 25 (2100) 14, 22, 27 (2120)	-	-	p454 – p455: 0.6, 0.7, 0.8 (reefs)	140, 175, 210 (p454 – p474)
	New Brighton Beach (p488 – p524)	0, +0.4, +0.5			-	-	p499 – p593: 0.6, 0.7, 0.8 (reefs)	-
	South Golden Beach (p525 – p583)	0, +0.4, +0.5			-	-		-
	Wooyung Beach (p584 – p596)	0, +0.3, +0.4			-	-		

5.4 Results

The probability of exceedance of the landward position of the Zone of Slope Adjustment (ZSA) and 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. Alongshore average results of the landward position of the ZRFC for each beach section are also provided in Table 23.
- For mapping and tabular data, only the position of the ZRFC for the 1%, 2%, 5% and 10% probability of exceedance levels are shown for the immediate, 2040, 2050, 2070 and 2120 planning timeframes. The probability exceedance curves for each beach section are provided in **Appendix D**.
- By exception, at Wategos Beach, the results present the ZSA (instead of ZRFC) due to the steep bedrock topography. For this location, calculation of the ZRFC 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).
- 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 Clarkes Beach, Main Beach, Belongil Beach and at New Brighton Beach (lower likelihood). By 2120, the hazard extents would affect a considerably larger number of additional public and private assets and foreshore area at the northern end of Seven Mile Beach, Broken Head to Suffolk Park, Clarkes to Main Beach, Belongil Beach, Brunswick Beach, New Brighton and South Golden Beach. A detailed asset exposure and risk assessment, including possible consequences, was not completed as part of this study.

Mapped erosion and recession hazard extents within the Byron embayment (Clarkes, Main and Belongil Beach) are subject to short term changes in beach volumes due to the effects of headland bypassing around Cape Byron and other sand supply processes discussed in Section 4.4. A reasonable allowance for such effects was considered in predicting the erosion and recession hazard extents within the Byron embayment across the planning timeframes (refer Section 5.3.4). However, during periods of low beach volumes it is possible (low probability) that the storm erosion hazard extends to areas further landward of the mapped extents. This complexity must be understood when assessing how vulnerable the embayment's beaches, dunes, and foreshore are to storm erosion and when planning coastal management in the future.

Table 23: Alongshore average distance from 0m AHD (2018 baseline) for the projected landward position of the Zone of Reduced Foundation Capacity (ZRFC) at each beach section – actual hazard extents may be limited by hard substrate in some areas.

Location	Section	Probability	Immediate	2040	2050	2070	2120
Seven Mile Beach to Broken Head	Seven Mile Beach	1%	-124	-142	-149	-165	-235
		2%	-114	-131	-139	-155	-221
		5%	-104	-122	-129	-144	-201
		10%	-95	-112	-119	-132	-181
Broken Head to Cape Byron	Broken Head	1%	-112	-118	-123	-135	-200
		2%	-104	-110	-114	-126	-186
		5%	-92	-99	-103	-113	-165
		10%	-82	-88	-92	-100	-145
	Suffolk Park	1%	-111	-109	-111	-120	-176
		2%	-106	-103	-105	-112	-160
		5%	-99	-95	-95	-98	-134
		10%	-91	-87	-85	-84	-110

Location	Section	Probability	Immediate	2040	2050	2070	2120
	Tallow Beach	1%	-118	-114	-115	-122	-172
		2%	-110	-107	-107	-112	-155
		5%	-99	-95	-95	-96	-129
		10%	-88	-83	-82	-81	-105
	Cosy Corner	1%	-156	-153	-153	-159	-205
		2%	-148	-144	-143	-146	-183
		5%	-121	-117	-116	-117	-146
		10%	-94	-90	-89	-89	-115
Byron embayment	Wategos Beach*	1%	-62	-67	-71	-81	-125
		2%	-57	-62	-65	-75	-116
		5%	-47	-51	-55	-64	-103
		10%	-36	-41	-44	-54	-92
	The Pass	1%	-109	-117	-123	-139	-210

Location	Section	Probability	Immediate	2040	2050	2070	2120
		2%	-101	-109	-115	-130	-196
		5%	-85	-93	-98	-113	-174
		10%	-66	-74	-80	-94	-155
	Clarkes Beach	1%	-97	-105	-111	-127	-200
		2%	-88	-96	-101	-116	-186
		5%	-72	-80	-85	-100	-166
		10%	-57	-65	-70	-85	-148
	Main Beach (east of JSPW)	1%	-108	-115	-121	-136	-202
		2%	-98	-106	-111	-126	-189
		5%	-83	-90	-95	-108	-167
		10%	-69	-76	-81	-94	-149
	Main Beach (west of JSPW)	1%	-122	-130	-134	-146	-187
		2%	-113	-121	-125	-137	-176

Location	Section	Probability	Immediate	2040	2050	2070	2120
		5%	-97	-104	-108	-118	-152
		10%	-81	-87	-91	-99	-130
	Belongil Beach	1%	-108	-122	-129	-143	-174
		2%	-102	-115	-121	-135	-166
		5%	-85	-95	-99	-107	-126
		10%	-70	-73	-74	-78	-88
	Belongil Beach (north of protective structures)	1%	-143	-161	-170	-192	-286
		2%	-133	-149	-158	-179	-266
		5%	-114	-130	-139	-158	-235
		10%	-96	-111	-120	-138	-207
Tyagarah to Brunswick River	Tyagarah Beach	1%	-125	-130	-132	-140	-175
		2%	-114	-118	-121	-130	-163
		5%	-101	-105	-108	-115	-144

Location	Section	Probability	Immediate	2040	2050	2070	2120
		10%	-88	-92	-95	-102	-128
	Brunswick Head Beach	1%	-134	-138	-141	-150	-189
		2%	-123	-127	-130	-139	-176
		5%	-108	-112	-115	-123	-156
		10%	-94	-97	-100	-108	-137
Brunswick River to Wooyung	North Head	1%	-130	-134	-138	-148	-199
		2%	-121	-125	-129	-139	-186
		5%	-109	-113	-116	-125	-165
		10%	-97	-101	-104	-112	-146
	New Brighton Beach	1%	-130	-132	-134	-140	-175
		2%	-120	-122	-124	-131	-163
		5%	-109	-111	-113	-119	-145
		10%	-100	-101	-103	-107	-128

Location	Section	Probability	Immediate	2040	2050	2070	2120
	South Golden Beach	1%	-139	-141	-143	-150	-182
		2%	-130	-132	-134	-140	-170
		5%	-117	-119	-120	-126	-150
		10%	-103	-105	-107	-112	-132
	Wooyung Beach	1%	-137	-139	-142	-149	-185
		2%	-128	-131	-133	-141	-174
		5%	-119	-121	-123	-130	-156
		10%	-109	-111	-113	-119	-140

6. Coastal cliff and geotechnical hazards

6.1 Overview

A high-level geotechnical assessment of the coastal cliffs within the Byron Shire was undertaken by Douglas Partners Pty Ltd. The scope of this assessment was to:

- identify potential areas where further investigation may be warranted
- complete a preliminary risk assessment for slope stability providing commentary with regards to 'risk of life'.

The areas investigated as part of this high-level assessment included:

- Broken Head
- Cape Byron
- Wategos
- The Pass.

The following sections provide a summary and key outcome from the high-level geotechnical assessment. The preliminary landslip hazard risk assessment report is provided in **Appendix E**. This summary should be read in conjunction with the full report.

6.2 Approach

The assessment included a desktop study of the regional geology, a walkover survey, qualitative and quantitative landslip hazard risk assessments and preparation of a geotechnical hazard report with relevant geotechnical engineering recommendations as required.

The assessment is limited to areas that were accessible during the site walkover on 20 April 2022. The assessment locations are mapped in Figure 80.

Figure 80: Assessment locations visited by Douglas Partners during the site walkover.

6.3 Results

A summary of the visual inspection of the coastal cliffs identifying any evidence of existing instability or potential instability is provided in Table 24.

During the site walkover and considering the access limitations and vegetation in part, no significant areas require further detailed assessment were observed. Although some areas of localised wedge failure or slumping were observed, they were generally minor and not representative of the overall rock mass.

Based on the qualitative assessment, the likelihood of landslip with 'risk to life' is 'very low to low'.

Table 24: Summary of site walkover results from Douglas Partners report.

Location	Approx. height (m)	Slope angle (°)	Rock mass description	Observed stability
Broken Head	6	45	Highly to moderately weathered metasiltstone	Predominantly the rock mass appeared intact. Some wedge block failure was observed. Previous slumping along dune west of headland (existing signage).
Cape Byron	8	45	Highly to moderately weathered metasiltstone	Some surface slumping in upper level highly weathered metasiltstone. No likely obvious potential instability was observed.
Wategos Beach (eastern headland)	20	45	Moderately to slightly weathered metasiltstone	Predominantly the rock mass appeared intact. No likely obvious potential instability was observed.
Wategos Beach (northern headland)	14	45	Moderately to slightly weathered metasiltstone	Predominantly the rock mass appeared intact. No likely obvious potential instability was observed. Some minor rock fall was observed and associated with an existing drainage gully near the beach/headland interface.
The Pass	8	55	Highly weathered metasiltstone (upper ~2m) underlaid by moderately to slightly weathered metasiltstone	Predominantly the rock mass appeared intact. Some minor slumping was observed in the upper profile. No likely obvious potential instability was observed.

6.4 Recommendations

Based on the preliminary landslip hazard assessment undertaken by Douglas Partners, the following actions were recommended (also see **Appendix E**):

1. Erect warning of potential 'rock fall' signage at each beach and headland interface.
2. In the area of slumping along the foreshore dunal system at Broken Head, remove the slumped material and batter slumped zones at the shallowest angle possible without causing damage to the ecosystem. The newly battered slope shall be planted out to assist in minimising erosion.
3. Carry out annual inspections by duly qualified coastal or geotechnical engineer to review each site and to update comments and recommendations, as site conditions can change rapidly depending on climate and weathering.

7. Coastal inundation hazard assessment

7.1 Overview

In line with the NSW Coastal Management Manual Part B (the Manual - OEH, 2018a), a coastal inundation hazard assessment for the Byron Shire open coast has been undertaken.

The inundation assessment is limited to the storm-related flooding by seawater due to elevated ocean water levels (storm surge) and wave processes (see Figure 81). 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 Byron Shire is not included in this assessment and has been previously assessed in relevant catchment flood studies. A tidal inundation assessment for the Shire's estuaries has been undertaken in Section 8.3.

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).

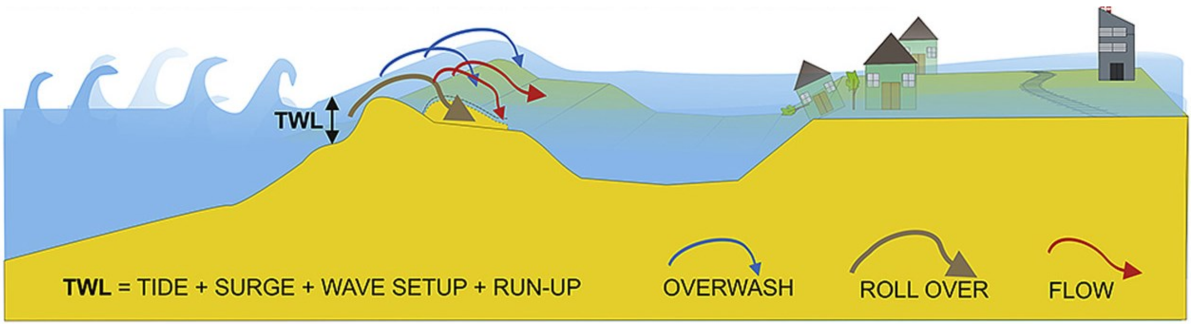

Figure 81: Schematic showing combined inundation by the total water level (TWL) comprising the 'quasi-static' elevated water level and 'dynamic' wave driven processes (source: Fernandez-Montblanc et al., 2020).

A two staged coastal inundation hazard assessment has been completed for the entire Byron Shire LGA open coast:

- **First-pass assessment:** calculation of wave runup levels using empirical formulae for regular shore-normal coastal profiles along the entire Byron Shire coast to identify potential areas exposed to coastal inundation.

- **Local assessment:** following the first-pass assessment, coastal inundation extents and inundation depths are determined by employing a state-of-the-art hydrodynamic and hydrological model, XBeach (Roelvink et al., 2009), for areas that were identified at high risk.

7.2 Approach

7.2.1 First-pass assessment

The wave runup levels are determined using the following data sources:

- 29-year hindcast of nearshore wave data derived from the NSW Coastal Wave Model (OEH, 2017a) at 10m depth every 100m along the entire Byron Shire (provided by Manly Hydraulics Laboratory). The data period available to this study extends from 1993 to 2022.
- Local water level data from the Tweed Offshore tide gauge.
- 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 median value (or 50th 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. 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 (see example results in Figure 82). 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 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. DPE 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.

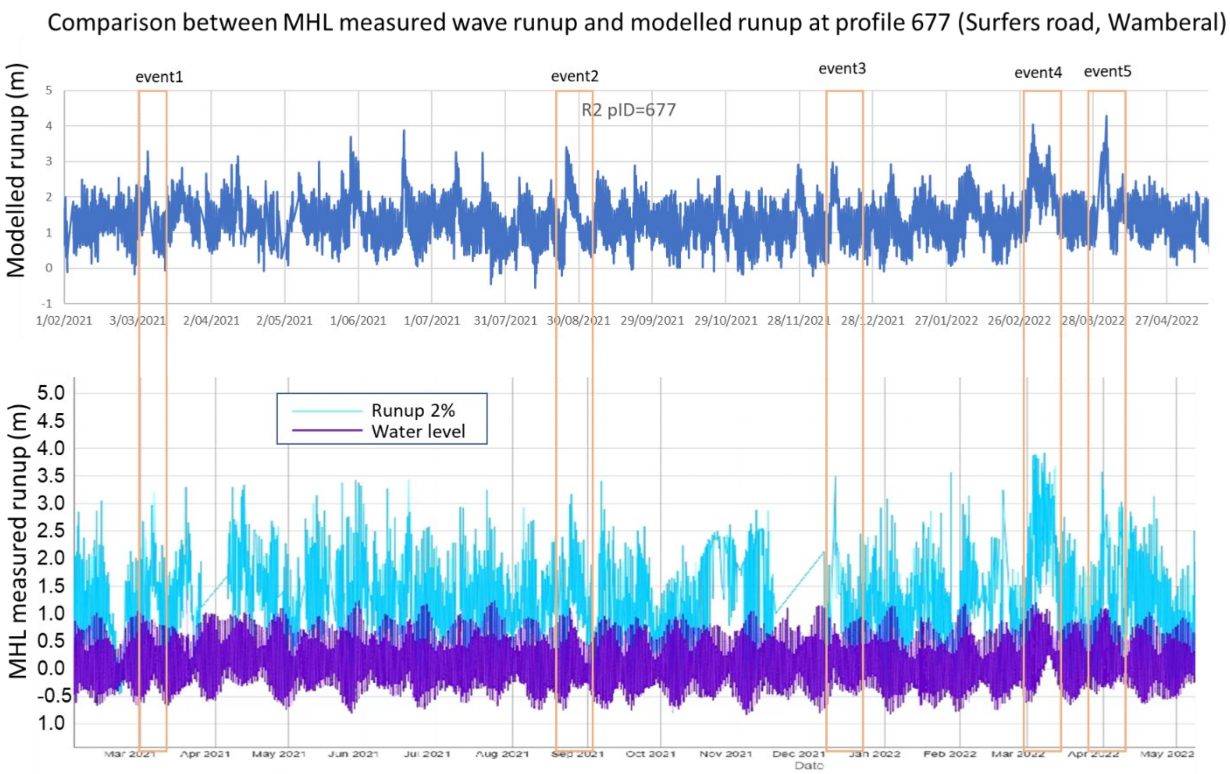

Figure 82: Validation of adopted wave runup calculation approach against measurements at Wamberal, NSW.

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

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

where:

R_p = *Runup for the p quantile or statistic value desired*

H_0 = *deepwater significant wave height*

θ = *angle of the beach slope*

a_p, b_p = *constants based on statistic or quantile value of desired runup*

$$I = \text{Iribarren number} = \frac{\tan\theta}{\left(\frac{H_0}{L_0}\right)^{\frac{1}{2}}}$$

$$a = 2.32, \quad b = 0.77, \quad \text{for } R_{max};$$

$$a = 1.86, \quad b = 0.71, \quad \text{for } R_2;$$

For areas where the wave runup level exceeds the crest level of the coastal barrier an empirical formula to estimate the wave overwash distance was employed. The following equation is used to estimate the propagation distance exceeded by 2% of wave bores (FEMA, 2005). The overwash extent is established using this offset distance from the crest position of the coastal barrier:

$$X = \frac{\sqrt{R - Y_0}\, A(1-2m) g \sqrt{T}}{5}$$

Where X = 2% bore propagation distance landward from crest (m)
R = 2% wave runup level (m AHD)
Y_0 = crest level (m AHD)
T = peak wave period (s)
g = 9.81 m/s^2
A = inland slope factor (default as 1)
m = positive upward inland slope valid for $-0.5 < m < 0.25$

The resulting 29-year hindcast of wave runup levels for each profile location was further analysed using the following steps:

- Calculate wave runup statistics, including maximum levels.
- Calculate wave runup for 2040, 2070 and 2120 planning periods considering the sea level rise projections in Table 9 (50th percentile values).
- Extract the calculated maximum wave runup level and estimated the wave overwash distance for each profile to map the alongshore variation in wave runup levels and overwash.

