Tweed Sand Bypassing

Letitia Beach Behaviour Report

Letitia Beach Behaviour Study

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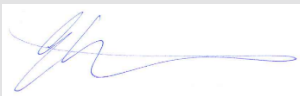
1.0	19/11/2021	H. Loehr, J. Gainza and H. Watson	E. Watterson, A. Short	DRAFT	
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1. Introduction

1.1 About this report

This report provides an investigation of observed beach behaviour from Fingal Head to Letitia Beach, NSW. Analysis of coastal processes was undertaken to understand potential influence of the operation of Tweed Sand Bypassing (TSB) on the study area to inform TSB's legislative, contractual and operational arrangements.

1.2 Project background

The Tweed River Entrance Sand Bypassing Company (TRESBCo - a subsidiary of McConnell Dowell Constructions) has operated the sand bypassing system since May 2001. The TSB system works to establish and maintain a safe, navigable entrance to the Tweed River and provide sand to the Southern Gold Coast beaches consistent with natural northerly longshore transport rates. The system comprises a sand collection jetty constructed across Letitia Beach, just south of the Tweed River entrance where a series of submerged jet pumps are suspended from the jetty structure to collect sand. Collected sand is transported through a buried pipeline to feed beaches north of the entrance. Supplementary dredging to clear the Tweed River entrance is commissioned by TRESBCo when required. Dredging is typically carried out using a trailer suction hopper dredge. The dredge deposits sand in placement areas along the southern Gold Coast beaches and south of the entrance to provide nearshore nourishment.

An Environmental Impact Statement/Impact Assessment Study (EIS/IAS) for the Sand Bypassing System was completed in 1997 to satisfy the environmental planning requirements of both states. The Concession Agreement (CA) sets out the current operation and maintenance requirements for the TSB system and is up for renewal on 30 September 2024. The CA sets out obligations related to shoreline recession at Letitia Beach based on predictions undertaken as part of EIS/IAS investigations.

1.3 Study area

Letitia Beach is located to the south of the Tweed River entrance in northern New South Wales. The Letitia Beach compartment extends from Fingal Head on its southern end to the southern Tweed River training wall in the north, a 3.6km long east-northeast facing beach (see Figure 1). This study focusses on the behaviour of this compartment but considers the sand movement pathways and exchanges with neighbouring compartments.

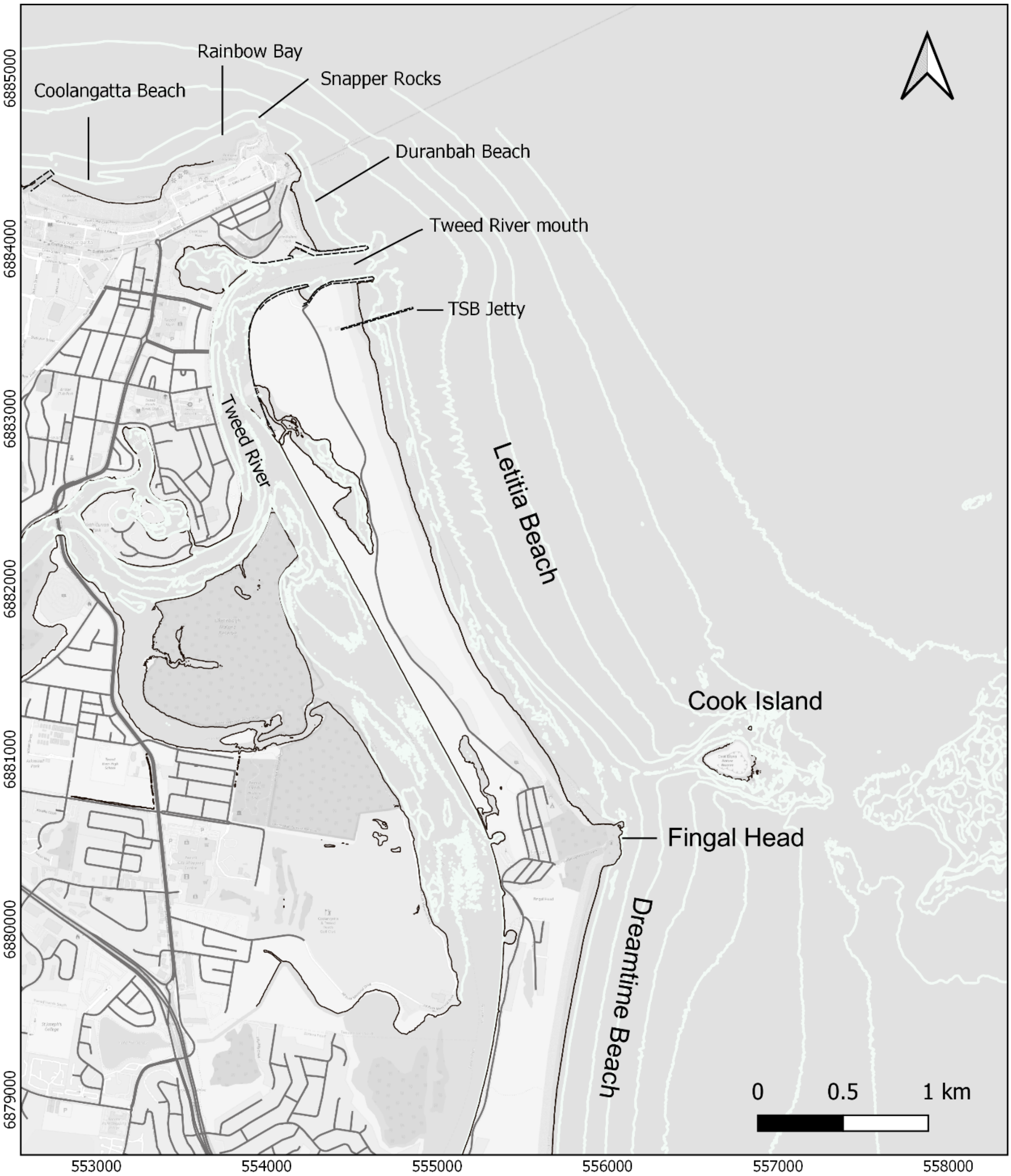

Figure 1: Map of study area (coordinates in MGA 56).

1.4 Project objectives

TSB's objectives of the Letitia Beach Behaviour Study are as follows:

- Understand the historical changes that have occurred in the coastal environmental along Letitia Beach in response to natural processes and anthropogenic influences.

- Determine how coastal processes and TSB operations contribute to the current beach behaviour and future coastal morphology trends at Letitia.
- Review and revise the shoreline recession limits set out in the Concession Agreement.

1.5 Scope and structure of this report

This report sets out the findings of the Letitia Beach behaviour study. The study uses a data-driven approach to quantify the pathways and rates of sand movement in the Letitia Beach to Fingal Head beach compartment and describes the underlying coastal processes driving the observed changes. The report is set out as follows:

- Section 2 provides background information including a critical review of previous literature on coastal processes in the study area, a timeline of key anthropogenic changes and a list of the existing data that has been utilised
- A description of the contemporary geomorphic setting and coastal processes at Letitia Beach is provided in Section 3
- Section 4 outlines the volumetric analysis of topographic and bathymetric surveys to establish observed historical changes in sand volumes as well as the study area's sand budget and quantified conceptual sand movement model
- Section 5 contains a summary along with recommendations.

2. Background information

2.1 History of Letitia Beach coastline

Letitia Beach and the adjacent Tweed River have been continually modified over the course of European settlement. Modifications that have impacted the beach response include the construction of the Tweed River training walls, subsequent extension of the training walls, capital and maintenance dredging of the navigation channel, as well as the ongoing operation of the sand bypassing system. Due to the training walls and dredging of the navigation channel the Tweed River mouth is now fixed and no longer subject to natural migration.

Figure 2 provides historical aerial photographs of northern Letitia Beach and the Tweed River entrance. A summary of the key anthropogenic influences on the coastal processes at the study site is outlined as.

- 1880-1910: Training walls were built along either side of the Tweed River entrance.
- 1962: Tweed River training walls were extended by 300m.
- 1994: The Tweed River Entrance Sand Bypassing Project (TRESBP) was formulated as an agreement between the New South Wales and Queensland Governments.
- 1995-1998: 3.05 million m^3 of sand was dredged from Tweed River entrance.
- December 1999: contracts were awarded to a consortium led by McConnell Dowell Constructors (Aust) Pty Limited for the design, construction, operation and maintenance of a permanent sand bypassing system until September 2024.

- February 2000: Construction of the permanent bypassing system commenced.
- May 2001: Full scale operation of sand pumping and dredging commenced.
- 2001-2008: ‘Supplementary Increment’ phase with initial sand volumes transferred to QLD around 1 million m^3/year.
- 2008: Bypassed sand volumes reduced to align with long-term average longshore sand transport rates at Letitia (around 500,000 – 600,000m^3/year).

Figure 2: Aerial photographs of the Tweed River entrance and northern Letitia Beach (source: TSB).

2.2 Introduction to coastal processes

Jacobs (2017) and the TSB website provide a general overview of coastal processes relevant to the study area. This section provides a summary thereof. Section 3 presents a site-specific description of the coastal environment along Letitia Beach and how that interacts with coastal processes, particularly in terms of sand movements.