7.2.2 Local assessment

A state-of-the-art hydrodynamic and hydrological model, XBeach (Roelvink et al., 2009), was employed to simulate coastal inundation extents and depth for areas that were identified at high risk during the first-pass assessment. The scope of the study was limited to complete such detailed numerical modelling assessment for up to three locations and three planning periods (immediate, 2050 and 2120). A detailed description of the XBeach model assessment is provided in **Appendix F**. An overview of the approach is provided below.

XBeach has been widely adopted in coastal inundation assessments and has been validated against field measurements of runup and overtopping in physical model testing (Roelvink et al., 2018). The model allows simulation of wave runup, overwash and overtopping with consideration of complex nearshore wave processes (including wave setup). The estimated maximum inundation extents and depths from the detailed assessment do not account for physical obstructions by buildings, vegetation or built infrastructure. Drainage and infiltration of seawater are also not included in the results. Therefore, the results are conservative and should be interpreted to identify areas potentially at risk.

Based on the first-pass assessment, the following locations have been selected in consultation with Council for the local coastal inundation assessment:

- Belongil Beach
- New Brighton Beach
- South Golden Beach

The three locations have been determined in collaboration with Council and have been selected based on their exposure (identified in first-pass assessment, refer to Section 7.3.1) and potential risk to coastal assets. For each assessment location, an independent XBeach model was setup in 2D and a three-hour storm event representative of a 100-year ARI joint probability (waves and water level) event was simulated. Sea level rise based on IPCC AR6 projections (50th percentile values in Table 9; see Section 3.6) was added to the 100-year ARI joint probability event water level for the 2050 (+0.23m) and 2120 (+0.93m) planning timeframes.

While the results provided herein are suitable for planning purposes and showcase areas potentially at risk and approximate inundation extents, these should be interpreted with consideration of the following limitations:

- 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 would also affect the inundation extents and depth. 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.
- Stormwater drainage, vegetation and infiltration have not been included in the modelling undertaken herein and would likely reduce the presented inundation extents and depth presented.
- The effects of wind on wave overwash and overtopping were not included. Heavy rainfall, antecedent precipitation and estuary flooding were also not considered in this study. These factors could exacerbate inundation. Wave forces and momentum of overtopping jets were also not considered herein.
- 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.

7.3 Results

7.3.1 First-pass assessment

Coastal inundation maps showing the wave runup limit for different percentiles and sea level rise scenarios are presented in the map compendium at the end of this report. A summary of the first-pass inundation assessment results for the maximum wave runup event derived from the 29-year hindcast adopted for the immediate planning timeframe is presented in Table 25. Where significant dune overwash or overtopping of structures was identified, i.e., Main Beach (east), Belongil Beach, New Brighton Beach and South Golden Beach, these sites were considered for further detailed coastal inundation assessment. As part of this study, a detailed coastal inundation assessment using the XBeach numerical model was limited to three sites (refer results in Section 7.3.2). The three sites were selected in collaboration with Council based on the first-pass assessment results and with the following considerations:

- Overtopping of the low-crested rock revetment at Wategos Beach was identified in the first pass assessment, however, no detailed assessment was undertaken as a relatively lower risk compared to other sites was assumed due to the steep bedrock topography landward of the road.
- Main Beach (east) was not further assessed as part of this study as a detailed numerical modelling assessment for this area has been recently undertaken in Bluecoast (2022b).
- While the first pass inundation assessment did not show public or private assets at South Golden Beach to be directly affected, this site was selected for detailed assessment due to the proximity of assets at dune overwash areas.

Table 25: Summary of the first-pass inundation assessment for maximum runup event from 29-year hindcast for immediate timeframe.

Beach	Wave runup level RUmax (m AHD)	Typical dune crest elevation* (m AHD)	Overwashes dune/ structure?	Affects public/ private development?
Seven Mile Beach	6.06	6.0	Yes	No
Broken Head Beach	6.06	6.0	Yes	No
Suffolk Park Beach	6.00	4.0	Yes	No
Tallow Beach	6.23	7.0	No	No
Cosy Corner	6.23	6.0	Yes	No
Little Wategos	5.71	10.0	No	No
Wategos Beach	5.66	5.0	Yes	Yes
The Pass	4.73	6.0	No	No
Clarkes Beach	4.87	4.0	Yes	No
Main Beach (east)	4.98	4.5	Yes	Yes
Main Beach (west)	4.67	7.0	No	No
Belongil Beach	5.51	5.0	Yes	Yes
Tyagarah Beach	5.86	4.0	Yes	No
Brunswick Head	5.78	4.0	Yes	No
New Brighton	5.95	5.0	Yes	Yes
South Golden Beach	6.00	4.5	Yes	No

Note: *Minimum typical dune elevation along beach section at which overwash occurs.
Grey shaded locations have been selected for assessment in local coastal inundation assessment.

7.3.2 Local assessment

Wave overtopping of the coastal barrier (overwash) at each location has been assessed using the XBeach model for the selected joint water level and waves scenarios. A summary of the overwash and overtopping discharge volumes for several observation points (see Figure 83) along each location is provided in Table 26. Measures of the mean overtopping volume (Qx) in litres per seconds per metre (l/s/m) during the three-hour simulations as well as maximum volumes (Qx_{max}) in litres per metre (l/m) and the peak water level behind the coastal barrier are provided. For a given mean overtopping discharge, small waves only give small overtopping volumes, whereas large waves may give many cubic metres of overtopping water in one wave and their severity are thus better described by the maximum volumes.

Coastal inundation maps showing the maximum flood extent and depth for the joint 100-year ARI (or 1% AEP) wave and water level simulations are presented for each planning period in the map compendium at the end of this report.

The XBeach results indicate the following key considerations regarding coastal inundation:

- Belongil Beach: The height of dune crests varies along the coast, with the most vulnerable sections being those where the dune crest is below 5 meters and where beach accesses exist. Belongil Spit is a low-lying area between the creek and the beach which enhances the inundation risk. Beach front properties and areas with beach access are shown to be affected by coastal inundation for the immediate scenario. The coastal inundation hazard increases with sea level rise, and properties located further away from the beach might also be affected. Significant barrier overwash extending to Belongil Creek is seen in the modelling for the 2120 planning period.
- New Brighton Beach: Along this stretch of coast there is a greater buffer between private properties and the dune crest which reduces the coastal inundation risk. For the immediate scenario, only beach front properties located in southern New Brighton Beach are affected. However, for the 2120 planning period most beach front properties along the southern and northern section of New Brighton Beach are predicted by the modelling to be affected.
- South Golden Beach: The lowest points along the dune crest are around 4.6m AHD. Behind the dune crest, the elevation drops and is around 2m AHD towards the Brunswick River. For the immediate scenario, some beach front properties are predicted to be affected by coastal inundation. For the 2120 planning period, significant overwash is observed in the modelling along the entire beach section resulting in significant coastal inundation at South Golden Beach.
- At the 2120 planning horizon, the mean overtopping volumes presented herein exceed the safe volumes provided in EurOtop (2018) for most locations (see **Appendix F**). This suggests that there is likely a safety hazard for people and property in the immediate overwash areas. Safe maximum overtopping volumes are also exceeded for the immediate planning horizon at Belongil Beach and 2050 planning horizon at South Golden Beach.

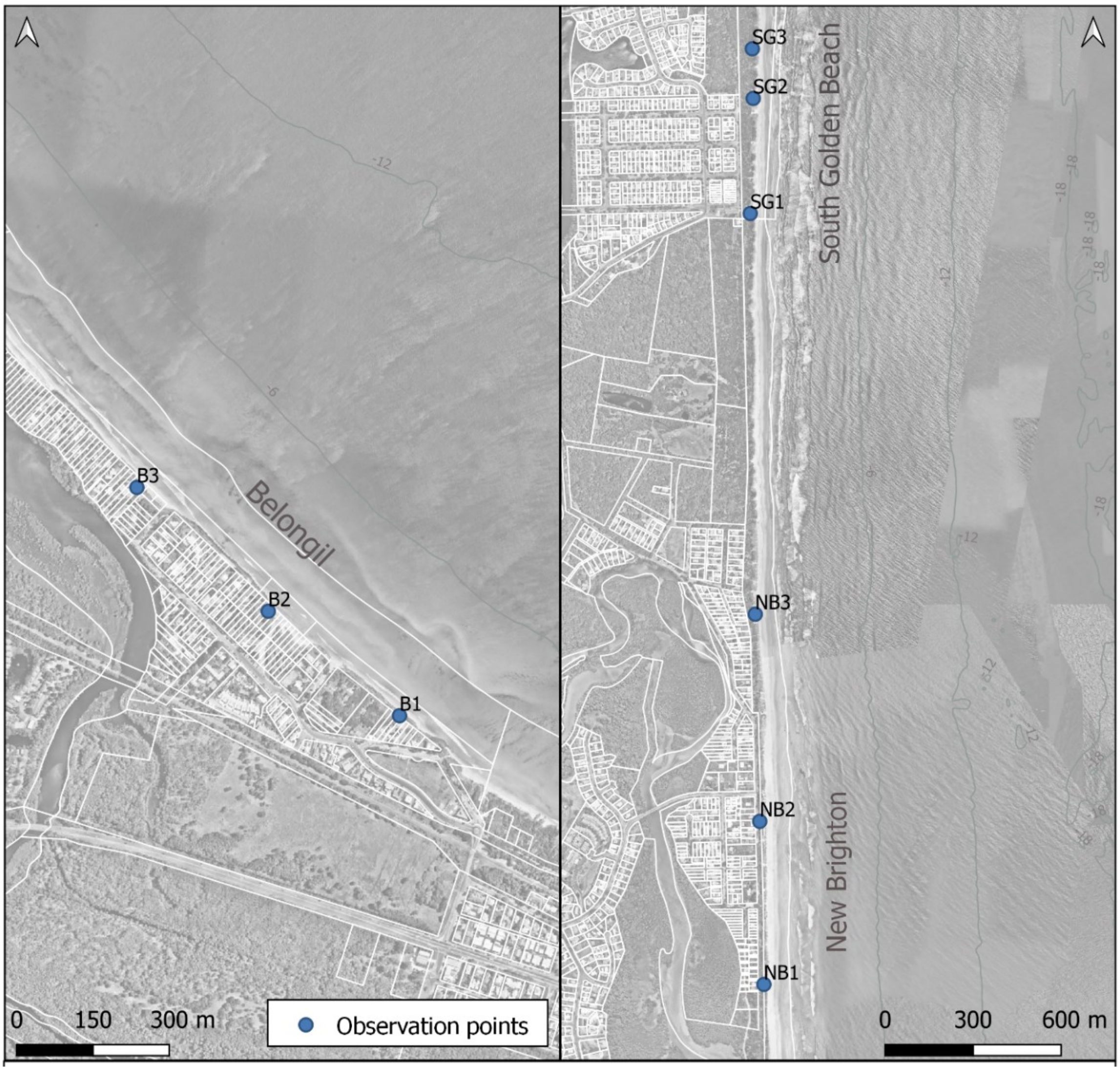

Figure 83: Location of the observation points where overtopping discharges and peak water levels were obtained.

Table 26: Peak water level and overtopping discharges (Qx) from the XBeach modelling.

Site	Planning period	Observation point	Max. water level (m AHD)	Qx (l/s/m)	Qx_{max} (l/m)
Belongil Beach	Immediate	B1	5.06	5.1	1,274
		B2	5.19	8.2	3,695
		B3	5.50	1.0	308
	2050	B1	5.06	9.4	1,470
		B2	5.20	10.8	2,523
		B3	5.50	7.0	721
	2120	B1	5.06	47.3	1,721
		B2	5.58	14.2	2,774
		B3	5.50	17.3	1,301
New Brighton Beach	Immediate	NB1	4.05	5.1	1,638
		NB2	4.61	-	-
		NB3	4.17	-	-
	2050	NB1	4.40	6.4	1,888
		NB2	4.80	-	-
		NB3	6.21	-	-
	2120	NB1	4.40	13.8	2,061
		NB2	5.15	6.1	1,748
		NB3	6.37	7.6	1,709
South Golden Beach	Immediate	SG1	4.72	6.8	1,734
		SG2	4.53	0.6	1,276
		SG3	4.90	2.9	951
	2050	SG1	4.78	9.6	2,431
		SG2	4.94	6.7	1,851
		SG3	4.91	4.3	1,052
	2120	SG1	4.78	16.8	2,546
		SG2	4.94	19.6	3,158
		SG3	4.91	21.2	2,635

Safe overtopping volume (cars) for $H_s < 2m$ (EurOtop, 2018)	
Qx (l/s/m)	Qx_{max} (l/m)
>20	>2000

Note: While not directly applicable, the adopted colour scale is aligned with the safe overtopping volumes in EurOtop (2018) for the use of vehicles in such areas as a proxy for the hazard level (see **Appendix F**). Darker shades of red indicate where safe overtopping volumes are exceeded; green and yellow/ orange shades within 'safe' limits.

7.4 Summary and recommendations

The coastal inundation assessment reveals that for the immediate timeframe, beachfront properties and areas with beach access along Belongil Beach, in southern New Brighton Beach and South Golden Beach are affected. For the 2120 planning timeframe, considering sea level rise, impacts on most beachfront properties along both the southern and northern sections of New Brighton Beach and extensive overwash along the entire beach at South Golden Beach are projected, resulting in significant coastal inundation. At Belongil, the 2120 coastal inundation hazard extends across the full width of

Belongil Spit to the creek. Estimated wave overtopping volumes exceed safe thresholds for most of the abovementioned locations at varying planning timeframes, posing a potential safety hazard for individuals and property in immediate overwash areas.

Other sites potentially exposed to coastal inundation but not assessed in detail as part of this study include Wategos Beach and Main Beach (including Jonson Street Protection Works - assessed in Bluecoast, 2022b). It is recommended that further detailed coastal inundation assessments are considered in future (as required), including for areas:

- potentially exposed to coastal inundation based on the first pass assessment but that did not receive detailed assessment as part of this study.
- 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.

8. Estuary hazard assessment

8.1 Overview

The *Coastal Management 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).

Estuary entrances along NSW coastline can generally be divided into two main categories based on their size and dynamics:

- Tidal estuaries which entrances of which 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, estuary hydraulics and sediment transport patterns are generally modified, with potential impacts on beach and bank erosion, catchment flooding and tidal dynamics.
- Intermittently Closed and Open Lakes and Lagoons (ICOLLs) are separated from the ocean by a sandy 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 estuary water levels, flushing, water quality, salinity and coastal sediment dynamics.

The main physical characteristics of the estuaries and catchments located within the study area are provided in Figure 84, Figure 85 and Table 27. This includes the three ICOLLs of Tallow Creek, Ti Tree

Lake and Belongil Creek as well as the Brunswick River, a tidal estuary which drains a larger catchment and has a trained and permanently open entrance.