Movement of water and sediments within and around the coastal zone occurs in three main areas, the shoreline and beach above the mean sea level (MSL) mark, in the intertidal swash zone, and in the subtidal surfzone-nearshore waters. 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 coastal zone 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 which have longer periods of 25-250 seconds and are formed due to the superposition of two different short-wave trains of similar lengths and frequencies. The waves are often reflected off the coast and the presence of a sandbar may trap infragravity waves between the bar and the beach. Wave breaking, particularly in the surf zone, and infragravity waves which can dominate the wave motions at the coastline particularly during storm events, result in radiation stresses and drive currents. This is

both cross-shore and longshore, which combined with the breaking waves are the main driver of sand transport. In addition, wave orbital motions drive mass onshore movement of sediments owing to differences in shear stress on the seabed leading to beach accretion, while undertow can result in transport of sediments offshore due to bottom return currents and rip currents in the surf zone leading to 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 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.
- **Wind** - wind driven (aeolian) sediment transport occurs over mobile 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, winds and ocean currents 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.

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

- **Longshore sand transport** (also known as littoral drift) occurs across the surf zone due to waves approaching the beach from an oblique angle which generates radiation stresses, driving currents along the shore. The direction of sediment transport along the coast is dependent on the prevailing wave direction (i.e., transport north could occur during a south-easterly wave direction). Longshore sediment transport occurs inshore of the surf zone where wave breaking occurs, reducing in strength with distance shoreward and offshore due to a typical increase in depth and therefore reduction in wave breaking.

In some circumstances, winds, tides and in places the East Australian Current may also contribute to longshore currents and may dominate the currents outside of the surf zone (i.e., currents outside the surf zone can run in the opposite or alternative directions to the wave driven current inside the littoral zone).

- **Cross shore sand transport** occurs across the surf zone-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.

2.3 Legislative and contractual context

TSB operates under overarching legislation in both New South Wales (NSW) and Queensland (Qld). The objectives, rights and responsibilities between the two states is defined in the Heads of Agreement (1994) and more detailed Deed of Agreement (1995). These apply in perpetuity, subject to amendment or repeal of the applicable legislation. The provisions and requirements under these agreements were enshrined in legislation in both states, through:

- Tweed River Entrance Sand Bypassing Act 1995 (NSW)
- Tweed River Entrance Sand Bypassing Project Agreement Act 1998 (Qld).

NSW is the Coordinating State, while Qld is the Reviewing State. TSB is currently operated by Transport for NSW and the Qld Department of Environment and Science. TRESBCo is responsible for the operation and maintenance of the sand bypassing system as detailed in the Concession Agreement (CA) executed in 1999 between TRESBCo, the Governments and McConnell Dowell Corporation Limited as Guarantor. Regular and ongoing compliance monitoring of the operator’s obligations set out in the CA are undertaken by TSB. The objectives and requirements for TSB operations are derived from the project specific legislation and the environmental planning approvals. These requirements are reflected in the operator's obligations under the CA (Clayton, 2020). The original CA (1999) sets out the ‘EIS-IAS Obligations’ which are the operator’s obligations arising under:

- Tweed River Entrance Sand By-passing Project, Permanent By-passing System, Environmental Impact Statement/Impact Assessment Study (EIS-IAS) dated June 1997
- Representations Report dated December 1997
- Approval of the Minister for Urban Affairs and Planning (NSW) dated 24 July 1998 and the conditions of the Approval

- Impact Assessment Review Report prepared by the Queensland Department of Environment and Heritage dated March 1998
- Extension of Avifauna Impact Assessment to Include Threatened Species Survey, Letitia Beach Report dated May 1998.

2.4 NSW Coastal Management Framework

Since obtaining the original planning approvals in the late 1990s there has been significant changes in the legislative space. Most significant, changes to the planning instruments relevant to coastal management in NSW have occurred through the NSW Coastal Management Framework, comprising:

- Coastal Management Act 2016
- Marine Estate Management Act 2014
- State Environmental Planning Policy (Coastal Management) 2018
- NSW Coastal Management Manual
- Coastal Management Programs
- NSW Coastal Council
- Coastal and Estuary Grants Program.

The *Coastal Management Act 2016* (CM Act) establishes the framework and overarching objects for coastal management in New South Wales. The CM Act also supports the aims of the Marine Estate Management Act 2014, as the coastal zone forms part of the marine estate. The Coastal Management State Environmental Planning Policy (CM SEPP) identifies development controls for consent authorities to achieve the objectives of the CM Act. The Coastal Management Programs (CMPs) set the long-term strategy for coordinated management of the coast with a focus on achieving the objects of the CM Act.

Tweed Shire Council is in the process of developing a CMP including Letitia Beach and the lower Tweed River estuary. TSB's operations play a major role in the management of the coastal zone set out in the CMP and consultation with Tweed Shire Council is ongoing.

2.5 Previous TSB sand movement studies

The TSB project area, including Letitia Beach, has been the subject of numerous studies to assess coastal processes. A non-exhaustive list of the previous key studies is used to inform this study. A summary is presented below in chronological order, which provides the most up-to-date understanding of the coastal processes at Letitia Beach. In addition, the previous literature is referred to throughout this document wherever relevant.

- Coastal Studies (2008) investigated potential management strategies for Letitia Beach considering the recession limits and sand transfer quantities set out in the CA. The report critically reviews the recession limits predicted in the EIS/IAS investigations and argues that these were both unrealistic and unattainable for the sand transfer rates at the time. It states that just like accretion occurred along the entire Letitia compartment following the extension of the training walls in 1962, so would recession due to TSB pumping at the northern end of Letitia Beach. Though to a lesser extent along the south of Letitia, observed shoreline recession occurs due to sand being lost from the entire embayment because of the pumping between 2000 and 2006. Likewise, sand losses were observed to extent well offshore (at least 1300m). However, were more equally distributed throughout the compartment beyond the 5m depth contour. The report also states that a permanent topographically controlled rip current exists along the jetty which may further exacerbate beach erosion in the lee. Further, natural erosion processes linked to large scale climate variability (El Niño/ La Niña conditions) are discussed. The report highlights that moderate erosion occurred along the entire NSW coastlines in 2007/08 (period of positive Southern Oscillation Index) including Dreamtime Beach south of Fingal Head. It is noted that the data reviewed as part of this study was representative of TSB's Supplementary Increment phase and is likely not representative of the present conditions since sand transfer volumes were reduced in 2007.

- BMT (2008) completed a review of the EIS/IAS investigations that informed the operator's requirements in the Concession Agreement as part of the *Erosion of Letitia Beach* study. The study highlighted key assumptions and uncertainties in the numerical modelling undertaken at planning stage. Further, the study reviewed the historical shoreline movements at Letitia using survey data and aerial imagery. The analysis suggested that while shoreline accretion was evident along all of Letitia Beach since extension of the training walls in 1962 until late 1990s, the pattern of shoreline behaviour at the southern and northern end are largely unrelated. In agreeance with more recent literature (e.g., Silva et al., 2021), the study suggested that shoreline behaviour at the southern end is largely related to sand bypassing around Fingal Head. In addition to longshore sand transport, onshore movement of sand from water depths of around 13m was identified in the survey profile data. This onshore movement of sand gradually supplies the active part of the beach profile and sand extraction at the TSB jetty. A total loss of 1.98Mm^3 sand until April 2007 was reported for the Letitia Beach compartment. The study assessed data concurrent to TSB's Supplementary Increment phase between 2001 to 2007. The trends identified in BMT (2008) are therefore unlikely to be representative of the present conditions at Letitia.

- Cardno (2009) investigated various modifications to TSB operations to address long-term recession of Letitia Beach. Of relevance was the numerical modelling of sediment transport patterns during northerly wave conditions (see Figure 3). The study suggests that due to the orientation of the northern section of Letitia Beach, there is limited southward directed sand transport during periods with northerly wave directions and most sand transport would be onshore directed for low to medium wave energy conditions. Cardno argues that sand extraction at the jetty during prolonged northerly wave conditions would lead to exacerbated beach erosion in this area due to a lack of sand supply from the south. It is noted that the numerical modelling undertaken in this study does not seem to be adequately validated against measured data and results should be interpreted with this in mind.

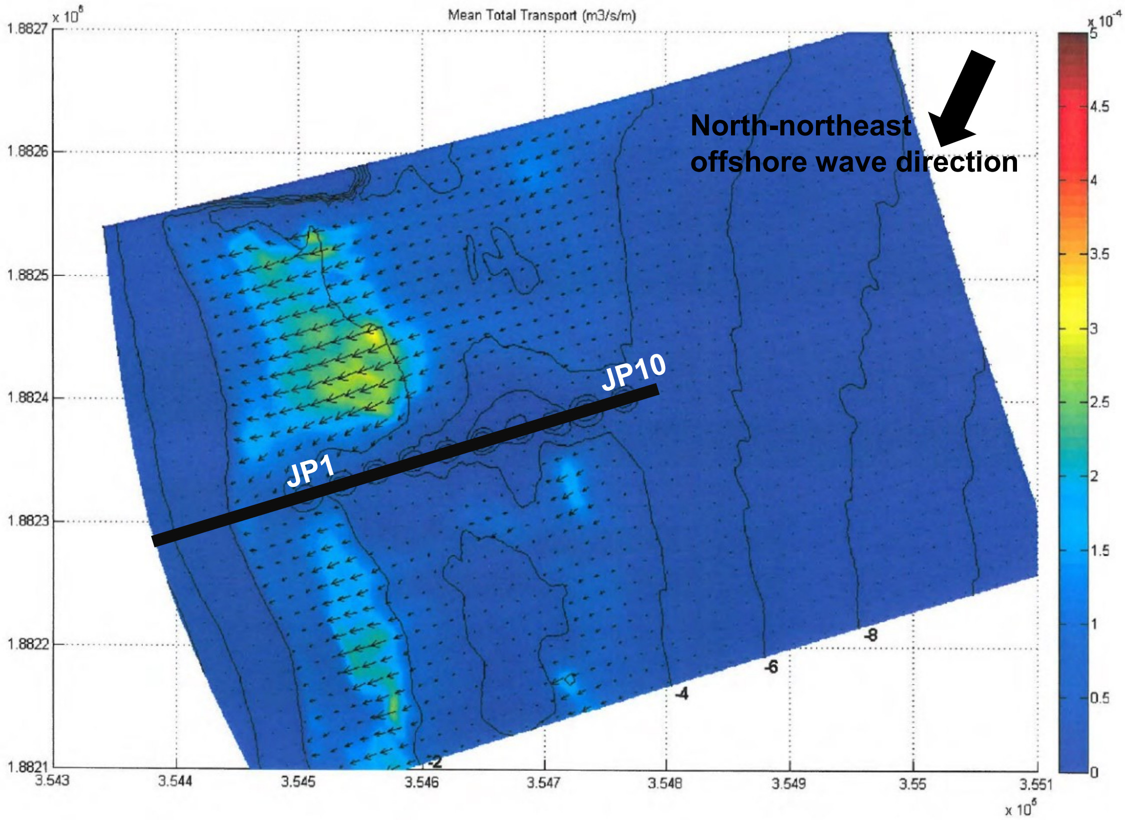

Figure 3: Modelled mean sand transport at the TSB jetty during low energy wave conditions, H_s 1m and D_p 65°TN (after Cardno, 2009).

- Jacobs (2017) synthesised and described the geomorphic processes within the TSB study area between Fingal Head and Currumbin based on existing available information at the time of writing. Quantified conceptual coastal processes models were graphically presented for five environmental scenarios for typical, storm and catchment flood conditions. The report provides a baseline high-level understanding for the coastal processes at Letitia Beach. Additional investigations have since been completed and new information has become available. The report states that while the dominant sand transport is from south to north, Letitia experiences considerable southward directed littoral sand transport from time to time (mainly in spring and summer). This statement is conflicting with Cardno's (2009) high-level numerical modelling investigations that found limited southward transport occurs during periods of more northerly wave conditions due to the alignment of Letitia Beach. At greater water depths, the East Australian Current becomes increasingly more significant which results in net southward sand transport beyond 12m water depth. The report states that 70% of the net longshore sand transport along Letitia Beach is trapped by the TSB jetty. While the pathways and mechanisms that cause sand leakage past the jetty are not fully understood it is assumed that a large portion of the leakage occurs during major storm events. It was assumed that during these conditions the littoral zone extends seaward of the jetty and the slurry pit is unlikely to trap all transport through the jetty. Further, the report states that during major flood events significant sand volumes are transported to the entrance area (e.g., ~150,000m^3 during March 2017 flood) and since commencement of TSB a net supply from the river to the coast is observed.

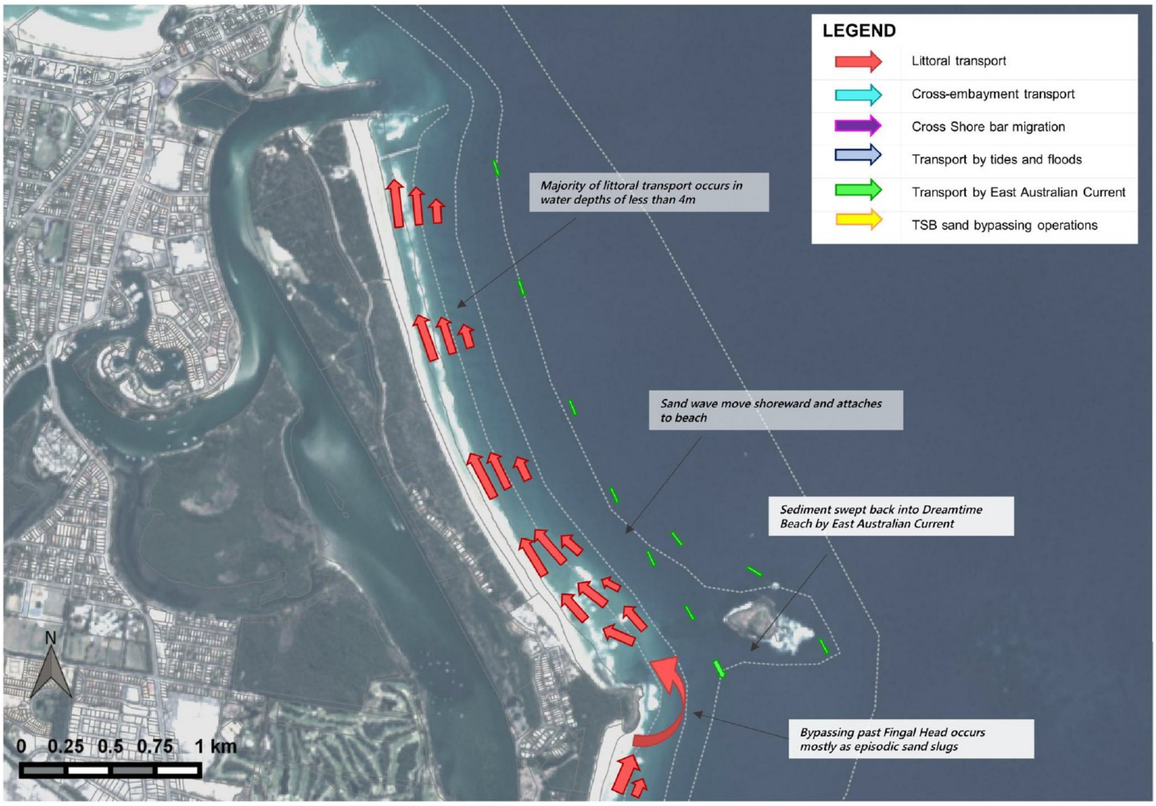

Figure 4: Conceptual model of sand movement patterns (source: Jacobs, 2017).

- Cardno (2020) reviewed a series of specialists reports on TSB operations undertaken as part of TSB's Transition Project. Most relevant to Letitia, they discuss that the coastline on Letitia Beach is continuing to evolve with the wave climate, longshore sand transport and TSB pumping regime. The report highlights that projected sea level rise (SLR) would cause an additional shoreline recession on Letitia Beach that requires consideration in Tweed Shire Council's CMP and future TSB operations. Cardno also argues that previously recommended reduced operation of the two inner jet pumps of the TSB jetty at Letitia for sand extraction closest to the sub-aerial beach is unlikely to result in beach widening at the jetty. It is stated that most of the longshore sand transport occurs where the two inner jet pumps are installed, and reduced sand extraction will increase sand leakage to the Tweed River entrance. Cardno proposes that only reducing the overall annual sand transfer volume to Queensland will result in widening of Letitia Beach.

- The legislative requirement to re-assess the long-term average (LTA) annual net sand transport rates for the TSB project area is undertaken at 5-year intervals based on sand transport modelling and observed sand budget considerations (BMT WBM, 2011, 2016 and 2020). The LTA net sand transport rates for the TSB project are defined in the Deed of Agreement as (essentially) the long-term average of the sand transport into Letitia Beach minus the natural bypassing to Queensland. The latest re-assessment report suggests that between 2015 and 2019 the net longshore sand transport rates have been lower than the long-term trend due to a less energetic wave climate. Over the period 1995 to 2019, the long-term net annual sand transport into Letitia Beach was estimated at approximately 546,000m^3/year (see Figure 5). BMT's (2020) best estimate LTA net sand transport rate for the TSB project was estimated at 490,000m^3/year (±20,000 m^3/year), comprised of 400,000m^3/year sand pumping and bypass dredging of around 90,000m^3/year. A natural average bypassing rate of approximately 43,100m^3/year to Queensland was calculated at the NSW/Qld border since commencement of TSB operation. Sand movement to deeper water (>20m) were identified at the entrance which have been reducing since 2000 with current estimated rates at about 5,000m^3/year. Since 2000 the average rate was around 7,000m^3/year. This 'loss' of sand was estimated to be in the same order of sand supply from the Tweed River.

The study suggests that previously identified trends of reducing sand volumes at Letitia Beach since the start of TSB pumping operations in 2001 had ceased by 2015. The report indicated that Letitia's response to TSB operations has therefore broadly stabilised. Further, it was identified that sand volume changes at southern Letitia Beach are more related to headland bypassing around Fingal than behaviour of central and northern end of Letitia Beach. A large variability of headland bypassing volumes was identified in BMT WBM (2020) with the average longshore transport rate at Letitia South ranging between 270,000m^3 in a low year (2013) and above 990,000m^3 in a high year (2003). This process was further investigated in recent research on headland bypassing at Fingal Head undertaken by Silva et al. (2021), described in the following paragraph.

Period of Calculation*	Average Annual Net Transport at Various Letitia Locations (m^3/yr)					
	Snapper	North Wall	Sth Wall	Letitia Nth	Letitia Cnt	Letitia Sth
1995 to 2000	393,700	306,400	626,400	591,700	575,500	539,900
1995 to 2009	622,400	141,300	396,900	691,500	606,600	565,500
1995 to 2019	568,800	99,200	270,400	620,800	554,400	546,400
2001 to 2009	775,000	31,300	243,900	758,000	627,400	582,500
2001 to 2019	624,100	33,700	158,000	629,900	547,700	548,500
2009 to 2019	511,700	48,400	97,300	528,900	477,800	506,600

Figure 5: Calculated longshore sand transport rates at Letitia based on review of survey data (source: BMT, 2020).