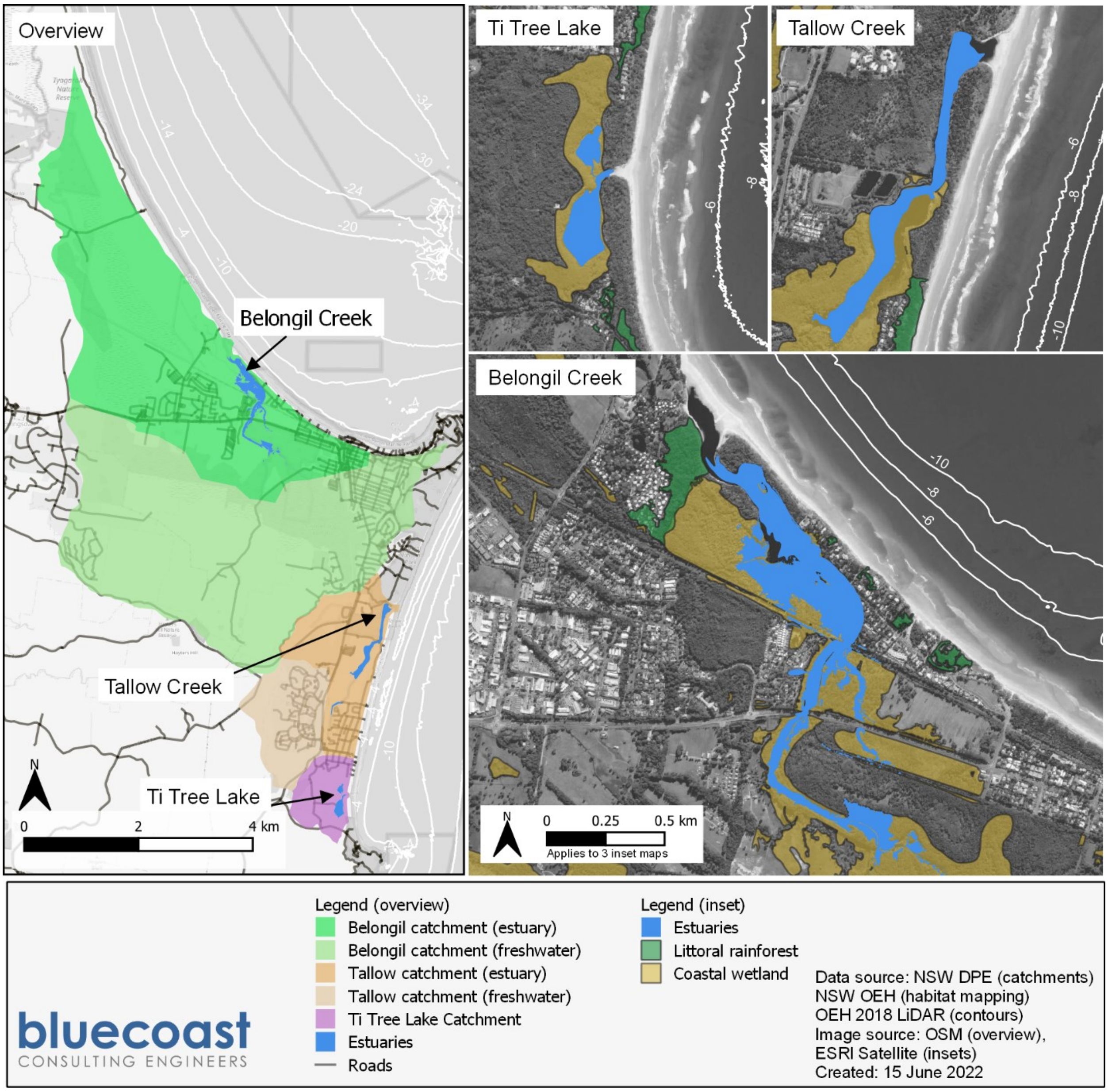

Figure 84: Overview of ICOLLs and their catchments in the study area.

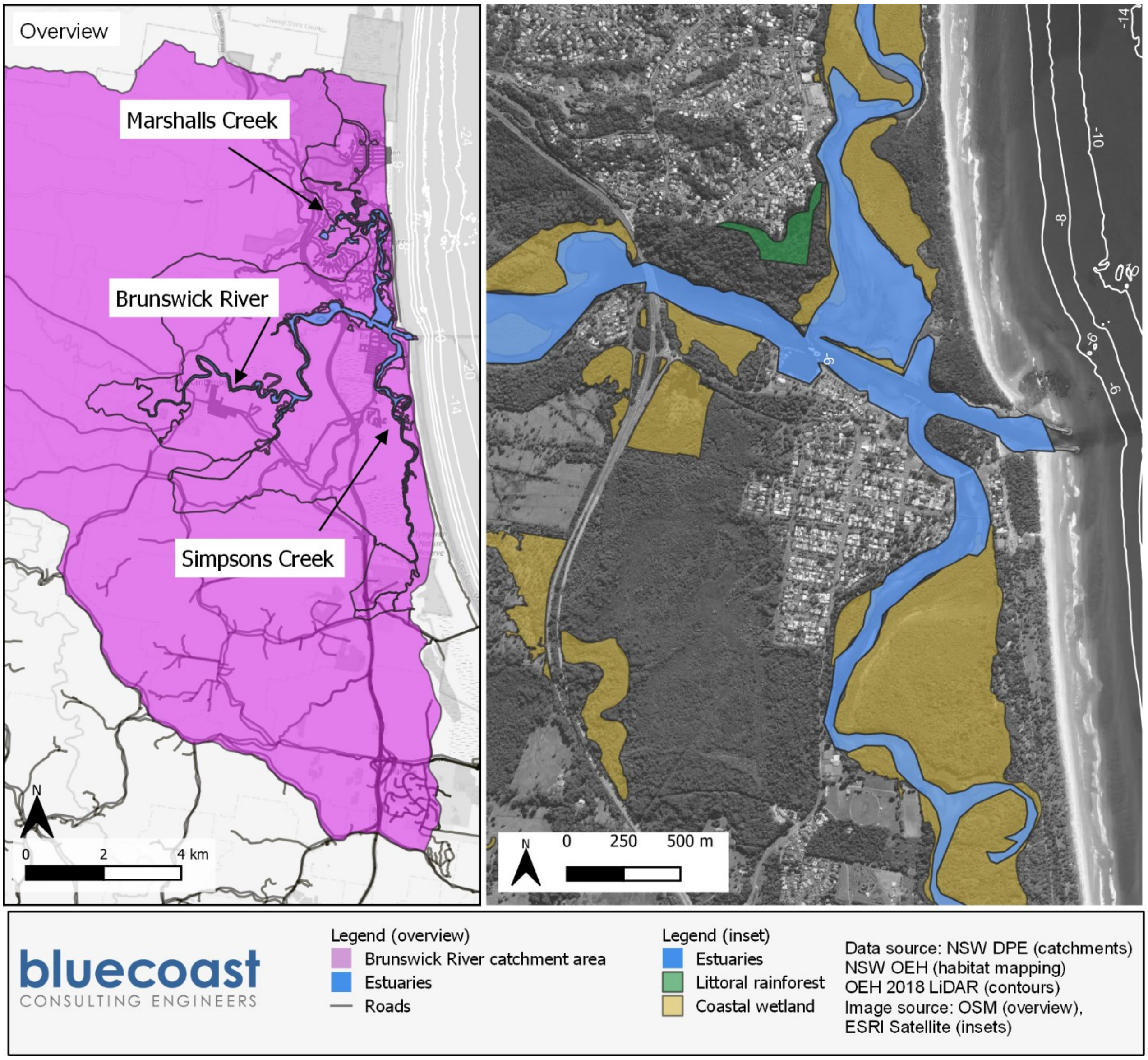

Figure 85: Overview of Brunswick River and catchment in the study area.

Table 27: 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)*	Entrance characteristics
Ti Tree Lake	~1***	Intermittently closed estuary/ small saline coastal creeks	0.05***	*No data*	~1***	• Untrained entrance • Not actively managed
Tallow Creek	5.4	Intermittently closed estuary/ small saline coastal creeks	0.1	46.6	0.4	• Untrained entrance • Actively managed by Council until 2019 • Since 2019, only berm scraping permitted
Belongil Creek	30.4	Intermittently closed estuary/ small saline coastal creeks	0.3	87.7	0.5	• Untrained entrance • Actively managed (mechanically opened) by Council
Brunswick River	226.3	Wave dominated estuary/ riverine barrier estuary	3.6	4,267.9	1.3	• Trained entrance since 1959

Note: * Source: https://www.environment.nsw.gov.au/topics/water/estuaries/ ** After Roy et al. (2001) classification of south-east Australian estuaries. *** Based on Baker and Pont (1998) as no data available on www.environment.nsw.gov.au.

8.2 Coastal entrance instability

An assessment of the coastal entrance instability of the three ICOLLs of Ti Tree Lake, Tallow Creek and Belongil Creek has been undertaken for the present day and future planning periods. As identified in BMT WBM (2013), the estuary entrances to Ti Tree Lake and Tallow Creek are relatively stable and only a basic assessment is required. At Belongil Creek, the dynamic entrance behaviour is a known issue. A detailed assessment of the entrance behaviour at Belongil Creek was therefore required and is reported herein. 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 and the findings from investigations described earlier in this report, the following data was used to complete the targeted entrance instability assessment:

- 2018 coastal LiDAR (DPE) and other available survey data
- Digitised historic survey plans dating back to 1883
- NSW Seamless Geology database
- Historic aerial imagery available since 1958
- WRL's InletTracker based on satellite imagery between 1988 and 2022.

8.2.1 Ti Tree Lake

Ti Tree Lake comprises two distinct lake lobes connected in the vicinity of a singular entrance channel. The lake and entrance channel is privately owned. An Indigenous land use agreement (ILUA) covers the lake, the entrance channel, much of the dune and beach adjacent to the lake, and the 10.5 hectare Aboriginal Area to the north of the lake. There is no entrance management being undertaken at present and the entrance is in a natural state. More information is provided as:

- An overview of the modern geomorphic setting and geology of the Ti Tree Lake entrance is presented inFigure 86.
- A series of historical aerial photographs of Ti Tree Lake is provided in Figure 87.

Based on the evidence available to this study, the following observations on the entrance behaviour are made:

- The entrance is predominantly in a closed state (i.e., there is no connection between the estuary and the ocean due to the presence of a beach berm) or it is in a heavily constricted conditon.
- The entrance area has remained in a similar alongshore position and the observed channel meandering has been minimal.

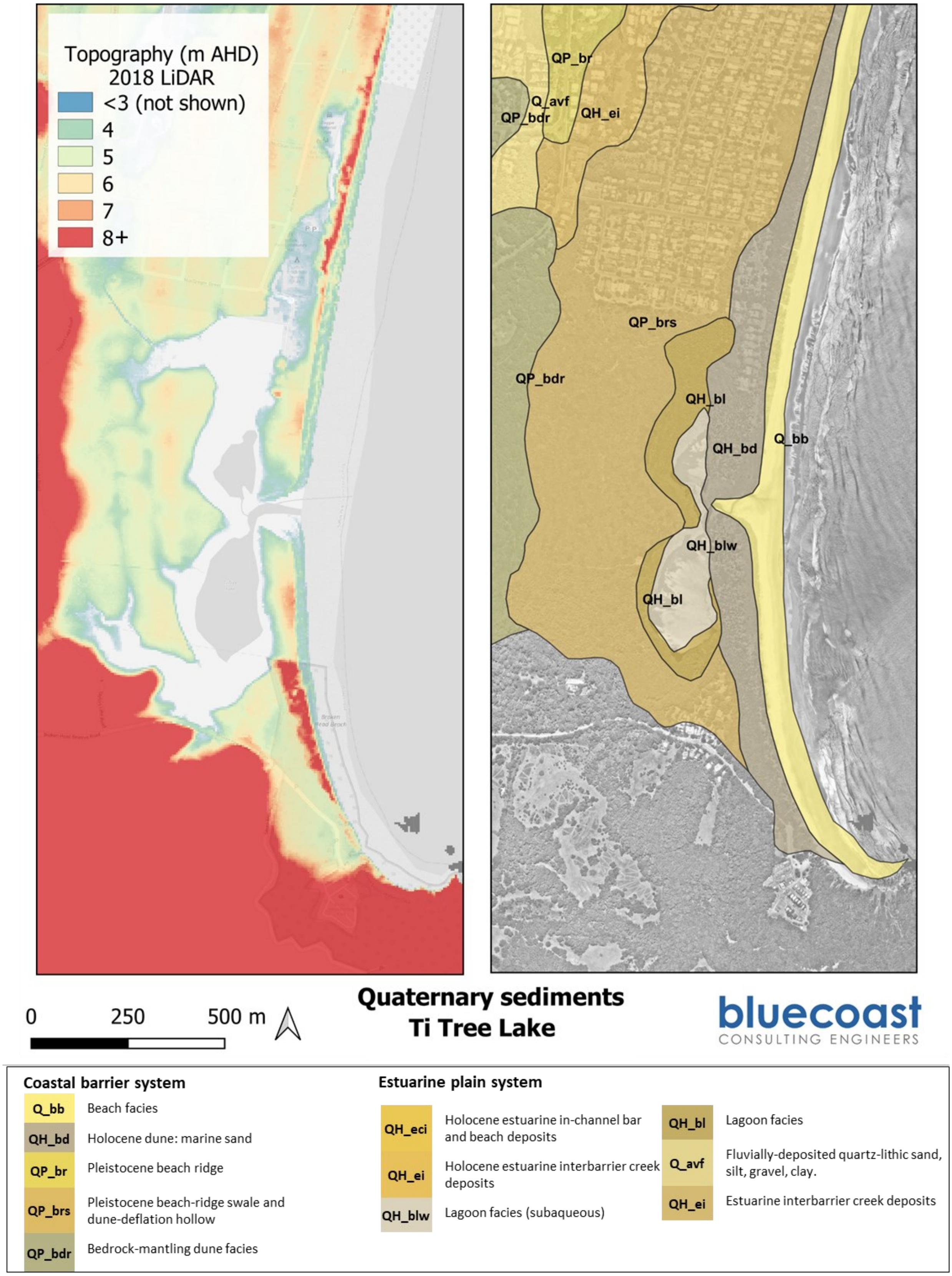

Figure 86: Geomorphic overview and Quaternary geology and sediments surrounding Ti Tree Lake.

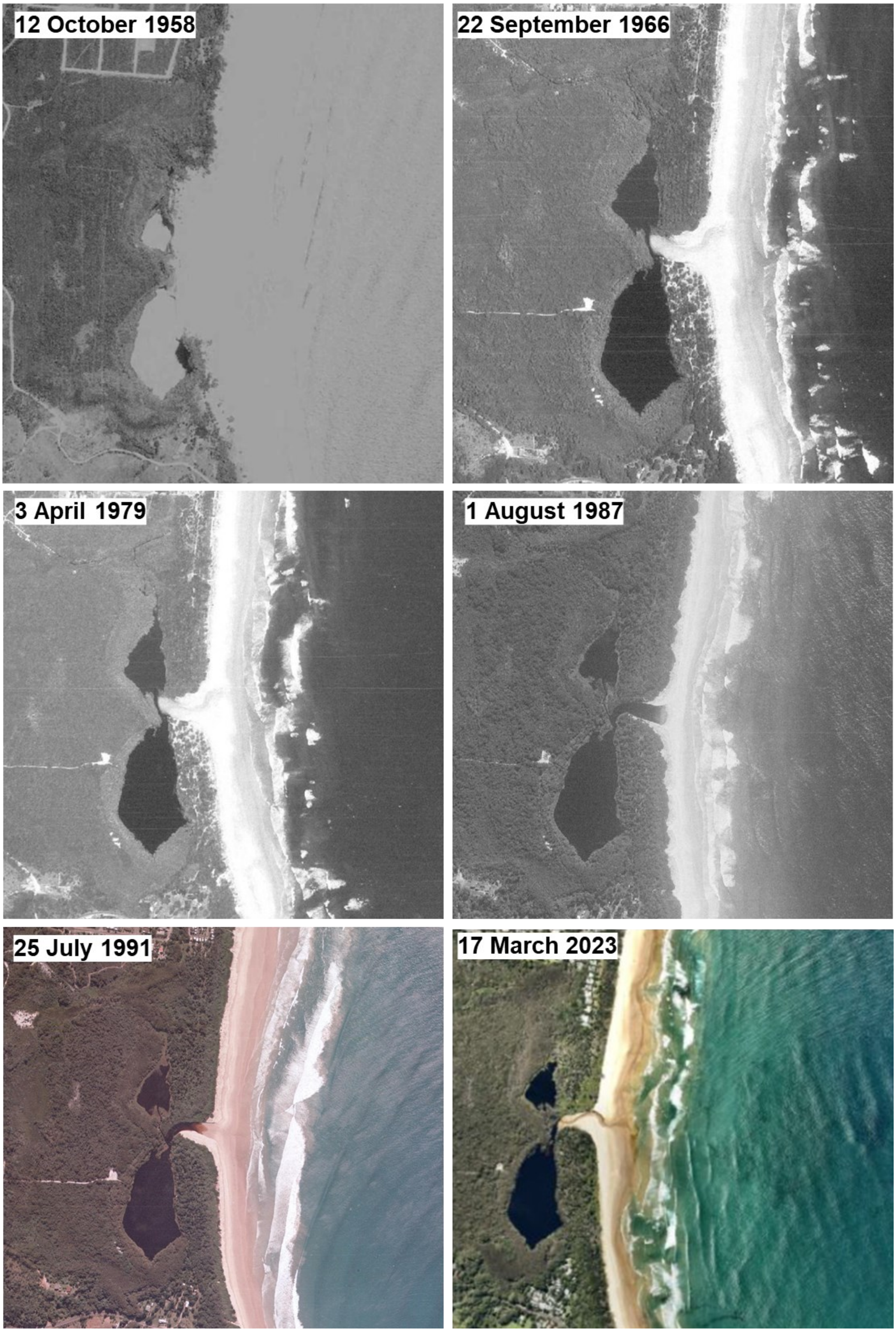

Figure 87: Aerial photographs of Ti Tree Lake between 1958 and 2023.

- A 1958 aerial photo shows the southern and northern sand spits either side of the entrance as being eroded. This would have resulted in frequent wave overwash along the full length of the estuary. At the time, sand mining had been active along Tallow Beach (see Section 2.2). Sand mining activities could have been a contributing factor to the depleted sand buffer seen in this image. Previous assessments suggest that established barriers on either side of the entrance existed prior to the 1950s (BMT WBM, 2013). The modern topography suggests that the barriers have since recovered and the dunes are rebuilding.
- The sand budget and coastal erosion and recession assessment completed herein has confirmed that this section of the coast is experiencing accretion (i.e., net sand gain), which for such a small entrance would tend to promote stability.