- Silva et al. (2021a) undertook a detailed review of survey data (1.5 years) and aerial/satellite imagery (30 years) between Dreamtime Beach and Letitia Beach to assess short-term and long-term behaviour of sand bypassing around Fingal Head. The commencement of TSB sand pumping was evident in the survey data along the northern section of Letitia Beach as after 2001 the beach profile translated shoreward in this area. A possible 'null' sector of the embayment was identified along the central part of Letitia Beach. Beach profile changes at the southern end, adjacent to Fingal Head, were found to be distinctly different to the northern region of Letitia. Profile variability at the southern end were predominantly linked to profile changes updrift of the headland at Dreamtime Beach. Further, a 'sand slug' (i.e., a large body of sand that moved around Fingal Head) was observed to gradually migrate northward along Letitia over the period between 2013 to 2020, resulting in shoreward translation of the respective beach profile. Finally, the study identified two distinct headland bypassing processes:
    - Sandbar-driven bypassing related to high-energy wave events
    - Sand leaking around Fingal Head following persistent low energy wave conditions and widening of the updrift beach

The headland bypassing processes were found to occur over multiple timescales, from interannual to seasonal variability due to the typical wave climate and interannual to decadal-scale variability linked to large scale climate drivers such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and Interdecadal Pacific Oscillation (IPO). It was found that prolonged (~years to decades) bias towards La Niña phases can result in erosive beach state updrift and downdrift of Fingal Head, reducing headland bypassing potential and supply to Letitia. With projected large-scale changes to the frequency of extreme ENSO events in a changing climate, particularly towards La Niña events, this would be expected to significantly alter the sand budget at Letitia.

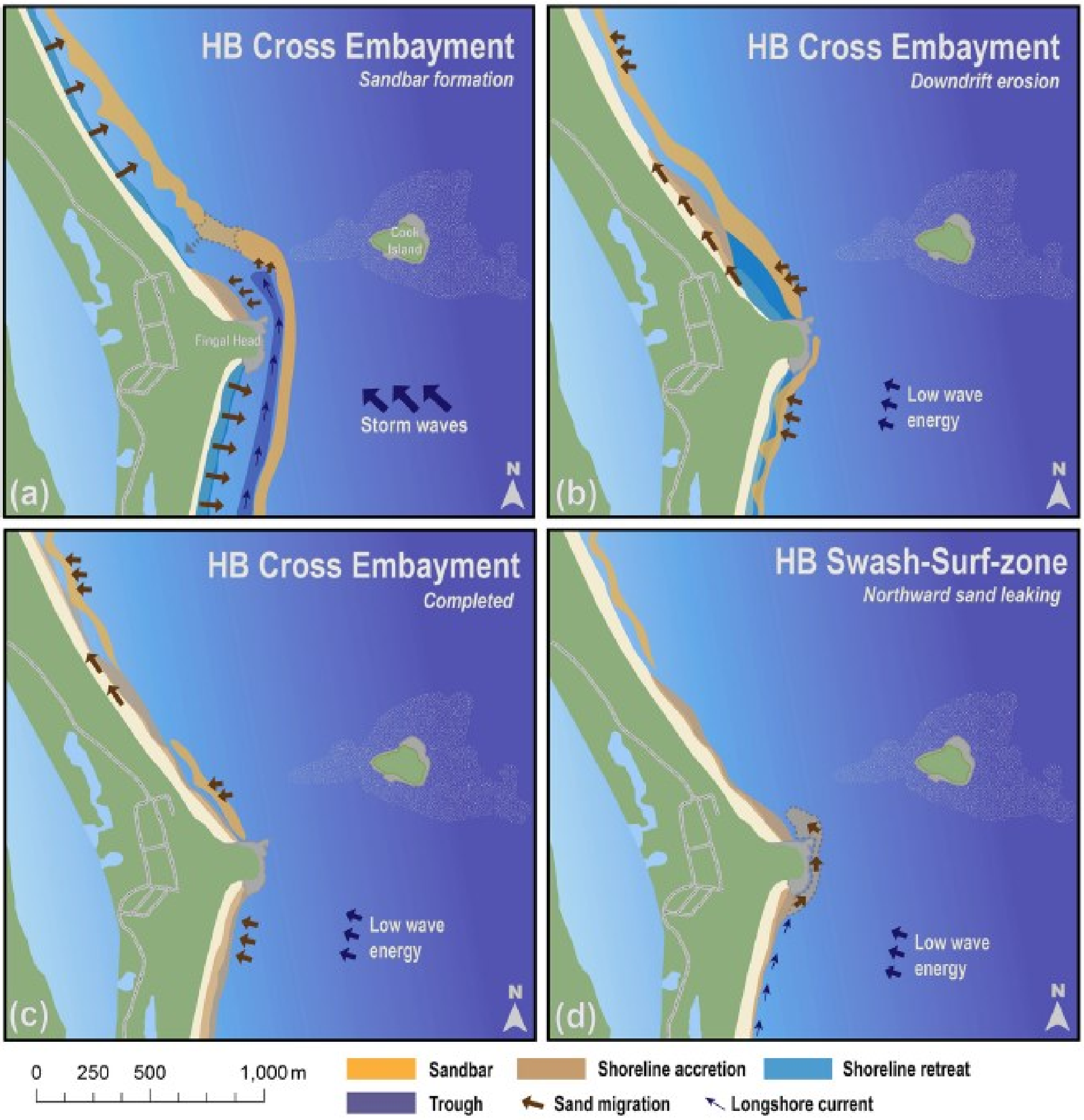

Figure 6: Headland bypassing processes at Fingal Head (source: Silva et al., 2021a).

2.6 Data used in this study

An overview of the datasets available for use in this project are presented in Table 1.

Table 1: Overview of observational data used in this project.

Type	Description	Source	Date
Waves	Measured wave data at Tweed Head directional waverider buoy (WRB)	QLD Department of Environment and Science (DES)	1989-2021
Water levels	Water levels from Tweed Heads Offshore tide gauge	MHL	1982-2021
Wind	Measured wind speed and direction at Coolangatta Airport	Bureau of Meteorology (BoM)	1987-2021
Sand transport rates	LITPACK modelling	Tweed Sand Bypassing	1995-2021
Topography and bathymetry	NSW 2018 LiDAR at 5m	OEH	2018
	Survey from Currumbin to Dreamtime Beach (various extents)	Tweed Sand Bypassing	1960, 1966, 1994, 1995, 1996, 1997, 1998, 2000 to 2021 (at least annually)
	Fingal Head upper beach and nearshore survey for 'Sediment Transport Interaction with Fingal Head' project	Griffith Centre for Coastal Management (GCCM) for Tweed Sand Bypassing (TSB)	Dec 2018, Mar 2019, Jun 2019, Jul 2019
	Entrance surveys over Tweed River entrance channel	Tweed River Entrance Sand Bypassing Project (TRESBP)	Jul 2016, Oct 2016, Jan 2017, monthly between Mar 2020-Apr 2021

Type	Description	Source	Date
Photogrammetry and shorelines	NSW Beach Profile Database at Tweed Entrance and Kingscliff (photogrammetry)	DPIE	1947-2020
	Satellite-derived shorelines	Digital Earth Australia (DEA)	1988-2019
Aerial imagery	High resolution, rectified aerial imagery	Nearmap	2009-2021
	Oblique and vertical imagery	City of Gold Coast	2010-2020
	Historical aerial imagery	TSB/ NSW Government	1956-1995
Dredging and placement records and surveys	Dredging/ nourishment records for all Gold Coast beaches	Tweed Sand Bypassing	2015-2021
Environmental and contractual obligation monitoring	Beach compartment sand volumes based on annual surveys (1993 baseline)	Tweed Sand Bypassing	1993-2020
	Monthly ‘Cope Pole’ distance measurements of RL +2.5m AHD beach contour at Letitia jetty	Tweed Sand Bypassing	2003-2021
TSB operation	Dredging records	Tweed Sand Bypassing	1995-2021
	Pumping records	Tweed Sand Bypassing	2001-2021

3. Coastal morphology and processes

3.1 Modern geomorphic setting

The TSB project area is part of a long coastal sediment compartment that experiences a predominant net northerly alongshore transport of sand extending from central and northern NSW to Moreton Bay in the north. Letitia Beach is a wave dominated coastal sand barrier system comprising of predominantly marine sand. These are common along the NSW coastline and are formed from long-term accumulation of marine sand by the action of waves, tide and winds. Cook Island is situated 600m seaward of Fingal Head which is believed to have been connected prior to attainment of present-day sea levels approximately 6,000 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 sequentially northward migration of the Tweed River entrance from Wommin Lake in the south. This northward migration of the river entrance would have led to the development of Letitia Spit (Druery and Curedale, 1979) acting as a barrier between the river and the ocean. Today, the Letitia sand spit is a ‘stabilised’ embayment characterised by the rocky Fingal Head on its southern end and the southern Tweed River training wall at its northern end. The distribution of Pleistocene and Holocene sediments that form the modern geological setting of the study area is shown in Figure 7. The beach system is composed of well sorted fine quartz sand with median grain size typically around 0.20 to 0.22mm (Hyder et al., 1997).

The key features of the modern geomorphic setting of Letitia Beach are shown in Figure 8. The topography of Letitia Beach is characterised by a low backshore and dune profile with maximum elevations of around 5 to 8 m AHD, varying alongshore. The highest dunes are found along central Letitia and a less established low dune profile is evident along the northern Letitia due to the relatively more recent stabilisation of the river entrance. In contrast, a continuous mid-height dune profile is evident south of Fingal Head.

The nearshore bathymetry along Letitia Beach is relatively alongshore uniform with profile slopes of around 1V:25H. The presence of rocky reefs and outcrops is evident around Fingal Head and Cook Island as well as seaward of the northern end of Dreamtime Beach.

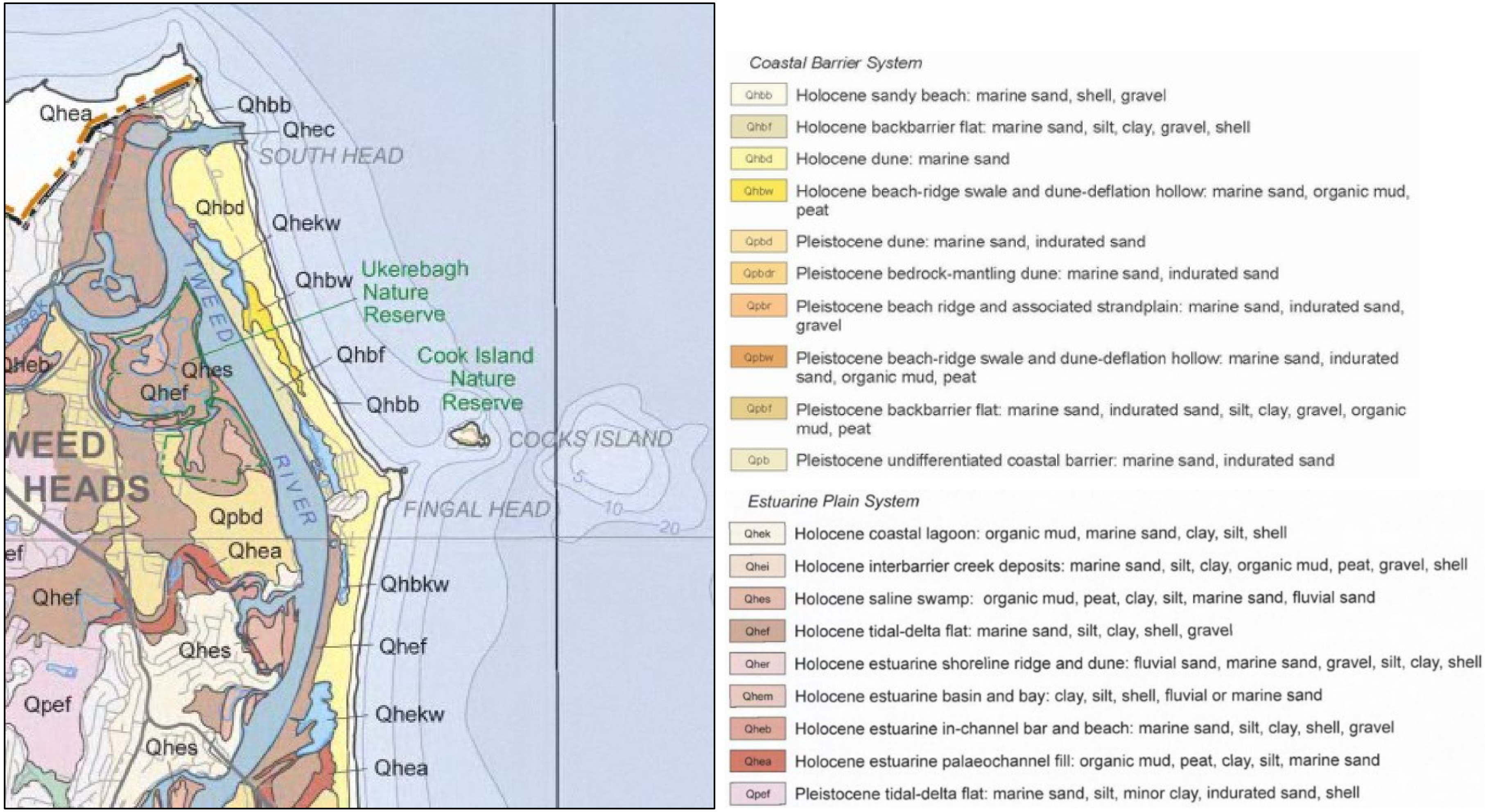

Figure 7: Coastal quaternary geology map for the wider study area (source: NSW DPI).

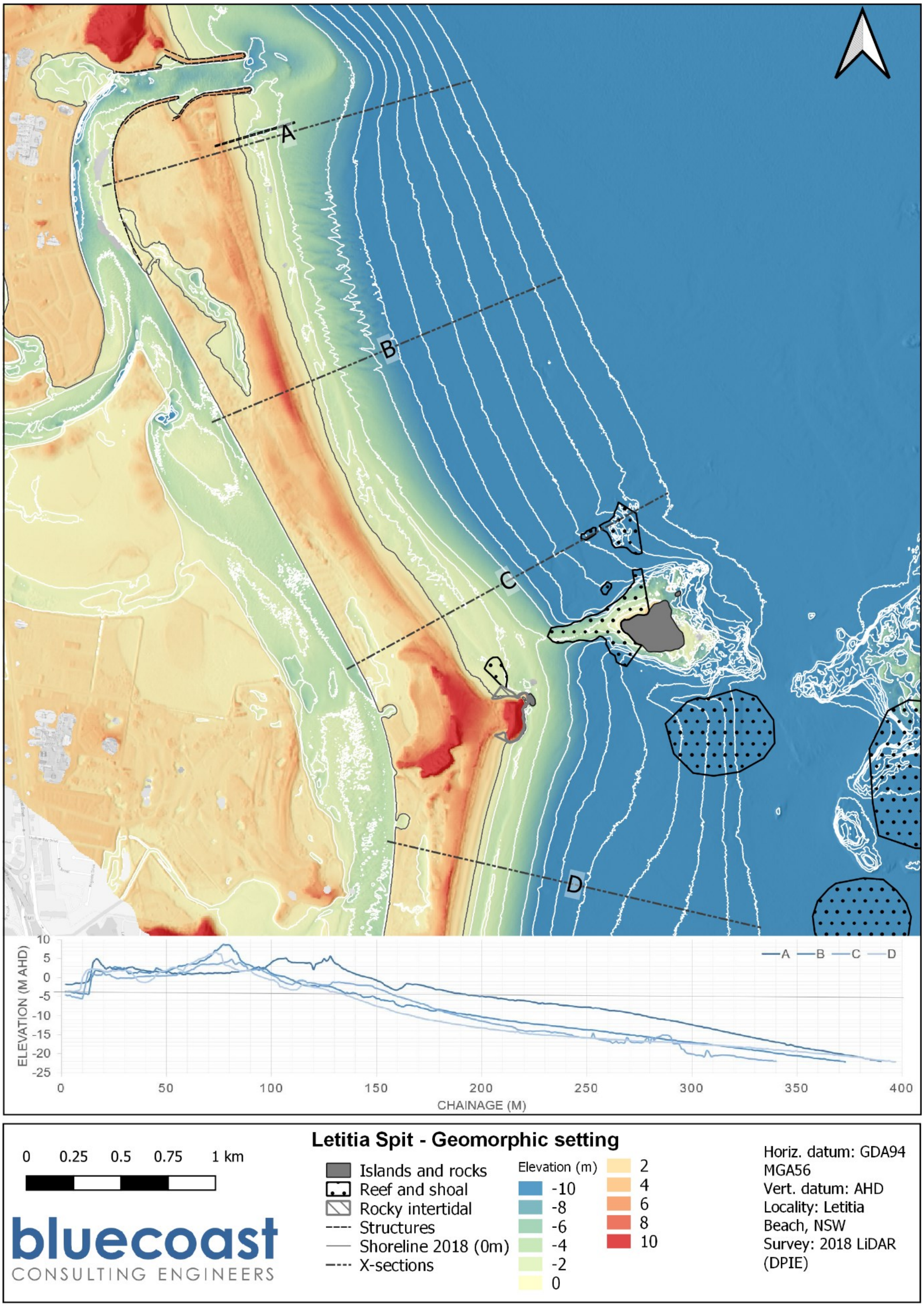

Figure 8: Geomorphic setting of Letitia Beach based on 2018 LiDAR data.

3.2 Wave climate

A review of observed wave data from the Tweed Heads waverider buoy (WRB) from 1995 to 2021 was undertaken. The buoy is in 22m of water depth off Letitia Beach. The average as well as seasonal wave climate statistics for the Tweed Heads WRB are provided in Table 2. Wave roses for total (combined swell and sea waves), swell (swell waves, peak period >8s) and sea (local sea, peak period <8s) are provided in Figure 9. Monthly average significant wave heights and peak wave periods are presented in Figure 10. The joint occurrence of observed significant wave heights and peak wave directions is shown in Figure 11.

The wave climate at the WRB site is described as consisting of low to moderate swell events from the east and east-south-east with peak wave periods generally between 9 and 13s. Locally generated sea waves come predominantly from the east to north-east with low peak periods (~7s). The mean significant wave height is 1.24m, with a 75th percentile wave height of 1.46m annually, predominately from the east.

Table 2 : Wave measurement statistics derived from Tweed Head WRB from January 1995 to May 2021.