Due to the relatively stable entrance position and accreting adjacent shorelines, the entrance is not expected to create a significant hazard for present day or future planning periods. While some adjustment of the entrance and estuary morphology due to sea level rise is likely, it is not expected that the entrance behaviour would change significantly for future planning periods.

8.2.2 Tallow Creek

Until 2019, Council had a licence to artificially open the entrance in accordance with the Environmental Management Plan and Opening Strategy for Tallow Creek (BMT WBM, 2015). It is noted that between 2004 and 2018 Council did not undertake any entrance management activities at Tallow Creek, however there is evidence that several unauthorised openings are likely to have occurred over this period. The licence provided the ability for berm scraping and mechanical opening of the entrance to manage flooding impacts on surrounding residential and commercial properties. Due to a significant fish kill event in 2019, NSW National Parks and Wildlife Service agreed on an interim position for Council to manage the estuary entrance for the purpose of flood mitigation while minimising risk to fish and other aquatic life. This interim position does not support mechanical opening of the creek at all and only supports scraping of the berm when water levels are high (above +2.2m AHD) and a range of other conditions (e.g., forecast rainfall and berm height).

More information on Tallow Creek is provided as:

- An overview of the modern geomorphic setting and geology of the Tallow Creek entrance is presented in Figure 88.
- A series of historical aerial photographs of Tallow Creek is provided in Figure 89.

Based on the evidence available to this study, the following observations on the entrance behaviour are made:

- The entrance is predominantly in a closed state (i.e., there is no connection between the estuary and the ocean) or it is in a heavily constricted conditon.
- The entrance area has remained in a similar alongshore position and the observed channel meandering has been minimal.
- Significant artificial modification (widening and straightening) to the lower estuary and entrance was undertaken as part of development of the surrounding area, as seen in the 1958 and 1965 aerial photographs.
- The sand budget and coastal erosion and recession assessment completed herein has confirmed that this section of the coast is experiencing accretion (i.e., net sand gain), which for such a small entrance would tend to promote stability. It is noted that the projected erosion and recession hazard extents for future planning periods (see map compendium) exceed landward of the narrow section of the sand spit approximately 500m south of the entrance (see Figure 88). It is likely that

sandy barriers in such eivronments are able to respond to sea level rise without a significant risk of breakthrough if these are not limited to translate landward by human development.

Due to the relatively stable entrance position and accreting adjacent shorelines, the entrance is not expected to create a significant hazard for present day or future planning periods. While some adjustment of the entrance and estuary morphology due to sea level rise is likely, it is not expected that the entrance behaviour would change significantly for future planning periods.

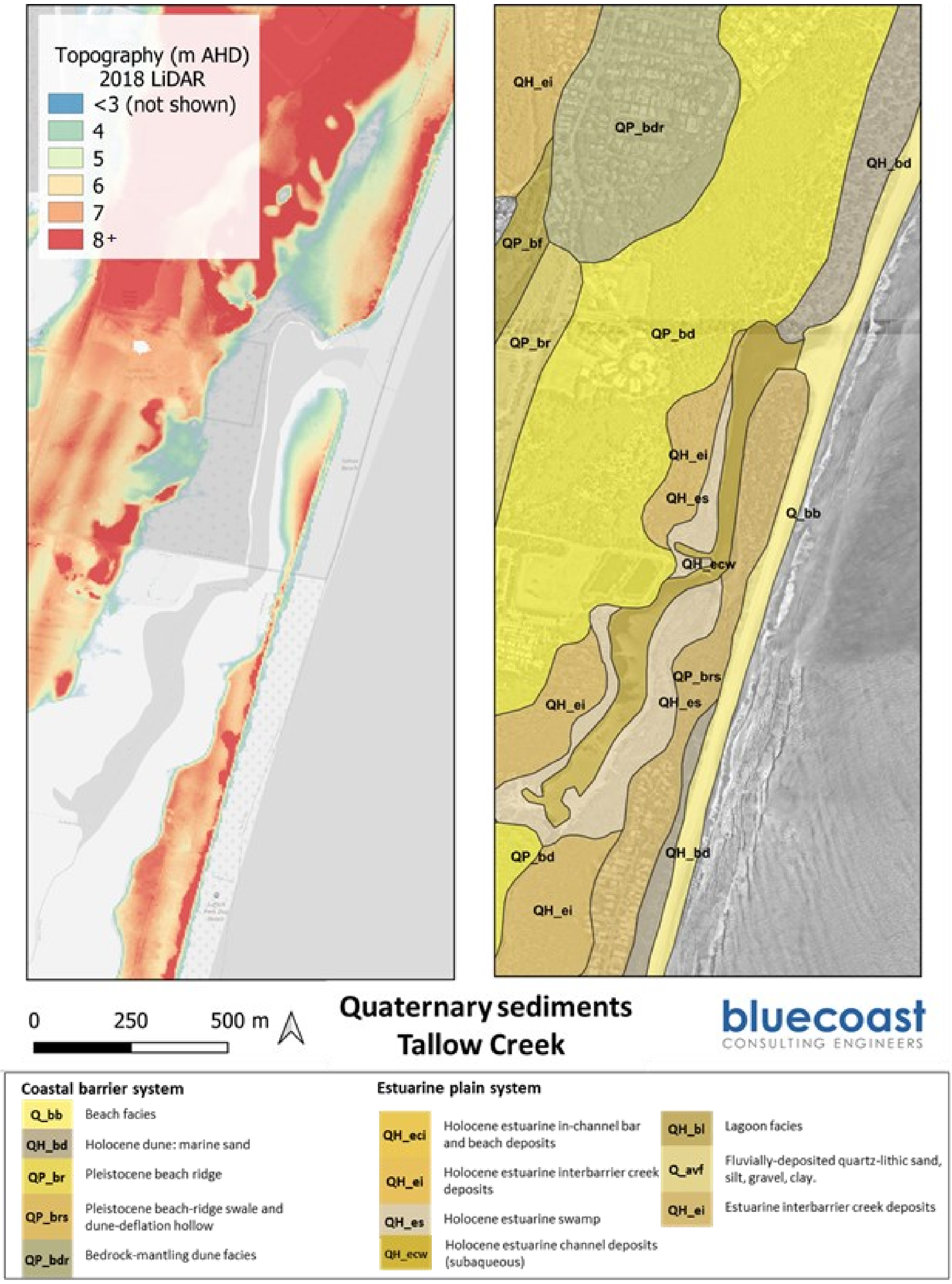

Figure 88: Geomorphic overview and Quaternary geology and sediments of the Tallow Creek entrance.

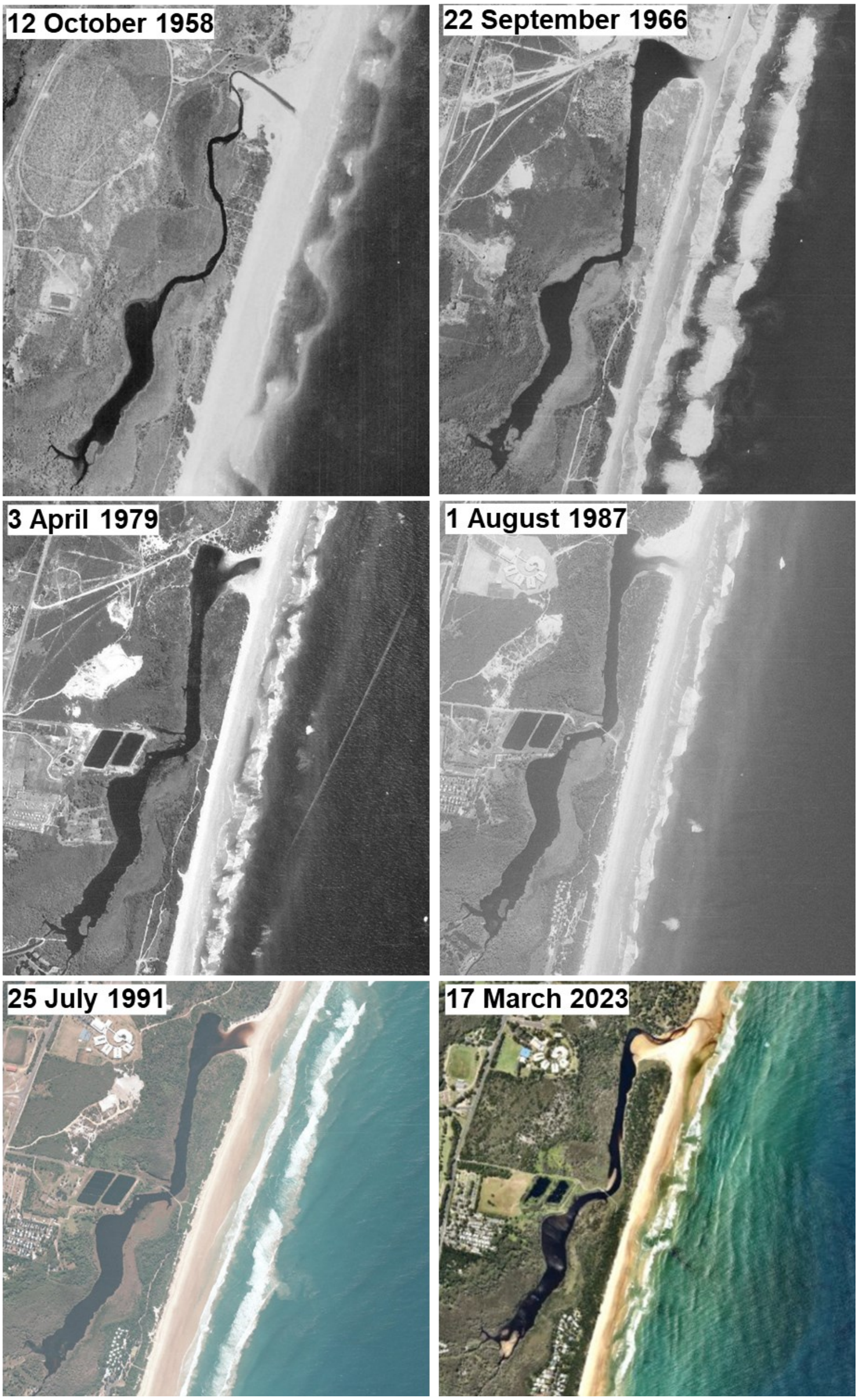

Figure 89: Aerial photographs of Tallow Lake between 1958 and 2023.

8.2.3 Belongil Creek

For the past 100 years Council has actively managed the entrance of the Belongil estuary, historically in an effort to alleviate inundation of low-lying agricultural swamp land and later for flooding risk to property and life in Byron Bay CBD (Alluvium, 2019). Over the past decade, the entrance channel has been predominantly in an open (i.e., connected to the ocean), albeit constricted condition. More information on Belongil Creek is provided as:

- An overview of the modern geomorphic setting and geology of the Belongil Creek entrance is presented in Figure 90.
- A series of aerial photographs of Belongil Spit and the entrance is provided in Figure 91.
- A summary of the entrance condition based on satellite imagery (WRL InletTracker) in the context of offshore wave energy, rainfall anomaly and large-scale climatic drivers represented by the Southern Oscillation Index (SOI) is provided in Figure 92.

Based on review of available literature, detailed data analysis undertaken herein and coastal entrance theory discussed below, a summary of the coastal entrance hazards for Belongil Creek is shown in Figure 100. The following observations are made:

- **Littoral processes** – As described in Section 4, a general net northward longshore sand transport of around 425,000m^3/year is estimated along Belongil Beach at present. Over geological timescales, this longshore sand transport and ample sand supply has led to the formation of Belongil Spit, creating a barrier between the estuary and the ocean as the entrance migrated northward. Since first mapped in an 1883 survey, the entrance location has been observed to vary over an approximately 600m length of coastline (see Figure 90). Over this period, the most southern known location of the entrance was around 230m north of existing properties on Belongil Spit in 1958. This is evidenced in the available surveys, aerial imagery and the modern geomorphology of the entrance area which suggest that the entrance has ambulated northward and southward along the coast over the past century. This dynamic entrance behaviour is linked to the complex interaction of prevailing littoral sand supply (including variability due to headland bypassing), wave climate and rainfall (which are all linked to ENSO and other climate cycles) as well as human modification.

  Littoral (longshore) sand transport is directed toward the estuary on both immediate updrift and downdrift shorelines. Flood tidal currents tend to move sand into the estuary to a flood tidal shoal while ebb currents jet sand seaward. Across the entrance, the waves breaking upon the entrance berm transport sand both toward (into) the estuary and toward the downdrift shoreline. During high catchment discharge events (or mechanical berm opening) scouring of the entrance channel occurs and sand is transported seaward and onto adjacent shorelines. The sand volume mobilised during entrance scour is relatively low due to the small size of the estuary. The available evidence suggests that there is no significant permanent ebb tidal shoal seaward of the creek entrance. A temporary ebb tidal shoal may form during and following entrance breakout events. Overall, the estuary when considered in the medium term, is neither a significant sink or source of sand to the littoral zone.

  BMT WBM (2013) suggest there had been a more recent pattern of southward entrance migration associated with shoreline recession which was evidenced by comparison of the 2009 entrance location to the 1883 survey plan. The analysis presented herein suggests that rather than a general trend of southward entrance migration there is evidence of the entrance moving in both, northward and southward direction. While such behaviour is typical of that observed at similar coastal entrances in NSW, the ongoing entrance management undertaken by Council also plays a key role (see below 'Opening mechanism').

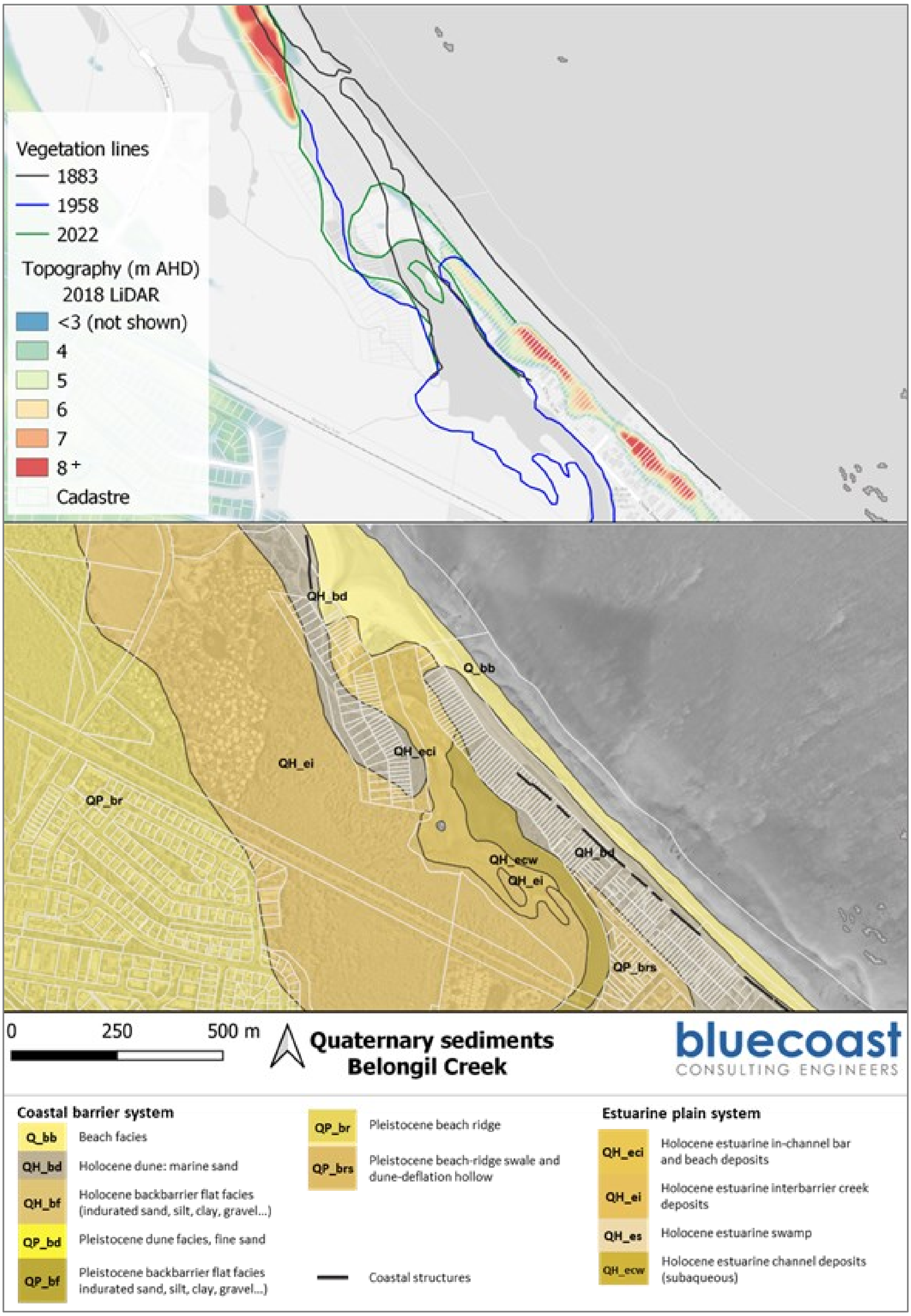

Figure 90: Geomorphic overview and Quaternary geology and sediments of the Belongil Creek entrance.

Figure 91: Aerial photographs of Belongil Spit between 1958 and 2022

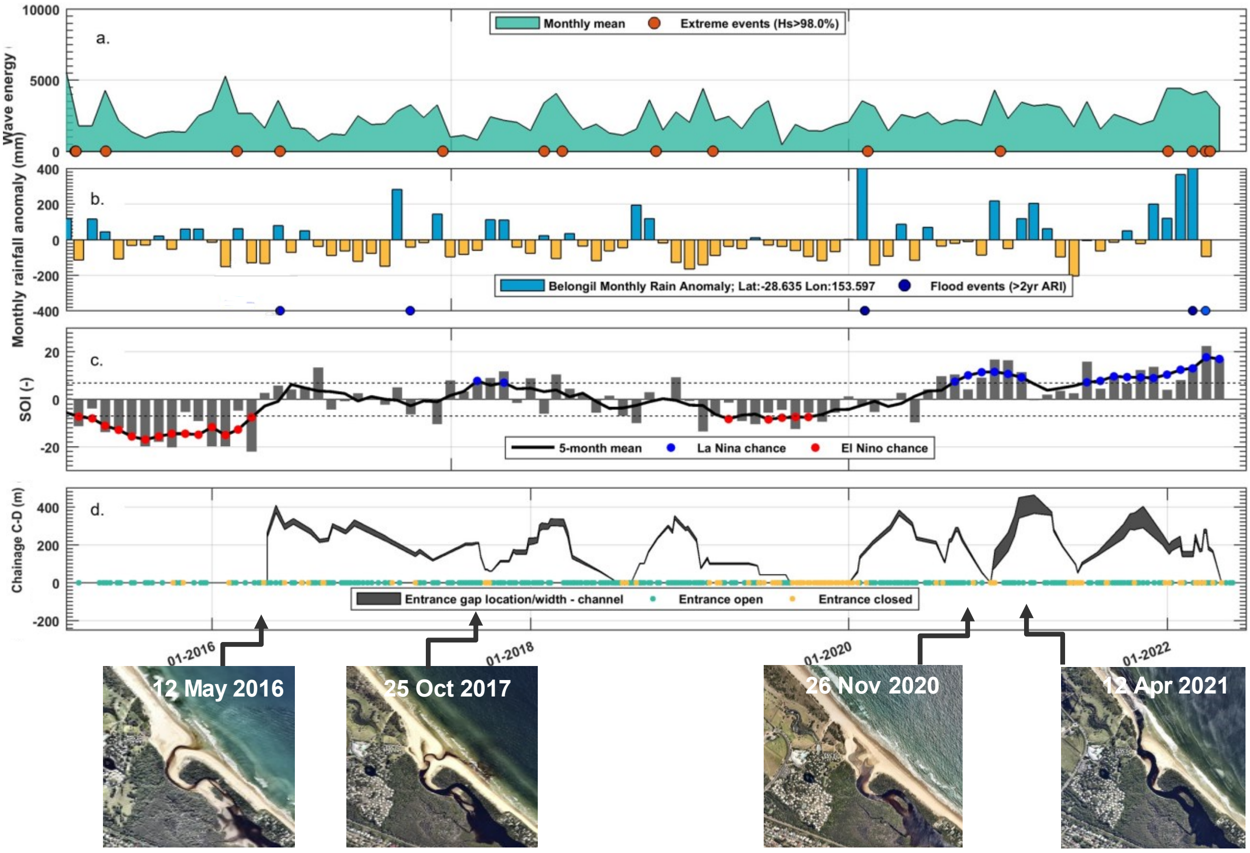

Figure 92: Timeseries of Belongil Creek entrance behaviour over the period 2016 to 2022: (a) Offshore wave energy^, (b) monthly rain anomaly, (c) SOI condition; (d) Belongil Creek entrance condition^^.

Note: ^Mean wave energy is derived from Bluecoast's Byron Bay wave hindcast model (Bluecoast, 2021); ^^the width of the entrance gap is depicted as the grey-coloured band in (d) based on satellite imagery, with the location of the entrance being presented along an alongshore chainage derived from each satellite image from the southern embankment (0m) to the northern embankment (500m).

Over the long-term, a trend of shoreline recession along this section of coast has been observed as described in Section 4.4 and Section 5.3.4. For the past decade, the observed shoreline positions and upper beach volumes have been relatively stable. The available evidence suggests that there may be a relationship between the entrance location and entrance morphology and periods of shoreline recession at adjacent beaches. For example, between 2006 and 2009 (see Figure 93), the entrance channel was in a relatively more northern location as the sand spit was building out northwards likely as a result of high northward longshore sand transport. During this period, around 30m of shoreline recession was observed at the northern end of Belongil Spit suggesting that the northward sand transport exceeded sand supply from south. This erosive phase along Belongil Spit is likely linked to reduced sand supply to the Byron embayment via headland bypassing around the Cape. The period coincided with a net reduction in the sand volume of the entire northern Byron embayment (see Section 4.2.5) and was preceded by a sand deficit in the southern embayment. That is, the reduced embayment sand volumes linked to variable headland bypassing sand supply had migrated from south to north. However, relative to the southern embayment, the effect of variable headland bypassing along the northern embayment is somewhat dampened and delayed (see Section 4.4.3). The observed entrance condition and shoreline erosion was also likely influenced by the then dominant La Niña climate cycle with higher-than-average rainfall and high wave energy, including a major east coast low in May 2009 (see Figure 34). A recovery in beach volumes and stabilisation of this section of the sand spit has since been observed in the available data. However, erosive cycles along Belongil Beach and observed effects on the Belongil Creek entrance are expected to continue to occur because of recent (2018-2020, see Section 4.4.3) or future reductions in rates of headland bypassing around Cape Byron.

Along Belongil Spit, a series of seawalls exist with varying engineering standard. To date, the seawalls have limited the landward extent of erosion but have also led to increased erosion rates at adjacent sections of beach (BMT WBM, 2013; Carley et al., 2010). This is most notable along unprotected shorelines downdrift (i.e., north-west) of the seawalls. The most northern seawall protects houses along Childe Street and is around 480m from the current entrance location. During erosive periods and/or large storms when there is little sandy buffer in front of the seawalls along Belongil Beach, their effect is to reduce sand supply to the north-west (downdrift) which has an erosive and destabilising effect of the Spit and the Belongil Creek entrance.

With sea level rise, the entrance berm and sand spit would typically be expected to roll back in landward direction, i.e., the barrier would recede in its current alignment, rebuilding further landward. However, the position of Belongil Spit and much of the lower estuary is largely fixed due to development, including the various seawalls, roads and railway bridge. 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. As argued in Kinsela et al. (2017), it is likely that the active flood delta and entrance berm will act as a sink for sand from the littoral zone as these features adjust (vertical growth) to higher sea levels. This potential sequestration of sand into the estuary would be a slow process and may contribute to future recession of the adjacent beaches (see Section 5.3.4). Should there be future changes to the sand budget due to climate change such as a reduced sand supply to Belongil Spit and the entrance, this could result in a southward migration of the entrance as the sand spit recedes allowing a breakthrough further south.

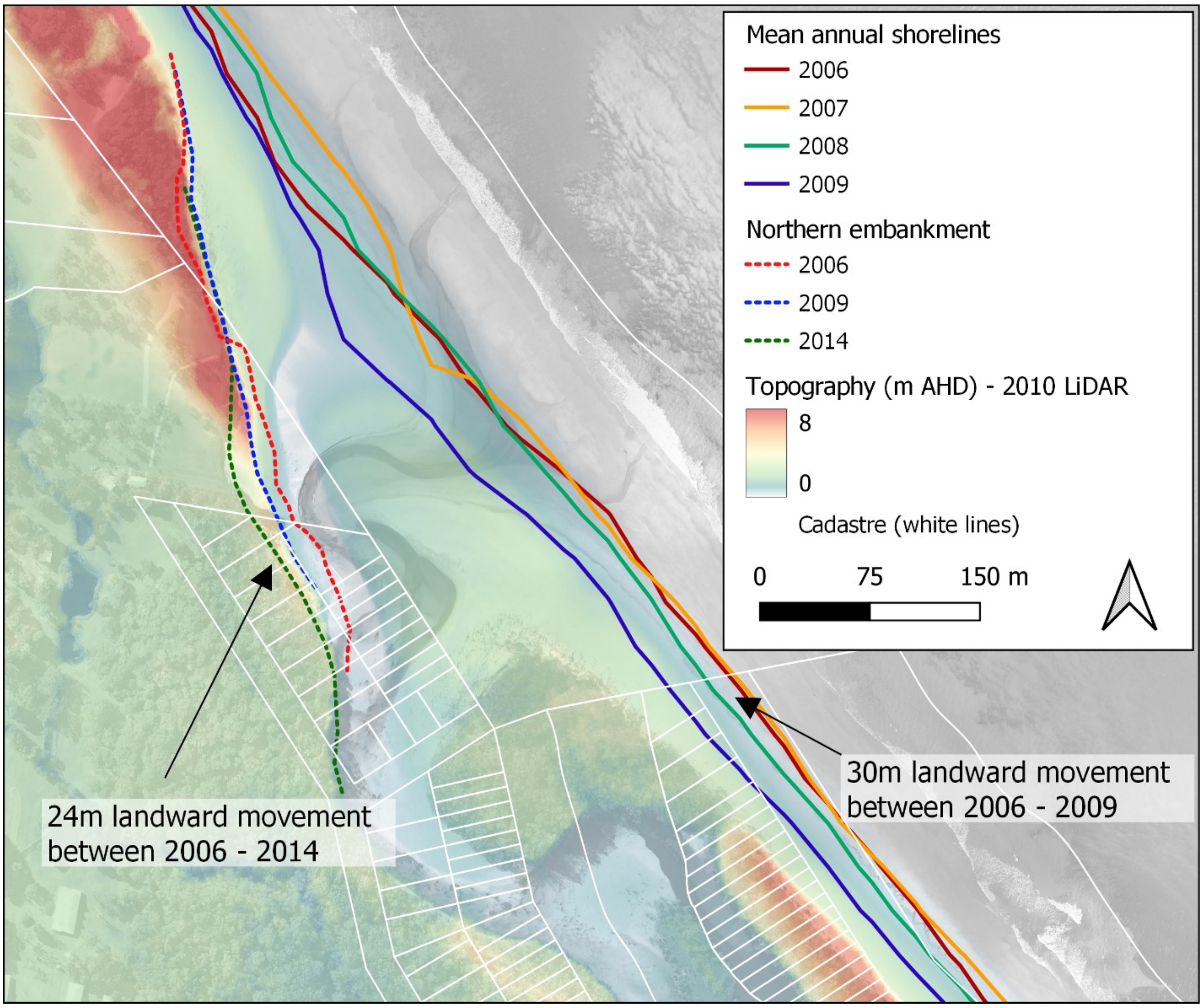

Figure 93: Entrance condition over 2006 to 2014 period.

- **Opening mechanism** – As described above, Council continues to actively manage the entrance of Belongil Creek for flood mitigation with adaptive water level triggers for mechanical opening set between 1.1 to 1.2m AHD (measured at the Ewingsdale Road bridge) in Council's adopted Entrance Opening Strategy (Alluvium, 2019; revised in 2021). Opening of the creek is based on flood risk and at present requires certain parameters to be met, most notably rainfall forecast. Council is presently reviewing the opening strategy as part of the CMP preparation to ensure it is fit for purpose on-going. Naturally, during high catchment runoff events the entrance berm would eventually be overtopped as estuary water levels rise and lead to subsequent scouring of a channel across the entrance berm. The size and cross-sectional area of the entrance channel depends on flood water discharge and the amount of head across the opening. Where recent artificial openings has been undertaken in the lead up to such events, this typically defines the location of entrance channel scour. Council's mechanical opening arrangement is shown in Figure 95 and is defined as follows:

> The entrance opening is to be excavated between the south-east corner of Lot 10 DP 243218 (Elements of Byron resort) and the northern extent of the 7(j) Scientific Zone, with the centreline being located approximately 10m north of any authorised bird protection fence subject to any significant site constraints.

The entrance berm is currently around 200m wide and the channels are observed to migrate across the berm in an alongshore direction (see ‘Closing mechanism’). During extreme estuary floods, storm waves or prolonged low sand supply from south (and associated recession) breaching of the northern end of Belongil Spit may occur. This is evidenced by the 1958 vegetation line and the low elevation topography of this section of the sand spit (see Figure 94). The risk of a breach of Belongil Spit further south is discussed below (see ‘Belongil Spit breakthrough’).

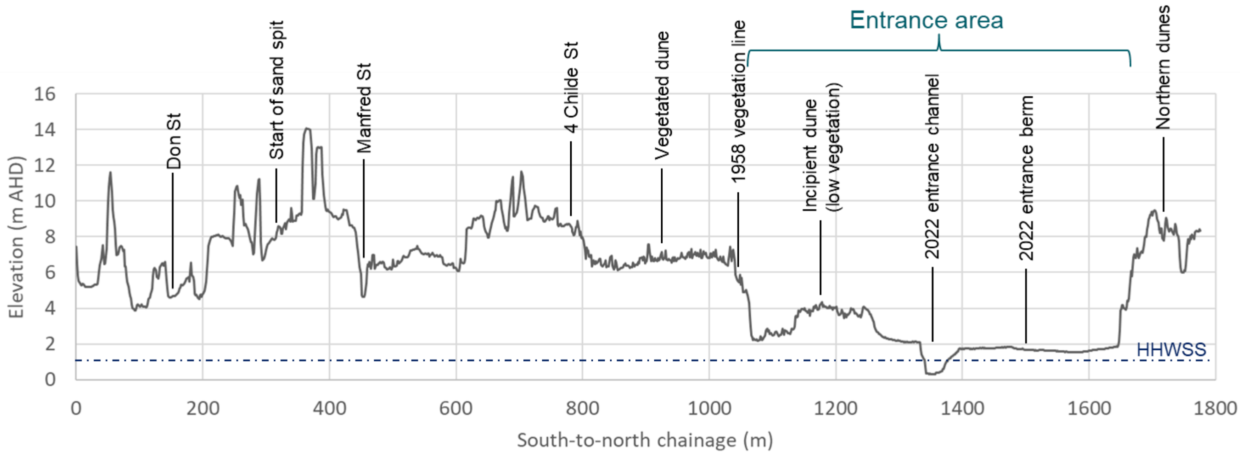

Figure 94: Alongshore elevation profile (south to north) along Belongil Spit and entrance area based on 2022 LiDAR.

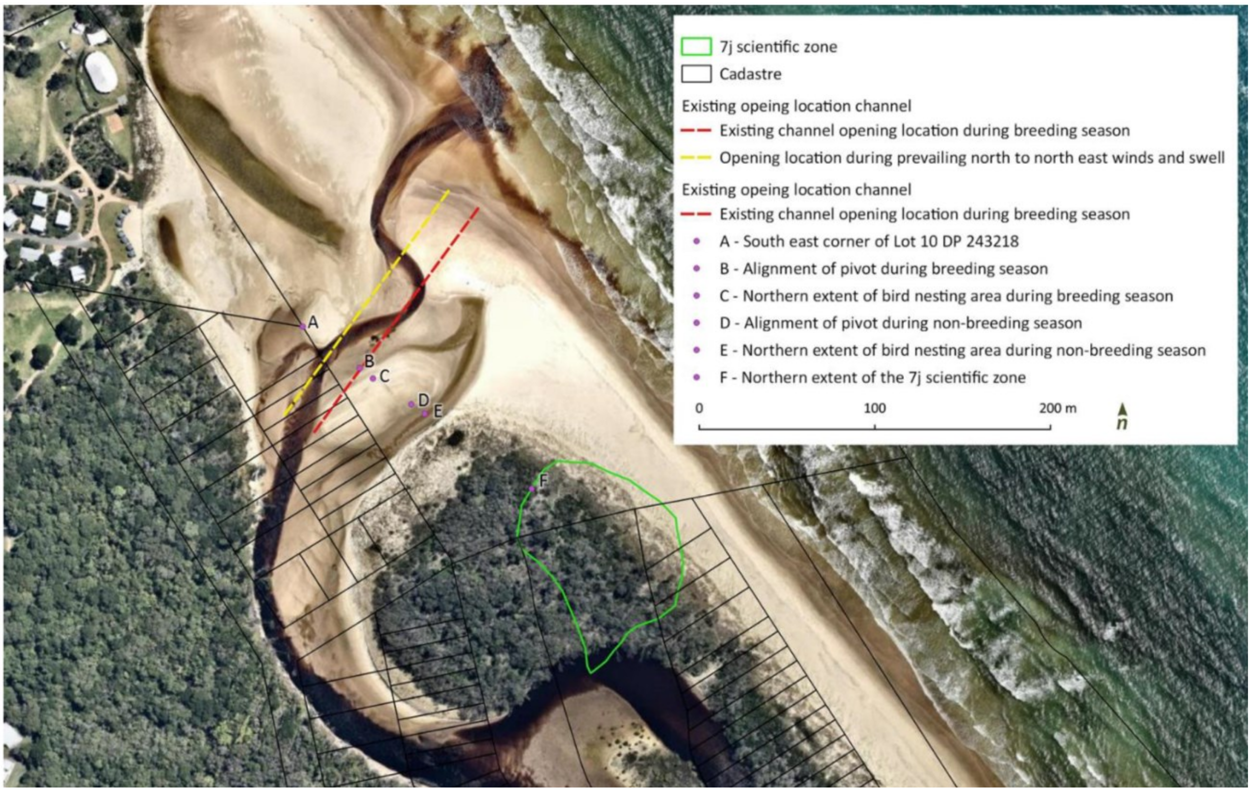

Figure 95: Adopted mechanical opening arrangements for Belongil Creek estuary entrance (Alluvium, 2019).