Parameter	Statistic	Long term averages (26-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.24	1.16	1.12	1.30	1.35
	50%ile	1.14	1.06	1.06	1.21	1.25
	75%ile	1.46	1.37	1.30	1.53	1.60
	99%ile	2.96	2.88	2.38	3.09	3.33
	Max	7.52	5.56	4.51	6.71	7.52
Peak wave period (Tp) [s]	Mean	9.4	10.1	8.8	9.0	9.7
	50%ile	9.4	10.2	8.9	8.9	9.7
	75%ile	10.9	11.6	10.5	10.3	10.9
	99%ile	15.0	15.8	14.8	14.5	15.0
	% of time sea (T_p < 8s)	30	20	40	30	20
	% of time swell (T_p > 8s)	70	80	60	70	80
	Weighted mean	91	96	92	89	96
	Mean	96	101	88	92	93

Parameter	Statistic	Long term averages (26-years)				
		All seasons	Winter	Spring	Summer	Autumn
Peak Wave Direction (Dp) [˚TN]	Standard deviation	23	22	36	21	29

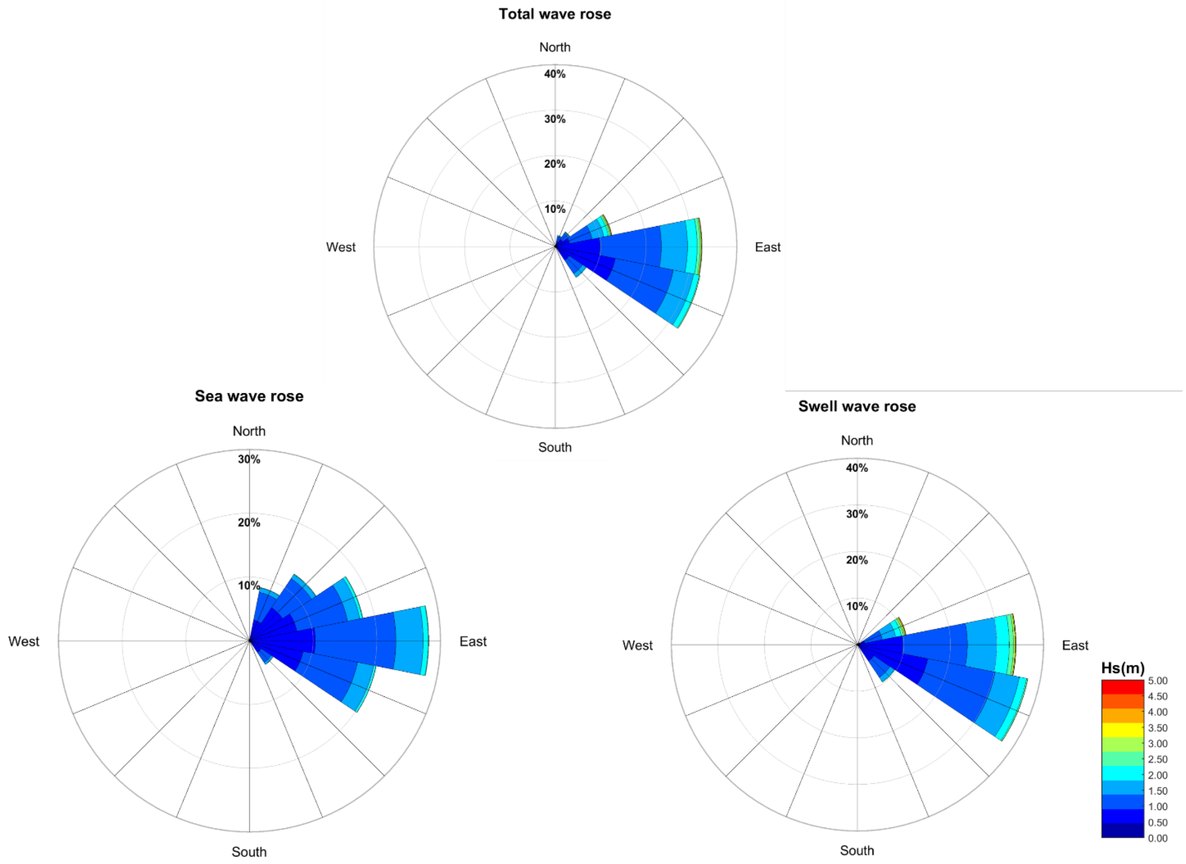

Figure 9: Long-term wave roses for total (sea + swell) wave (top) and sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) (bottom) at the Tweed Head WRB.

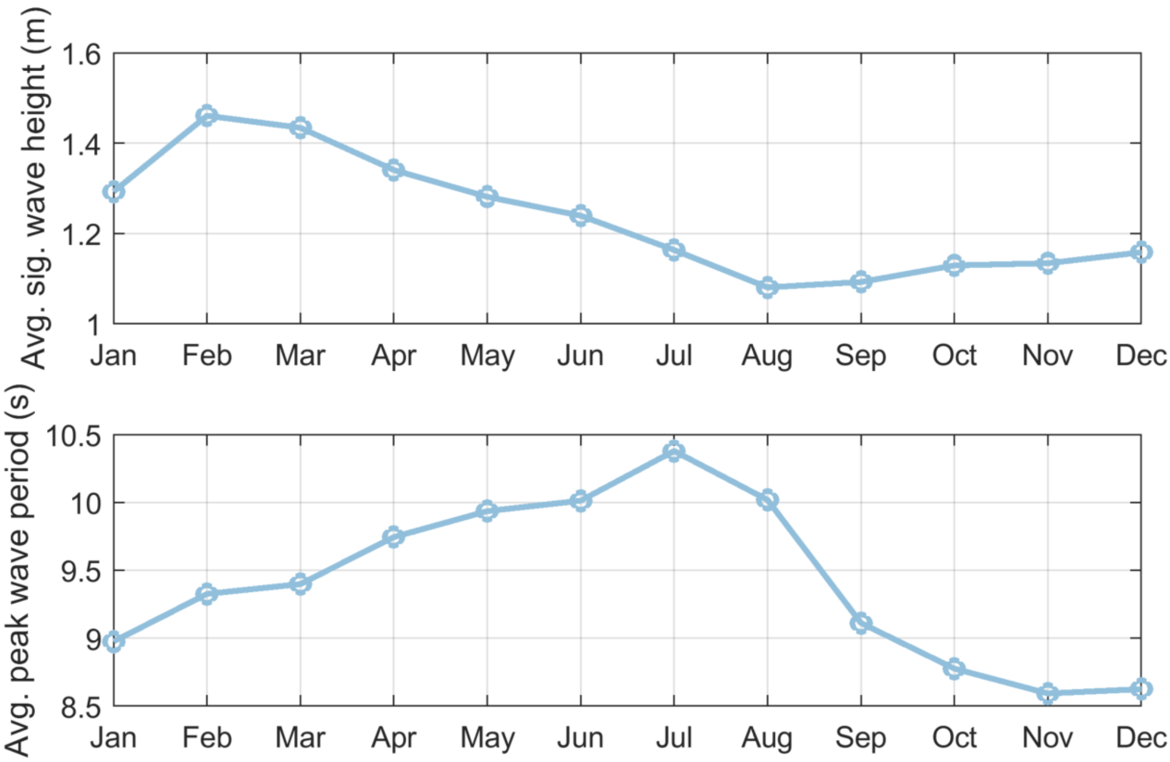

Figure 10: Average monthly significant wave heights and peak periods at the Tweed Heads WRB between 1995-2021.

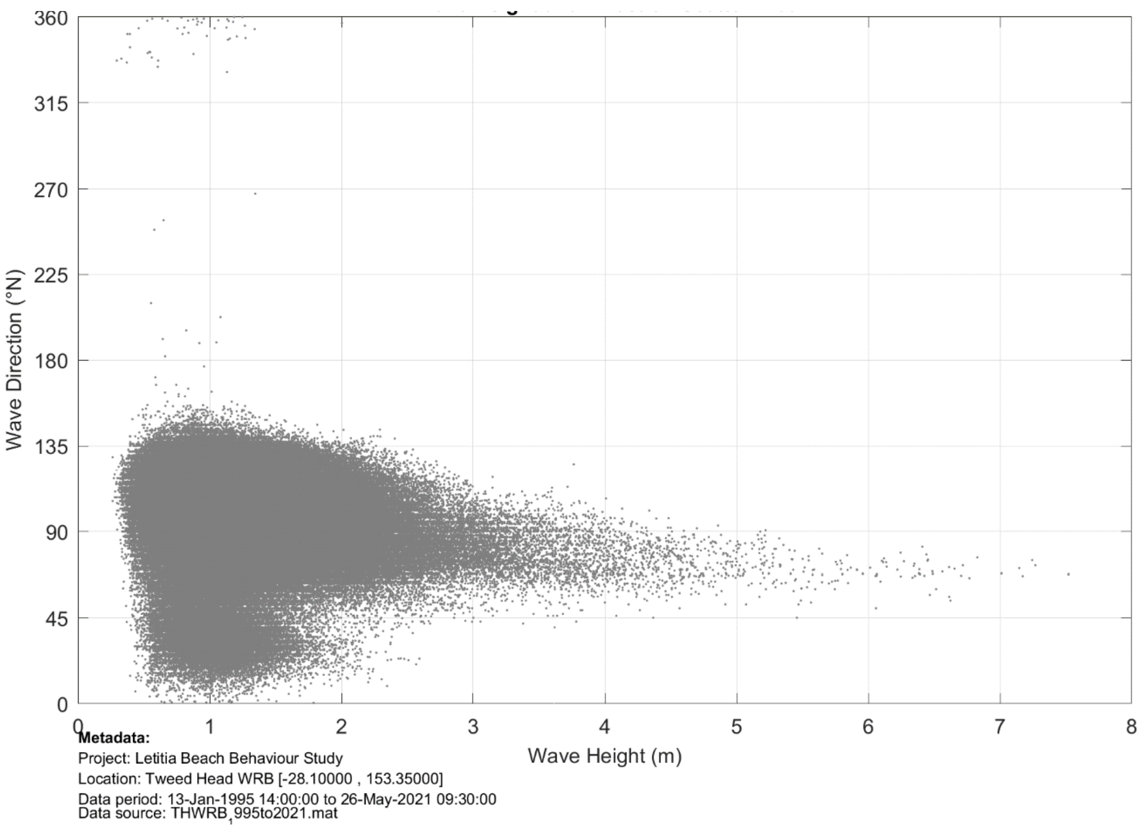

Figure 11: Joint occurrence of measured significant wave heights and peak wave directions at Tweed Heads WRB between 1995-2021.

An Extreme Value Analysis (EVA) of the Tweed Heads WRB spanning the 27 years of available data was undertaken. A peak over threshold analysis of the measured wave heights identified the extreme events and a Weibull distribution was fitted to the extreme wave heights to provide the average recurrence interval (ARI) wave heights. The resulting design ARI wave conditions are presented in Table 3. Figure 12 shows the extreme value distribution of significant wave heights and associated wave direction. The 50-year and 100-year ARI significant wave heights are 7.60m and 8.27m, respectively for a 1-hour duration. As shown in Figure 12, extreme wave events at the Tweed Heads WRB typically arrive from east to north-east directions.

Table 3: Average recurrence interval (ARI) wave heights for Tweed Heads WRB.

ARI (year)	H_s (m)	98% confidence limit (m)
1	4.27	4.11 - 4.43
5	5.51	5.0 - 6.02
10	6.11	5.45 - 6.77
25	6.95	6.06 - 7.84
50	7.60	6.50 - 8.7
100	8.27	6.94 - 9.61

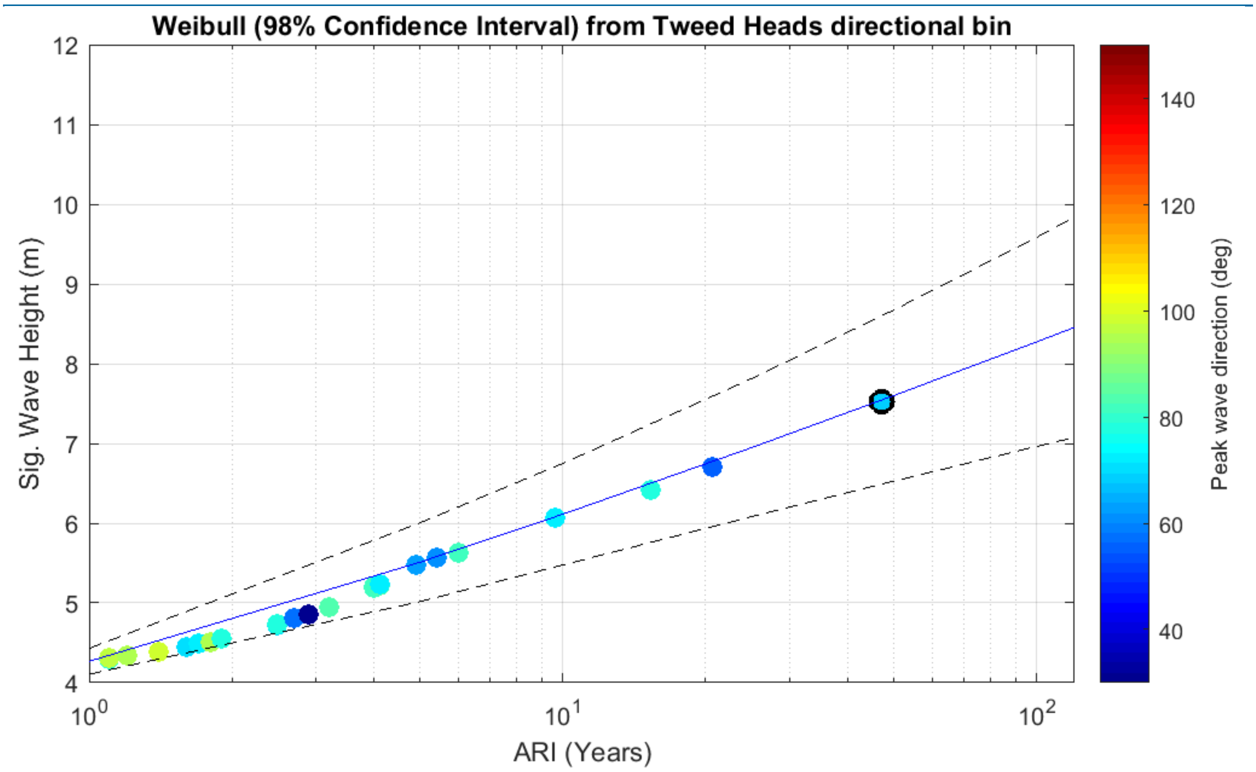

Figure 12: Results of extreme value analysis at Tweed Heads WRB.

3.3 Water level climate

Tides in the project area are semi-diurnal with an open ocean mean spring tidal range of 1.39m and a neap tidal range of 0.76m (MHL, 2012). Tidal planes for the nearby Tweed Heads (Offshore) tide gauge are provided in Table 4.

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 (MHL, 2018).
- 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 4: Tidal planes at Tweed Heads Offshore (MHL, 2012).

Tidal plane	Height (metres relative to AHD)
High High Water Solstice Springs (HHWSS)	1.088
Mean High Water Springs (MHWS)	0.690
Mean Sea Level (MSL)	-0.003
Mean High Water Springs (MHWS)	-0.696
Indian Spring Low Water (ISLW)	-0.980

The latest advice from IPCC (2021) 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 global SLR (above 1995 - 2014 baseline) projections for the 'likely' global mean SLR by 2100 are (refer to Figure 13):

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

- 0.28-0.55m under the very low greenhouse gas (GHG) emissions scenario (SSP1-1.9[2])
- 0.32-0.62m under the low GHG emissions scenario (SSP1-2.6)
- 0.44-0.76m under the intermediate GHG emissions scenario (SSP2-4.5)
- 0.63-1.01m under the very high GHG emissions scenario (SSP5-8.5).

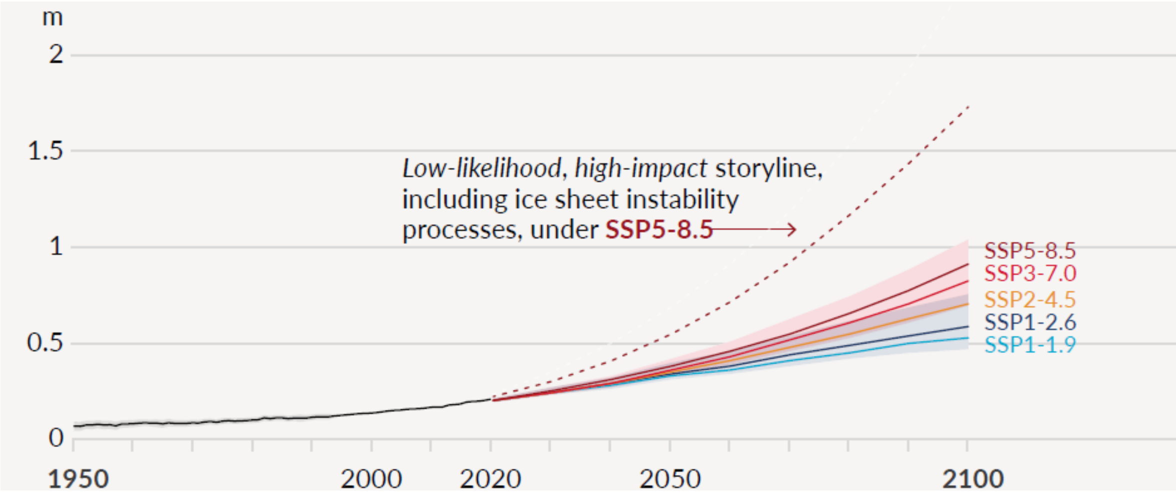

Figure 13: Global sea level rise changes relative to 1900 for the possible future greenhouse gas emission scenarios (IPCC, 2021).

3.4 Wind climate

The wind measurements at the Coolangatta Airport AWS station were analysed. This dataset provides measured wind speeds and directions from 1987 until 2021. Seasonal wind roses and wind measurement statistics are presented in Figure 14 and Table 5.

Wind data show an inclination for winds to arrive from the northerly sector during spring and a predominance for south and west winds during winter and autumn. Summer shows a more bi-modal pattern with winds generally coming from either the northern or southern sectors.

[2] 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.

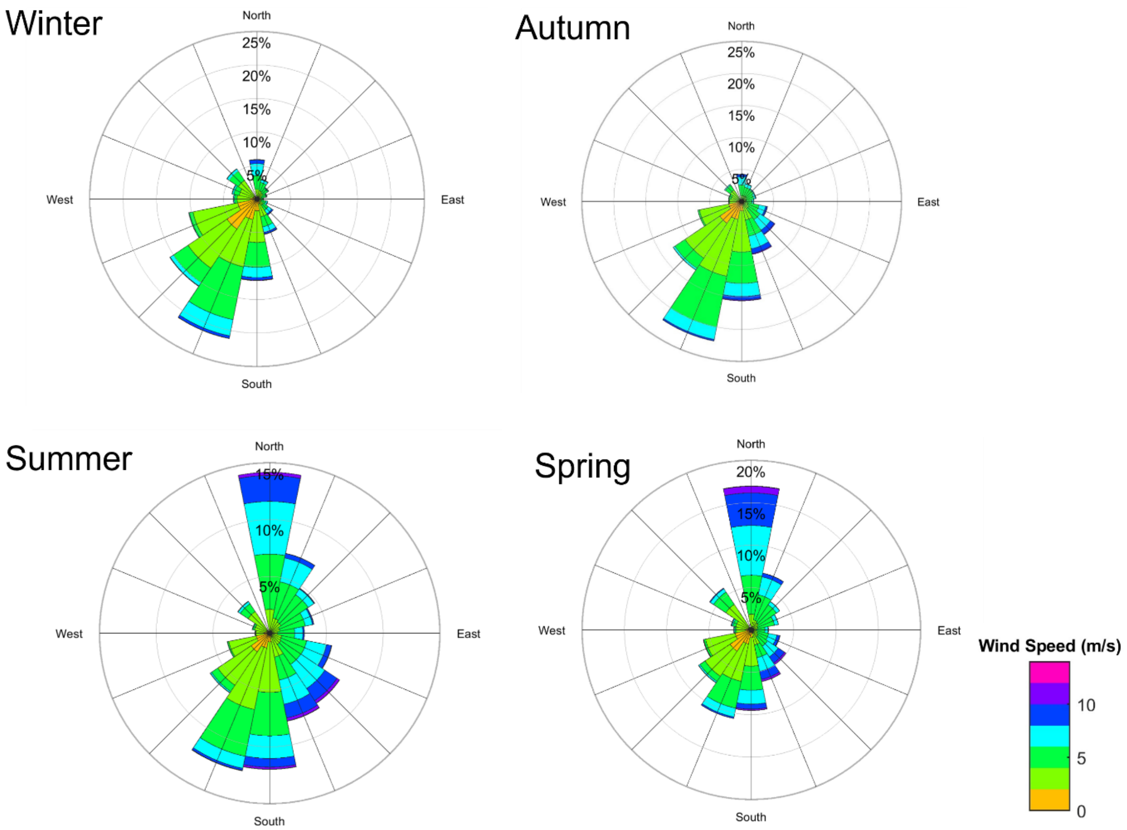

Figure 14: Wind roses of one minute data from Coolangatta from 2003 to 2021.