- **Closing mechanism** – Due to the relatively small estuary size and low tidal exchange during open entrance condition, the entrance channel can become constricted within days to weeks from breakout. As concluded in previous studies, following opening the entrance channel tends to migrate northward due to the net northward longshore sand transport along the Byron Shire coastline (BMT WBM, 2013; Alluvium, 2019). The alongshore migration of the entrance channel occurs as the adjacent sand spit builds out in the direction of the prevailing longshore sand transport. At times, this prevailing longshore sand transport is from north to south and can lead into entrance closure from the north (see Figure 96).

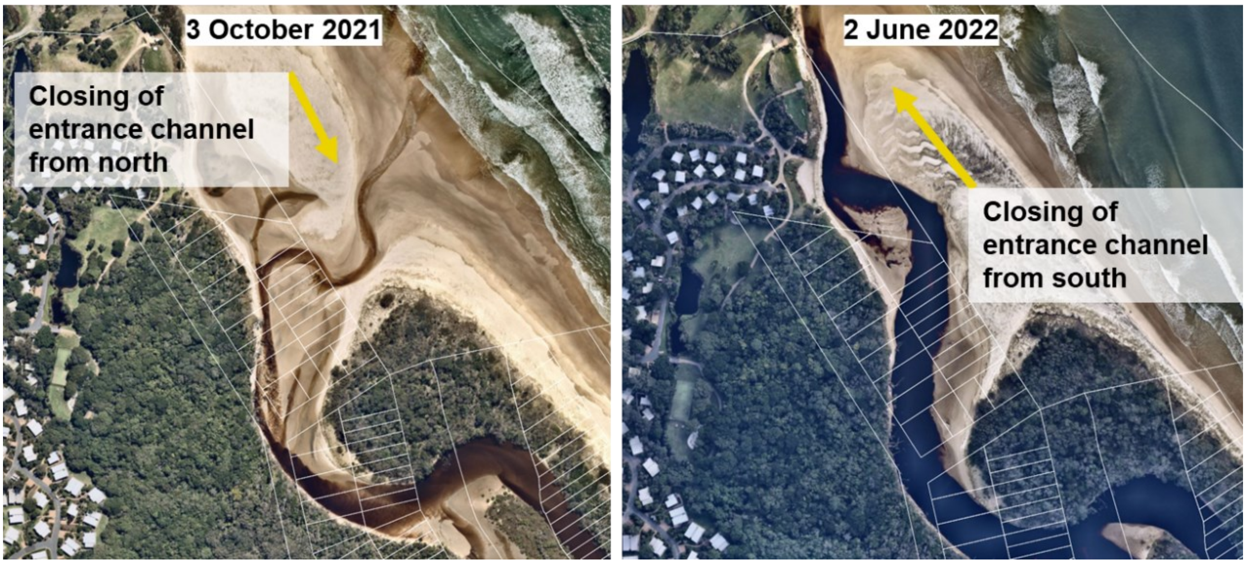

Figure 96: Aerial photographs captured during entrance closing.

- **Erosion of northern embankment** - Erosion of the northern embankment has been observed near the entrance (e.g., Figure 97). This erosion has significantly affected a section of littoral rainforest and the Elements of Byron resort foreshore (Lot 10 DP 243218) with erosion rates up to 3-5m/ year (Alluvium, 2019). In 2015, a geotextile container revetment was constructed to help protect this section of foreshore from further erosion. Erosion along the northern embankment occurs due to several factors, including:
  - Meandering of the entrance channel, specifically when the channel ‘hugs’ the northern embankment leading to bank erosion during high flows in and out of the estuary.
  - High waves propagating over the low berm fronting the northern embankment resulting in wave overwash and undercutting of the low dune. Belongil Spit provides a level of protection against wave attack for the northern embankment. During periods when the entrance area extends further south, for example as observed in the 1958 aerial photograph, erosion due to wave attack may be observed further upstream along the northern embankment.

BMT WBM (2013) notes that the cadastral boundaries indicate the historic entrance position and location of the northern embankment when these were defined over a century ago. The cadastre aligns well with the entrance and channel position mapped in the 1883 survey. In this relatively more northern position of the entrance, the northern embankment along Lot 10 DP 243218 was around 120m further seaward compared to present day. The data suggests that most of this landward movement occurred during the first half of the 20th century when around 100m recession was observed between 1883 to 1958. The modern topography and geological mapping (see Figure 90) suggest that much of the Holocene dune along this section of coast has been fully eroded, leaving a low buffer against erosion.

The observed meandering entrance channel behaviour is likely to continue. Sea level rise is likely to exacerbate the experienced erosion in this area as the embankment is inundated higher up on the profile.

Figure 97: Aerial photographs showing progressive erosion of northern entrance embankment at Belongil Creek prior to geotextile container revetment construction in 2015.

- **Estuary water levels** - When open, Belongil Creek becomes tidal for some 3.0 to 3.5km upstream of the entrance (Alluvium, 2019). However, tidal amplitudes are significantly attenuated across the entrance and with distance upstream. A timeseries of estuary water levels measured near the railway bridge during an opening and closing cycle of the entrance is presented in Figure 98. A comparison to observations at Brunswick River (as an indication of ocean water levels) is provided which shows the significant tidal attenuation in the estuary. Alluvium (2019) reported that during estuary floods peak water levels in the estuary would reach 2-2.4m AHD as a result of natural berm development if no artificial opening of the entrance would be undertaken. This corresponds to the typical elevation of the entrance berm at present. The elevation of the berm is expected to increase with sea level rise which would in turn increase the peak water levels during estuary floods (without artificial opening). As described above, the entrance is actively managed for entrance breakout at estuary water levels generally between 1.1 and 1.2m AHD (depending on flood risk including other factors such as rainfall). An assessment of tidal propagation during open entrance condition and associated estuary water levels and inundation is provided in Section 8.3. Flooding of estuary foreshores may also occur if extreme ocean water level events coincide with open entrance conditions.

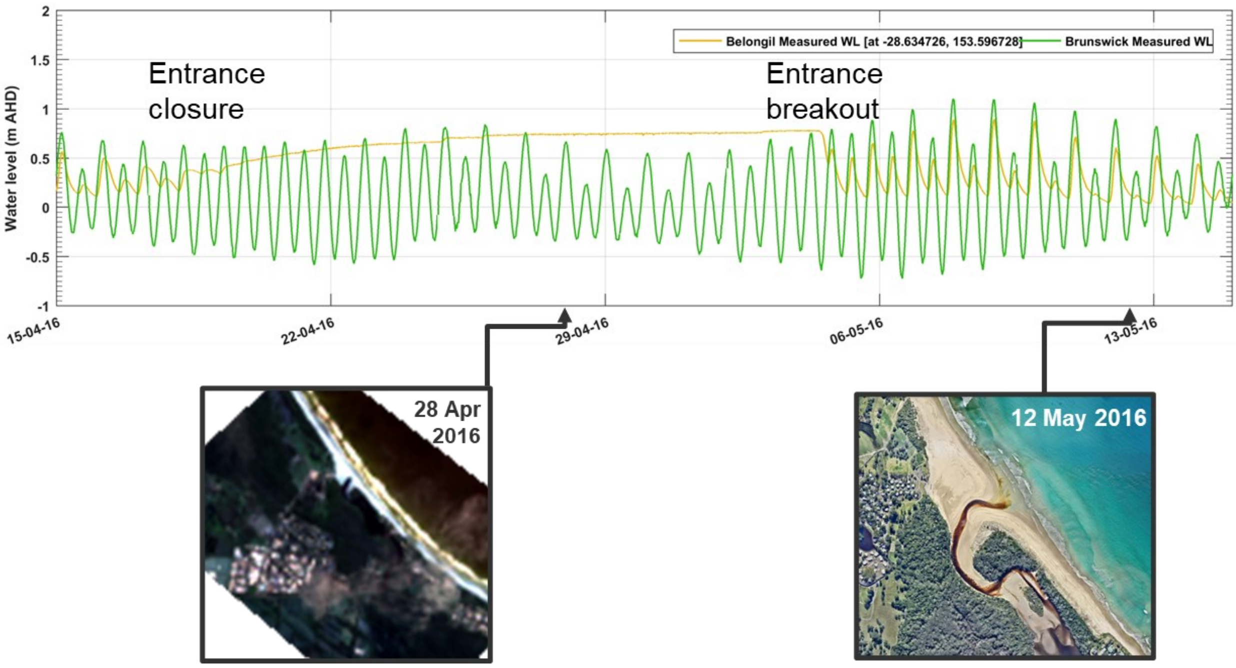

Figure 98: Measured water levels in Belongil estuary (near railway bridge) during open and closed entrance conditions in 2016.

Note: Measured water levels at Brunswick River tide gauge shown as a proxy of concurrent ocean water levels.

- **Belongil Spit breakthrough** – A section of the southern sand spit with a narrow and low elevation dune exists at Manfred Street (see Figure 90 and Figure 94). This section has been previously identified as being at risk of breakthrough (BMT WBM, 2013). The land behind the dune crest at Manfred Street (and along other sections of Belongil Spit) slopes down towards Belongil Creek. This approximately 80m long and 100m wide section has historically been exposed to coastal erosion (both storm erosion and shoreline recession) and overwash processes. On the estuary side, the Childe Street road corridor extends up to the creek embankment. No evidence of progressive bank erosion has been identified in aerial imagery since 1958 suggesting that the risk of breaching from the estuary is low at this location under present conditions.

  Recession of the narrow dune effectively lowers the barrier elevation reducing the sand spit's buffer against storm erosion and wave overwash (see Figure 99). A low elevation rock seawall was built by Council in 2015 as part of 'interim beach access stabilisation' (replacing a temporary geotextile sand container revetment) providing a level of protection along the ocean frontage adjacent to Manfred Street. Further seawalls exist along many sections of Belongil Spit (see Section 5.3.6). In the absence of effective and long-term management of the ocean beach and dune at Manfred Street a risk of breakthrough due to recession and storm erosion may persist. A relatively simplistic assessment of a future breakthrough due to coastal erosion was undertaken considering the following:

  - A coastal profile (see 'P1' in Figure 100) derived from the LiDAR survey in 2018 shows a 26m wide dune above 3m AHD.
  - A volumetric recession rate for Belongil Spit of up to around 2.9m^3/m/year (between 1940 to 2021, see Section 5.3.4). It is noted that more recently this rate has been significantly lower as discussed earlier in this report.
  - Recession due to sea level rise adopting the projections and method in Section 5.3.5.
  - No permanent coastal protection works or natural/ artificial rebuilding of dune.

- Cyclic erosion trends linked to headland bypassing effects that are known to occur in addition of the long term recession trends and storm erosion at Belongil Spit (see Section 4.4.3) are not included in the assessment. These effects would likely further increase the risk of breakthrough.

Only considering long-term recession (including sea level rise) in the absence of storm events or estuary bank erosion and headland bypassing effects, a breakthrough would likely occur by approximately 2070. If coastal erosion during storms is also considered, the results suggest that:

- At present day (based on 2018 profile), a 1% AEP event could result in a breakthrough.
- By 2040, a 5% AEP event could result in a breakthrough.
- By 2060, a 50% AEP or more frequent event could result in a breakthrough.

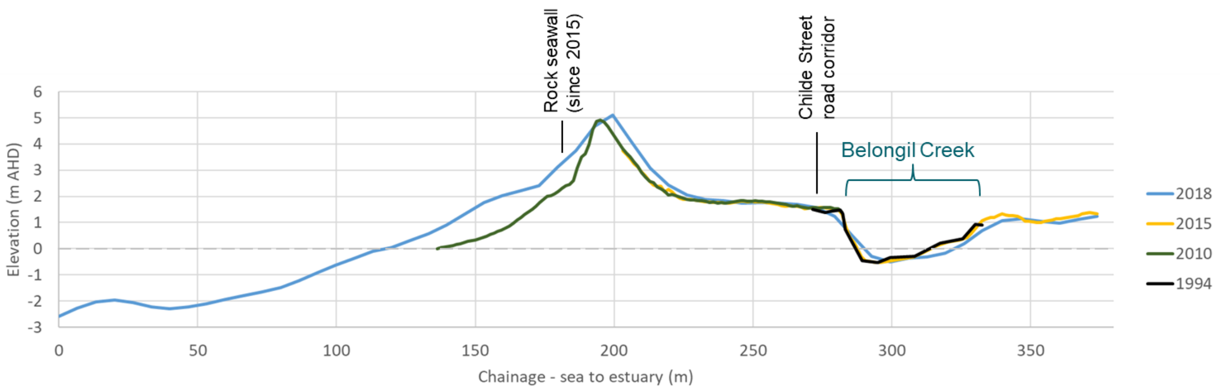

Figure 99: Elevation profiles (1994 to 2018) across Belongil Spit at Manfred Street based on available surveys and LiDAR data.

Note: The 2018 LiDAR data has a horizontal resolution of 5m which may misrepresent steep slopes and narrow elevation peaks.

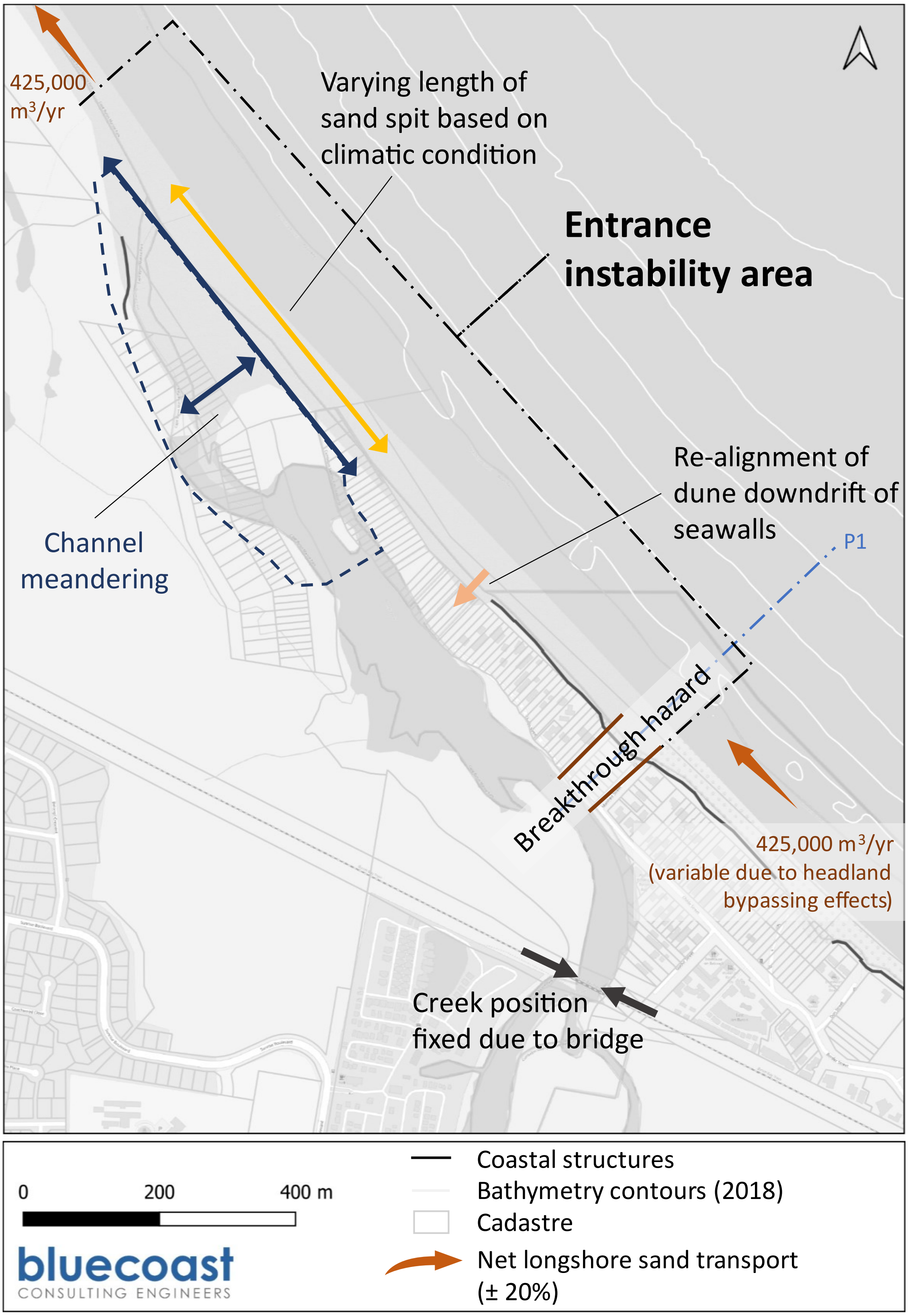

Figure 100: Overview of Belongil Creek entrance instability hazards.

8.3 Tidal inundation hazard assessment

8.3.1 General

A tidal inundation assessment has been undertaken for Tallow Creek, Belongil Creek and the Brunswick River. Numerical modelling was used to simulate the propagation of ocean tidal conditions into the estuaries. The numerical modelling was undertaken by study partner Rhelm. The methodology and results of the assessment are provided in the following sections.

8.3.2 Methodology

Numerical models

TUFLOW models were provided by Council covering the entrance and some portion of the upstream catchment for Tallow Creek, Belongil Creek and the Brunswick River estuaries. The details of these TUFLOW models are summarised in Table 28. The model extents are shown in Figure 101 to Figure 103. The bathymetry at the entrance for each of the three models is shown in Figure 104. All estuaries have been modelled in an open entrance condition.

Changes made to these models to undertake the tidal inundation modelling are discussed below. It is noted that the adopted numerical models had been developed for the purpose of flood studies and no further calibration for this tidal inundation assessment was undertaken. The models incorporated available bathymetric, terrain and structure data and were considered suitable for the assessment of tidal inundation.

Table 28: Overview of characteristics of estuaries in study area.

Estuary	Study	Date	Author	TUFLOW Version	Calibration
Tallow Creek	Tallow Creek Floodplain Risk Management Study and Plan	2009	SKM	TUFLOW_2006-06-DB	Catchment flood only
Belongil Creek	Belongil Creek Flood Study	2009	SMEC	TUFLOW_iSP_w64_2011-09-AF	Catchment flood only
Brunswick River	North Byron Shire Flood Study	2016	BMT WBM	TUFLOW_iSP_w64_2013-12-AC	Catchment flood and tide

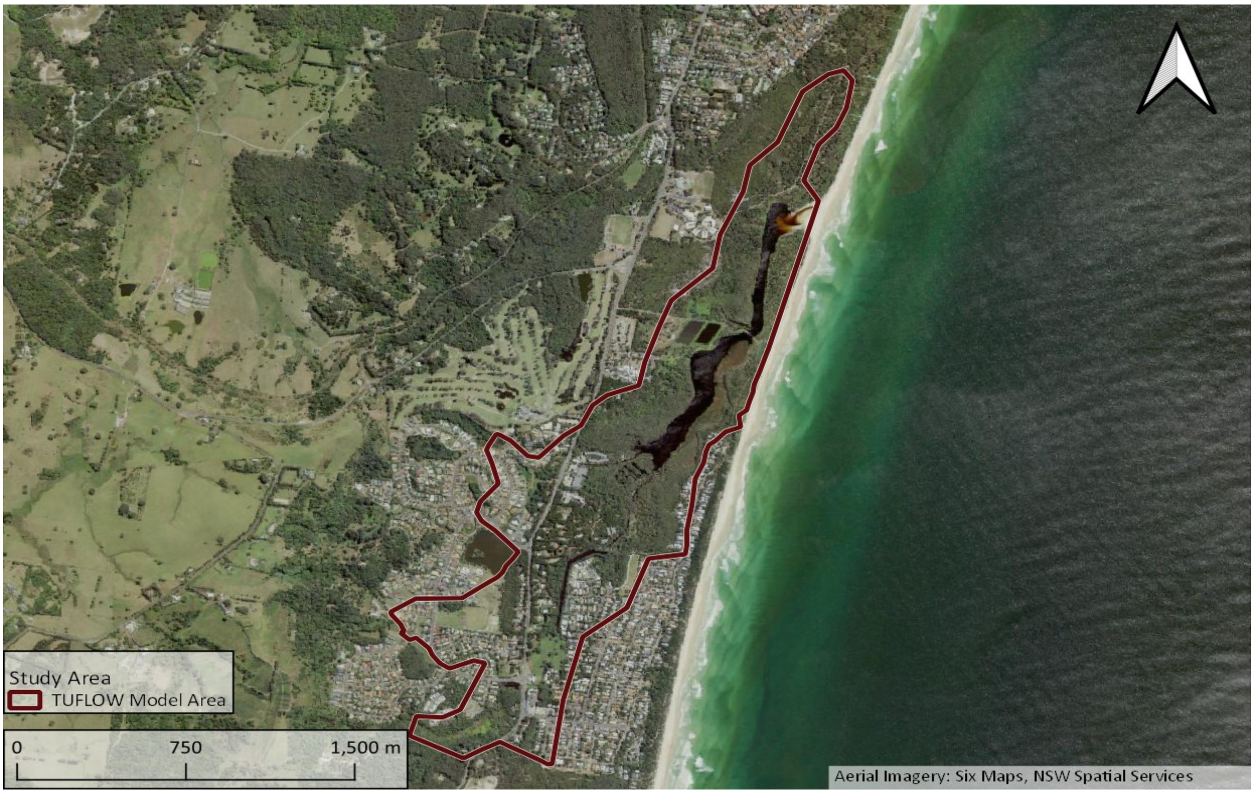

Figure 101: Tallow Creek TUFLOW model area.

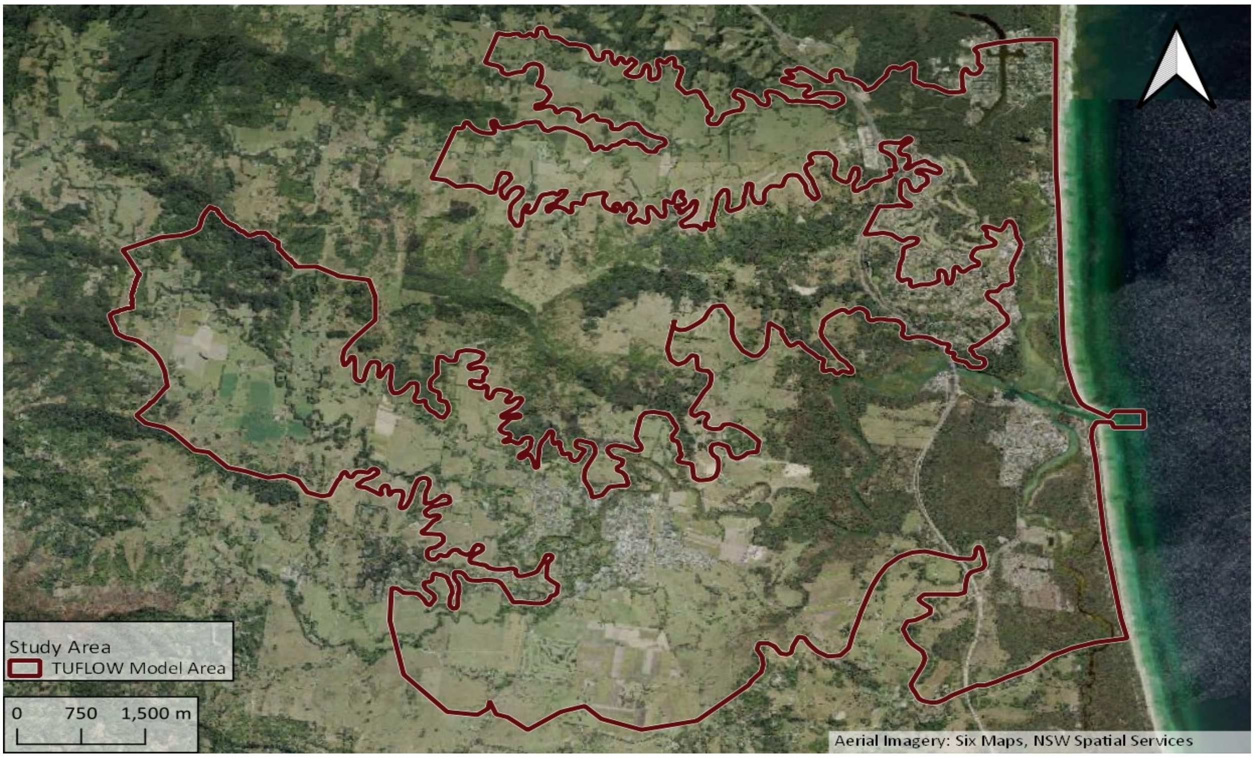

Figure 102: Brunswick River TUFLOW model area.

Figure 103: Belongil Creek TUFLOW model area.

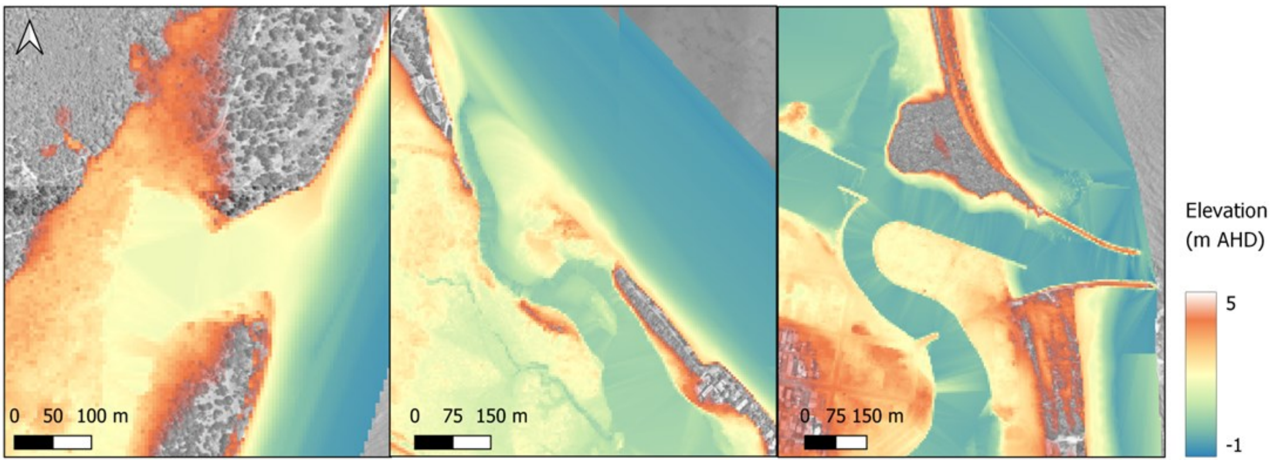

Figure 104: Model bathymetry at the entrance of each estuary. Left (Tallow Creek), Centre (Belongil Creek), Right (Brunswick River).

Model revisions

All three TUFLOW models were updated to:

- Remove the application of catchment inflows by deleting them from the TUFLOW boundary file.

- Update the downstream boundary to incorporate the tidal timeseries. Model initial water levels were also revised to align with the new boundary data. The initial water levels of any ponds, dams, lakes, etc. that were not connected to the main waterway channels were not changed.

A change to the model grid size was also undertaken for the Brunswick River model. The provided TUFLOW model had a series of nested grids with a finer grid cell resolution at the river entrance, and other key areas of interest in the North Byron Shire Flood Study (BMT WBM, 2016). For the purposes of this modelling, the finest grid resolution of all the grids (5m) was adopted across the full model area. This provides an increased resolution for the tidal modelling.

In all other respects, the TUFLOW models remained as per the provided models. The detailed setup of each model is provided in the reference studies (listed in Table 28). Each TUFLOW model was run using the specific TUFLOW version reported in Table 28 to ensure that the model and results are consistent with the adopted Council studies.

Boundary conditions

An ocean tidal boundary was prepared covering 30 days. The tide data was derived from the Brunswick River tide gauge from 20 November 2021 to 17 December 2021 which includes peak levels representative of the High High Water Solstice Spring (HHWSS) tidal plane. HHWSS was adopted as a proxy for a 'king tide' which is commonly used for tidal inundation assessments in NSW (OEH, 2018b). The adopted level is 1.065m AHD based on the 2019-2020 HHWSS tidal plane at Brunswick River published on Manly Hydraulics Laboratory's web portal. A water level exceedance curve for this tide gauge is presented in Section 3.5.

For the future planning horizons of 2040, 2070 and 2120 a sea level rise allowance was added to the tidal signal. The adopted sea level rise values are in accordance with those adopted for the coastal inundation assessment described in Section 7.2.1. The median value (or 50th percentile) of the adopted ranges presented in Table 9 (Section 3.6) was used.

Time series were developed for four planning horizons, noted below with the peak tidal level:

- Immediate: 1.07mAHD
- 2040: 1.23mAHD
- 2070: 1.47mAHD
- 2120: 2.00mAHD

For the TUFLOW model, a 14-hour period was extracted, covering the period between two low tides, with the peak HHWSS tide in the middle. The adopted TUFLOW time series are shown below in Figure 105. The same tidal boundary condition time series was used for each study area.

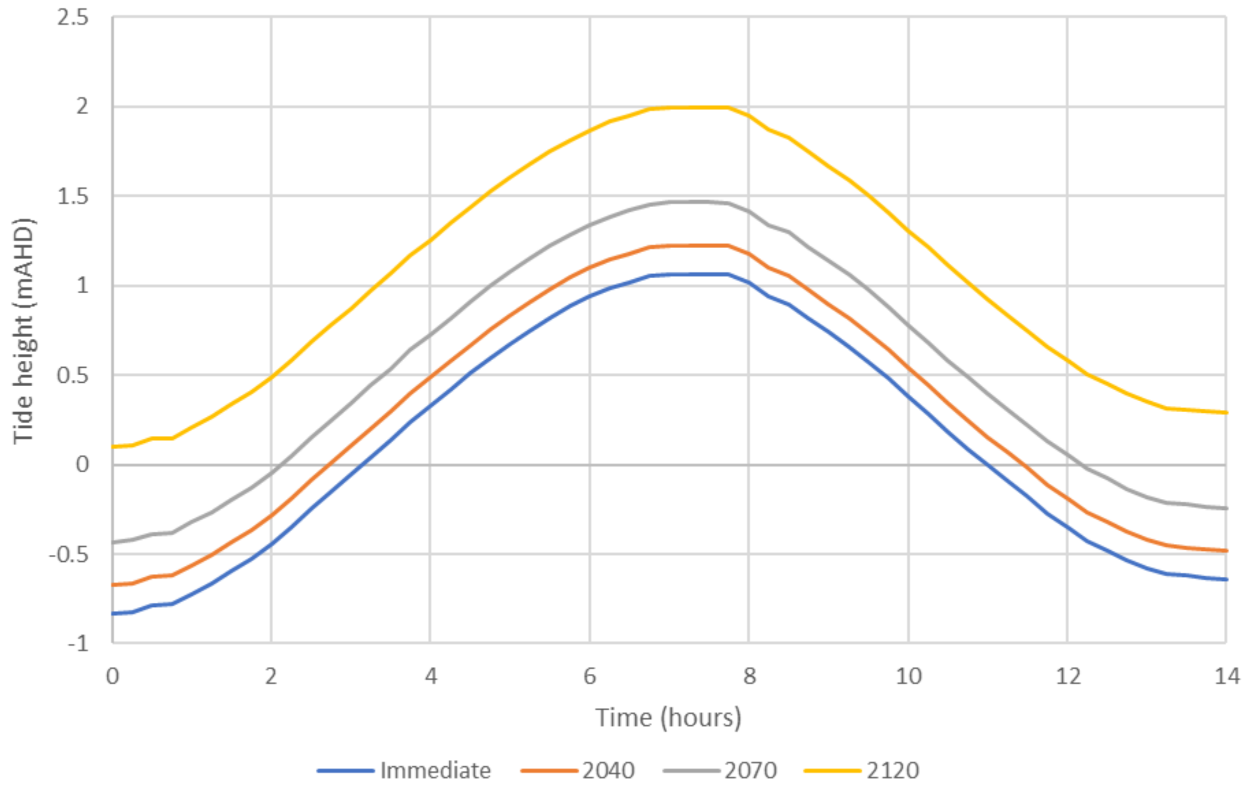

Figure 105: Tidal time series adopted as ocean model boundary for each planning horizon.

8.3.3 Results

Each model was run for a 14-hour simulation period for the four planning horizons.

The peak tidal extents are shown in the map compendium at the end of this report (see 'Maps'). A description of the tidal inundation results for each of the three estuaries modelled is provided in the following sections.

Tallow Creek

- Under present day conditions, the tidal influence extends approximately 1.6km upstream of the entrance and is typically contained within the region of open water, with little influence extending into the narrow channels upstream.
- There was little change in the 2040 scenario, with some lateral expansion of the tidal extent, but no significant increase in the extent of tidal influence upstream.
- In 2070, tidal flows break out of the eastern bank into adjacent vegetated areas, and the upstream extent pushes further south into the narrower reaches of Tallow Creek.
- In the 2120 scenario, the tidal influence extends an additional 1.3km upstream compared to the existing scenario, reaching as far as the Broken Head Road crossing of Tallow Creek. The northern sites of the Crystalbrook Luxury Resort become tidally inundated in the 2120 scenario.

Belongil Creek

- The upstream extent of tidal inundation was similar for the existing, 2040 and 2070 scenarios, with the tidal influence extending approximately 4.5km from the entrance.

- In the 2040 scenario, property accesses from Ewingsdale Road, to the immediate south west of the Ewingsdale Bridge, become inundated by tides along with some fringing areas around existing areas of tidal inundation along the middle section of the Union Drain (primarily forested).
- In the 2070 scenario, much of the area between Ewingsdale Road and Skinners Shoot Road becomes inundated, including several areas of existing developments along Skinners Shoot Road and several agricultural areas along the middle section of the Union Drain.
- The 2120 tidal extent is significantly larger than the 2070 scenario, extending a further 1.5km to the west of the 2070 floodplain impacts, and affects a large region of existing development along both sides of Skinners Shoot Road, Ewingsdale Road, and low-lying developed areas around Kendall Street and Shirley Street.
- Under no scenarios did the tidal inundation extent continue upstream of the existing tidal boundary in the upper Union Drain at Ewingsdale Road.

Brunswick River

- The tidal extent of the Brunswick River is the largest of the three study areas, with the modelling showing the existing tidal influence extending 13km to the west of the entrance along the Brunswick River, 7km north along Marshalls Creek, and over 4km south along Simpsons Creek.
- The upstream tidal inundation extents remain relatively consistent across all planning horizons.
- The lateral extents were also relatively well contained to the rivers and creeks and vegetated overbanks (existing natural areas) up to and including the 2070 scenario.
- The 2120 scenario resulted in a significant increase in the lateral extents of the tidal inundation. This was most pronounced on the Brunswick River upstream of the Princes Motorway in the vicinity of Kings Creek, Midjimbal Creek and drained agricultural land at Brunswick Heads to the west of the highway. Increased lateral extents were also evident upstream of the Orana Road Bridge on Marshalls Creek. While much of the tidal inundation remained within vegetated and open space regions, the 2120 tidal extent did result in inundation across existing development at:
    - Ferry Reserve Holiday Park on the Brunswick River
    - North Head Road, north of the entrance
    - Residential properties south of Strand Avenue, New Brighton
    - Access along River Street, New Brighton
    - Residential properties along Pacific Street, Park Street and Ocean Avenue, New Brighton
    - Areas of the golf course grounds of Ocean Shore Country Club
    - Access along parts of New Brighton Road, South Golden Beach.

8.4 Erosion and inundation of foreshores

The hazards related to estuary bank erosion and foreshore inundation due to the combination of coastal and estuarine processes have been reviewed for the Belongil Creek and Brunswick River 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 to map elevation changes in the riparian area, including:

- 2007 survey (Brunswick River)
- 2015 survey (Belongil Creek)
- 2018 coastal LiDAR data

- Review of previous literature, tidal inundation and flood model results.

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.

8.4.1 Belongil Creek

Erosion of foreshores is a known issue along the northern embankment at the Belongil Creek entrance. This is further discussed in Section 8.2.3. However, no detailed studies that map erosion across the Belongil estuary are available.

A map showing surveyed elevation differences along the riparian area of Belongil Creek between 2015 and 2018 (3-years) is provided in Figure 106. Where available, photographs showing affected erosion sites are also shown. A map of peak tidal current speeds in the estuary for present day and 2120 (including sea level rise) is provided in Figure 107.

Based on the evidence available to this study, the following observations have been made:

- The survey differences suggest bank erosion in the lower estuary is most pronounced at:
  - the northern embankment near the entrance
  - along the north-western part of Belongil Spit
  - along both banks immediately downstream from the railway bridge
  - in the vicinity of Ewingsdale Bridge and Childe Street.
- The cadastral boundaries shown in Figure 106 suggest that the above identified areas have undergone significant movement since the boundaries were first established over a century ago.
- Modelled tidal currents (shown in Figure 107) show areas of higher current speeds align well with those areas identified undergoing bank erosion. Periodic bank erosion occurring because of high catchment flow events is likely the dominant driver of bank erosion upstream from the entrance. However, the simulated tidal currents are expected to provide some indication of areas experiencing high current speeds during both ambient and flood conditions. Other drivers of bank erosion likely include wind waves as well as vegetation health which can increase erosion vulnerability.
- The modelled tidal currents for the 2120 scenario (including sea level rise) shows increases in current speeds along both banks for most of the lower estuary. Sea level rise likely results in tidal currents (and wind waves) to more frequently affect parts of the upper banks that are currently not adapted to regular inundation. This is likely to cause ongoing bank erosion where this is already occurring as well as affect additional areas. The highest increases in current speeds are shown in the entrance area[7] where this may exacerbate erosion along the northern embankment already

[7] The hydraulic model does not include morphological changes during simulation. In reality, the current speeds would be expected to decrease as a result of natural channel scour.

affecting littoral rainforest and private property. As discussed in Section 8.2.3, the entrance configuration and associated channel meandering plays a key role in the erosion risk along this northern embankment.

As described in Section 8.2, the natural berm height of the estuary is expected to rise with sea level which likely results in increased estuary water levels. However, the estuary hydraulics will continue to be largely controlled by the entrance condition, including Council's ongoing entrance management. Alluvium (2019) expects the artificial opening events will become more frequent with sea level rise and that a higher trigger level will need to be adopted in future. Higher berm levels and higher trigger levels likely increase the frequency and extent of nuisance flooding around the estuary. Sea level rise is likely to influence the tidal regime in the Belongil estuary during open entrance condition. As noted above, this will affect the frequency and duration of inundation of foreshores, impacting bank stability and vegetation health.

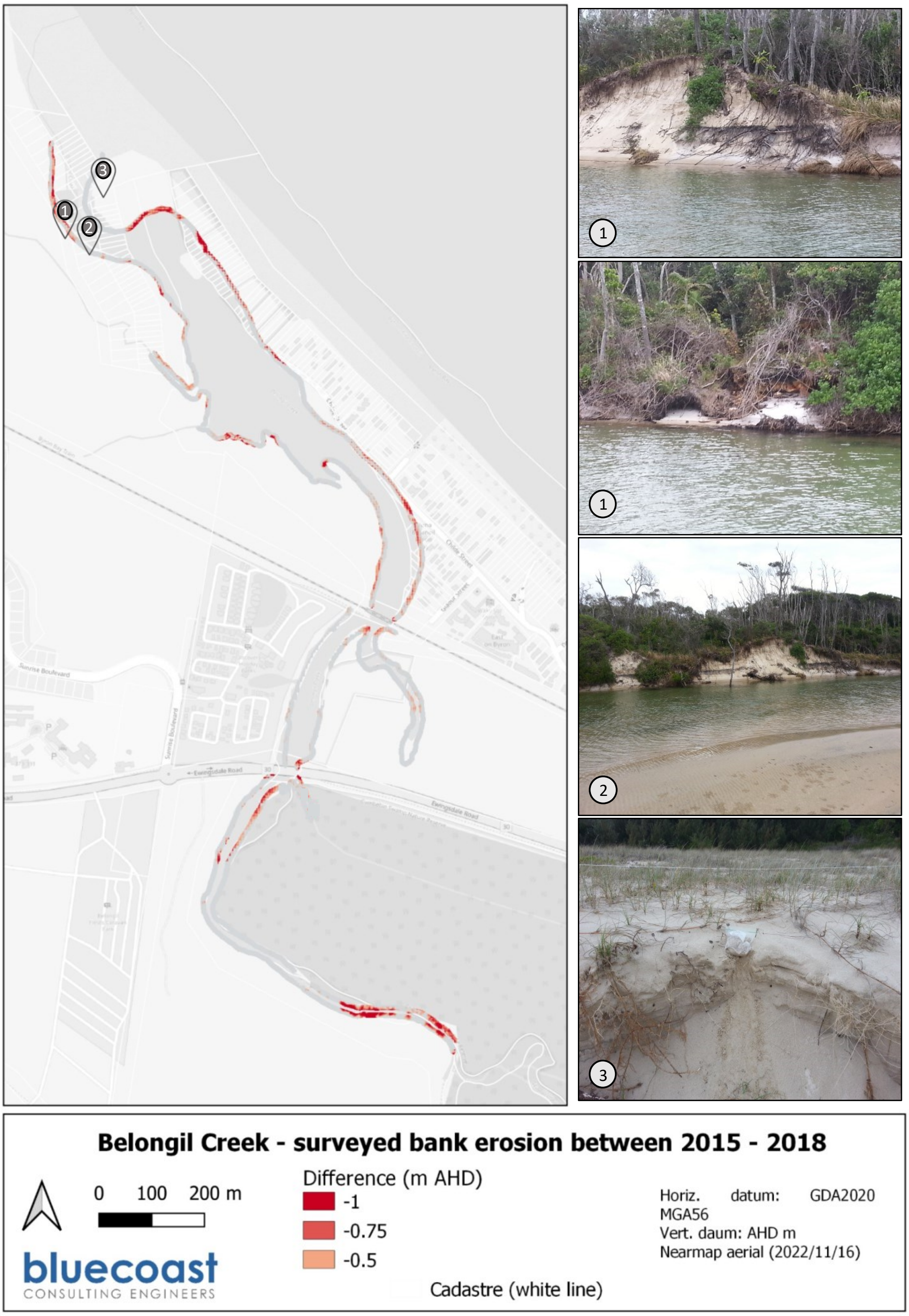

Figure 106: Surveyed elevation changes along riparian area in Belongil Creek with photos from July 2015.

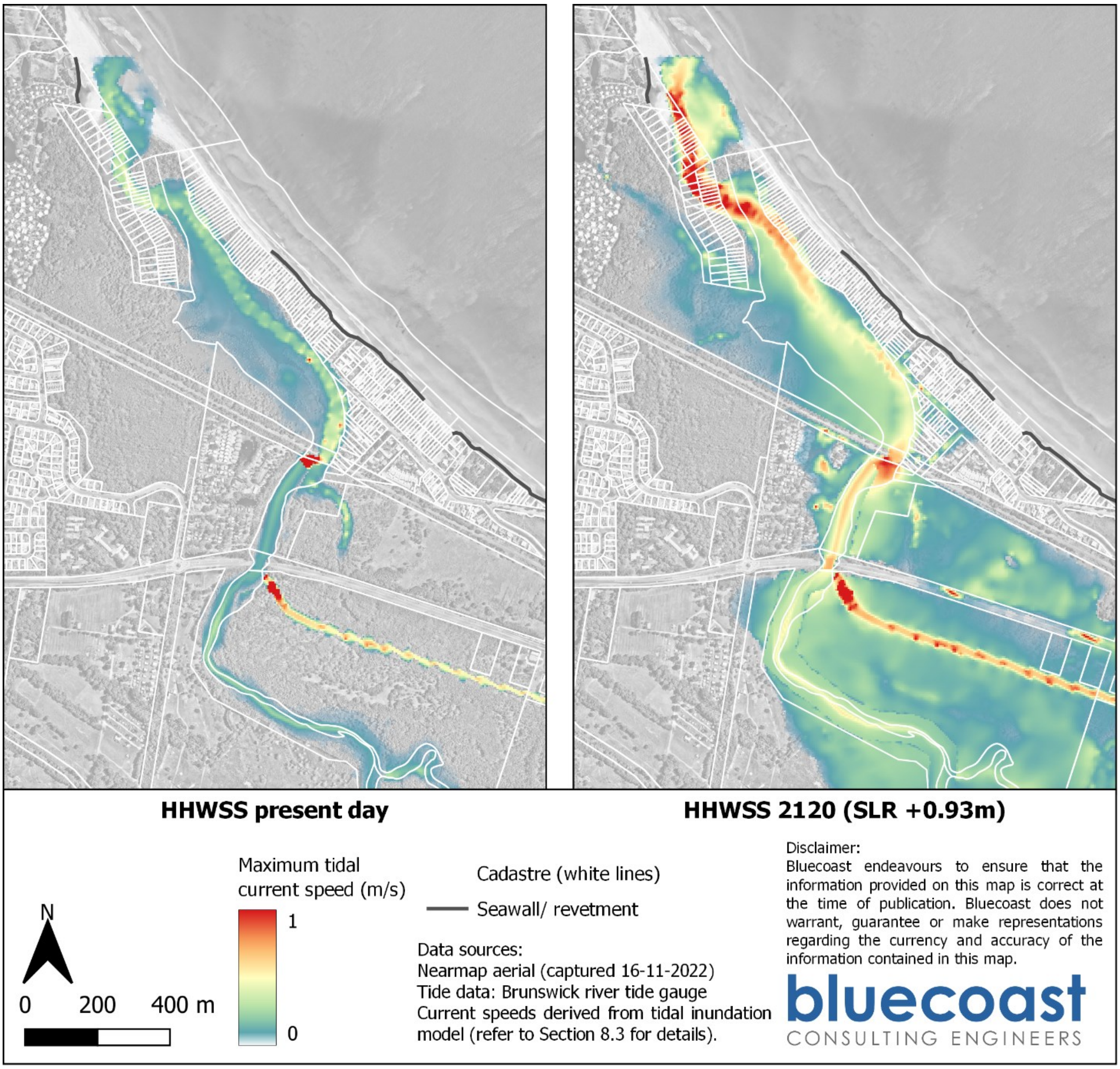

Figure 107: Modelled peak tidal currents in Belongil estuary for present day and 2120 scenarios.

8.4.2 Brunswick estuary

The Coastal Zone Management Plan (CZMP) for the Brunswick River estuary identified bank erosion sites within the estuary based on a site survey undertaken in January 2017 (Byron Shire Council, 2018b). The CZMP identifies a number of sites in Brunswick River, Simpsons Creek and Marshalls Creek that required on-ground works comprising bank stabilisation (hard, soft or combination), revegetation of the riparian buffer zone, or repair of existing structures (such as revetment walls). Some of these site works have been completed to date, including sites at Banner Park and Terrace Park (Lower Simpsons Creek), North Head Road (Marshalls Creek) and Brunswick Heads foreshore (west of freeway) (pers. comm. Council). A site survey was not repeated herein.

The assessment undertaken herein focusses on the lower estuary downstream from the Pacific Motorway bridge, including lower sections of Simpsons Creek and Marshalls Creek. A map showing surveyed elevation differences along the riparian area of the lower estuary between 2007 and 2018 (11-years) is provided in Figure 106. Bank protection structures identified in aerial imagery are also shown. It is noted that current speed maps could not be derived from the tidal inundation model for this estuary due to the adopted model setup.

Based on the evidence available to this study, the following observations have been made:

- Rock protection structures exist along much of the riverbanks in the lower entrance area which effectively limit foreshore erosion.
- The survey differences and aerial imagery suggest bank erosion in the lower estuary is most pronounced:
    - In the lower reach of Simpsons Creek, with significant bank erosion observed adjacent to the Sea Scouts Hall, adjacent to the bowling club, along Bayside Way and the end of Omega Circuit.
    - In Marshalls Creek opposite River Street at New Brighton.
- Periodic bank erosion occurring because of high catchment flow events is likely a key driver of bank erosion upstream from the entrance. Other drivers of bank erosion likely include wind waves and boat wakes as well as vegetation health which can increase erosion vulnerability. The CZMP also identified uncontrolled public access (incl. illegal camping) and trampling of bank vegetation as a key driver for bank erosion in the estuary.
- Sea level rise likely results in tidal currents as well as wind waves and wakes to more frequently affect parts of the upper banks that are currently not adapted to regular inundation. This is likely to cause ongoing bank erosion where this is already occurring as well as affect additional areas.

It is noted that the Brunswick River training walls play a key role in the stability of the entrance, adjacent beaches and lower entrance area as well as the estuary hydraulics. For the purposes of Stage 2 of the CMP, it has been assumed that the training walls will be maintained into the future. The sand budget analysis and erosion and recession assessment undertaken as part of this study suggest that the sections of beach either side of the training walls have been long-term accreting or stable (see Section 4.4.8). When considering recession due to sea level rise, the training walls may be further exposed to coastal processes compared to present day. However, based on the projected landward extent of future erosion and recession (see map compendium) it is reasonable to assume that the function of the training walls would not be significantly compromised if typical structure maintenance is continued. The potential impacts on the training walls including their structural integrity and performance require further consideration during subsequent stages of the CMP.

The estuary response to sea level rise is complex and depends on energy drivers (e.g., tides and river inflows), estuarine geometry, intrinsic fluid properties (e.g., density), and bed/bank roughness. For most estuaries sea level rise is expected to amplify the tidal range and it is likely that sea level rise alters the tidal range patterns in an estuary such as the location of the points with minimum tidal range (Khojasteh et al., 2021). Khojasteh et al. (2021) found that this is largely an effect of sea level rise increasing the water depth and reducing bed friction. It is noted however, that uncertainty around the lower Brunswick River estuary's morphological response to sea level rise and associated tidal effects remains.

Figure 108: Surveyed elevation changes along riparian area in the lower Brunswick River estuary with photos sourced from Byron Shire Council (2018b).

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