Table 5: Wind measurement statistics for the Coolangatta station from 2003 to 2021.

Parameter	Statistic	Annual long term average (19 -years)
Wind speed [m/s]	Mean	4.2
	50%ile	4.1
	95%ile	8.2
	Max	21.6
Wind Direction [˚TN]	Mean	205

3.5 Tidal, fluvial and other currents

The key nearshore currents acting at Letitia Beach identified in Jacobs (2017) and that are typically observed adjacent to trained river entrances in NSW are as follows:

- *Wave-driven currents* – these include onshore and offshore directed currents driving cross-shore sand transport as well as longshore currents induced by wave breaking resulting in longshore sand transport:
  - Longshore currents at Letitia are predominantly from south to north due to the east to east-south-easterly wave climate. Limited southward directed wave-driven

currents or sand transport is experienced along Letitia Beach during northeast waves (Cardno, 2009).

- Onshore directed currents during ambient swell conditions drive onshore movement of sand while offshore directed currents during high-energy wave conditions drive sand from the shore to the nearshore.

- *Tidal currents* – the tidal wave at the open coast was found to propagate east to west resulting in low current speeds that have little effect on sand transport (Jacobs, 2017). At the Tweed River entrance and adjacent areas, tidal currents are constricted and much higher. During typical conditions a concentrated seaward directed ebb jet is observed which may be deflected to the north or south under the influence of winds, waves, the East Australian Current and the local entrance morphology (Jacobs, 2017). Flood tide currents radiating into the river are much lower than peak ebb currents. During river flood events, fluvial currents exiting the river entrance can be multiples higher than tidal currents and move significant volumes of sand seaward.
- *Wind-driven currents* – shore-parallel currents due to wind stresses on the water surface are relatively minor in comparison to wave and tidal currents along the open coast and have little effect on sand transport. On the subaerial beach, strong winds can transport sand along the beach face and to the dunes (i.e., aeolian sand transport).
- *East Australian Current (EAC)* – in the deeper nearshore at depths greater than 6m this large-scale ocean current typically flows in a south-easterly direction with variable low to moderate magnitude along Letitia and adjacent beaches. It was found that the EAC can interact with Point Danger resulting in clockwise circulation cells within the Letitia embayment which interfere with tidal currents and sand transport around the Tweed River entrance (Jacobs, 2017).

3.6 Climate variability

The directionality of the modal metocean climate is well correlated with a climate phenomenon called the El Niño–Southern Oscillation (ENSO) which significantly alters the wave climate in both intensity and direction (Mortlock and Goodwin, 2016). Typically, during La Niña events 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). The southeast Australian shelf sees more storms occurring during La Niña. A timeseries of historical occurrence of El Niño and La Niña periods is shown in Figure 15.

Climate change is likely to force a continued expansion of the tropics which would maintain a strong coupling between the southeast Australian shelf and ENSO (Allen et al., 2014). Although the issue has been studied extensively, there is no consensus on exactly how a warming climate will influence ENSO (Mortlock and Goodwin, 2016). However, the expansion of the tropics with warming climate is expected to lead to a poleward shift in storm type, with more tropical origin storms than extra-tropical storms with a southern origin. The anticipated outcomes of these changes on the Eastern Australia wave climate would be an anti-clockwise rotation of the mean wave direction and associated changes to sand movement (Silva et al., 2021). The mean wave height offshore of the Gold Coast is expected to decrease as well as an anticlockwise rotation of around 5° in the mean wave direction (GCCM, 2020).

Climate modelling projects a decrease in the number of small to moderate East Coast Lows (ECLs) in the cool season with little change in these storms during the warm season. However extreme ECLs in the warmer months may increase in number but extreme ECLs in cool seasons may not change (Ji et al., 2015).

An increase in pole-ward penetration of the East Australian Current (EAC) due to increasing intensity of the EAC jet and eddying at its southern extend is being observed and projected to continue in future (Malan et al., 2021). This increase in poleward directed heat transport is likely to result in more frequent marine heat wave events (Oliver et al., 2015). As described Section 4.3.7, the EAC interacts with nearshore features (e.g., Point Danger, Cook Island) creating complex nearshore currents and eddies in the study area. The implications of a strengthening EAC jet on the sand movements at Letitia Beach are therefore not fully understood.

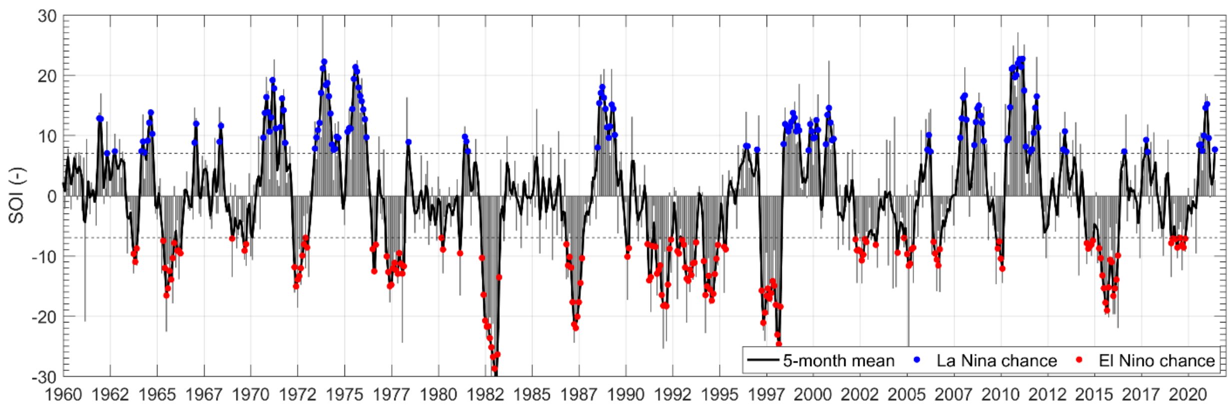

Figure 15: Timeseries of southern oscillation index (SOI) indicating periods of El Niño (red) and La Niña (blue) conditions (data source: BoM).

3.7 TSB operations

TSB sand delivery areas from pumping and dredging are presented in Figure 16. An overview of the total dredging and pumping volumes since commencement of the TSB operations in 1995 are provided in Table 6 and Figure 17. There are four distinct operational periods characterised by different dredging and pumping volumes:

- *1995 to 1998* – Stage 1 operations prior to construction of the bypassing jetty with a total dredging volume of over 3Mm^3
- *April 2000 to April 2001* – Stage 2 pre-commissioning dredging with a total volume around 400,000m^3
- *May 2001 to December 2007* – Supplementary increment phase with average dredging volume of 220,000m^3/year and average annual pumping volume of around 625,000m^3/year
- *January 2008 to present* – present operation aligned to the estimated net longshore sand transport rate resulting in an average annual pumping volume of around 425,000m^3/year and re-commencement of dredging in 2016 with average annual volumes of around 130,000m^3/year.

Table 6: Summary of dredge material placement and sand pumping volumes since 1995.

Year	Dredging (m^3)			Pumping (m^3)	
	Qld	Dbah	Fingal	Qld	Dbah
1995 to 1998	3,047,549	-	-	-	-
2000	406,283	-	-	-	-
2001	416,206	-	-	508,611	67,258
2002	228,799	11,330	-	649,492	71,872
2003	220,717	10,175	-	716,802	70,224
2004	149,333	20,594	-	459,554	36,813
2005	182,550	16,510	-	683,244	41,687
2006	181,658	18,639	-	485,185	67,099
2007	-	-	-	514,968	47,279
2008	72,029	126,950	-	520,312	65,497
2009	-	-	-	365,421	43,811
2010	-	-	-	373,828	21,781
2011	-	200	-	457,765	60,404
2012	-	-	-	378,610	57,482
2013	-	-	-	309,279	10,604
2014	-	-	-	450,232	15,269
2015	-	-	-	508,190	44,492
2016	-	41,938	-	400,931	18,633
2017	76,607	139,997	-	371,818	33,706
2018	-	-	-	345,982	15,265
2019	83,959	36,035	31,366	344,841	15,211
2020	55,199	30,229	24,750	393,778	33,253
2021^	73,790	52,181	7,345	217,688	55,583
Total	**5,194,679**	**504,778**	**63,461**	**9,456,531**	**893,223**

Note: ^ until 30 September 2021

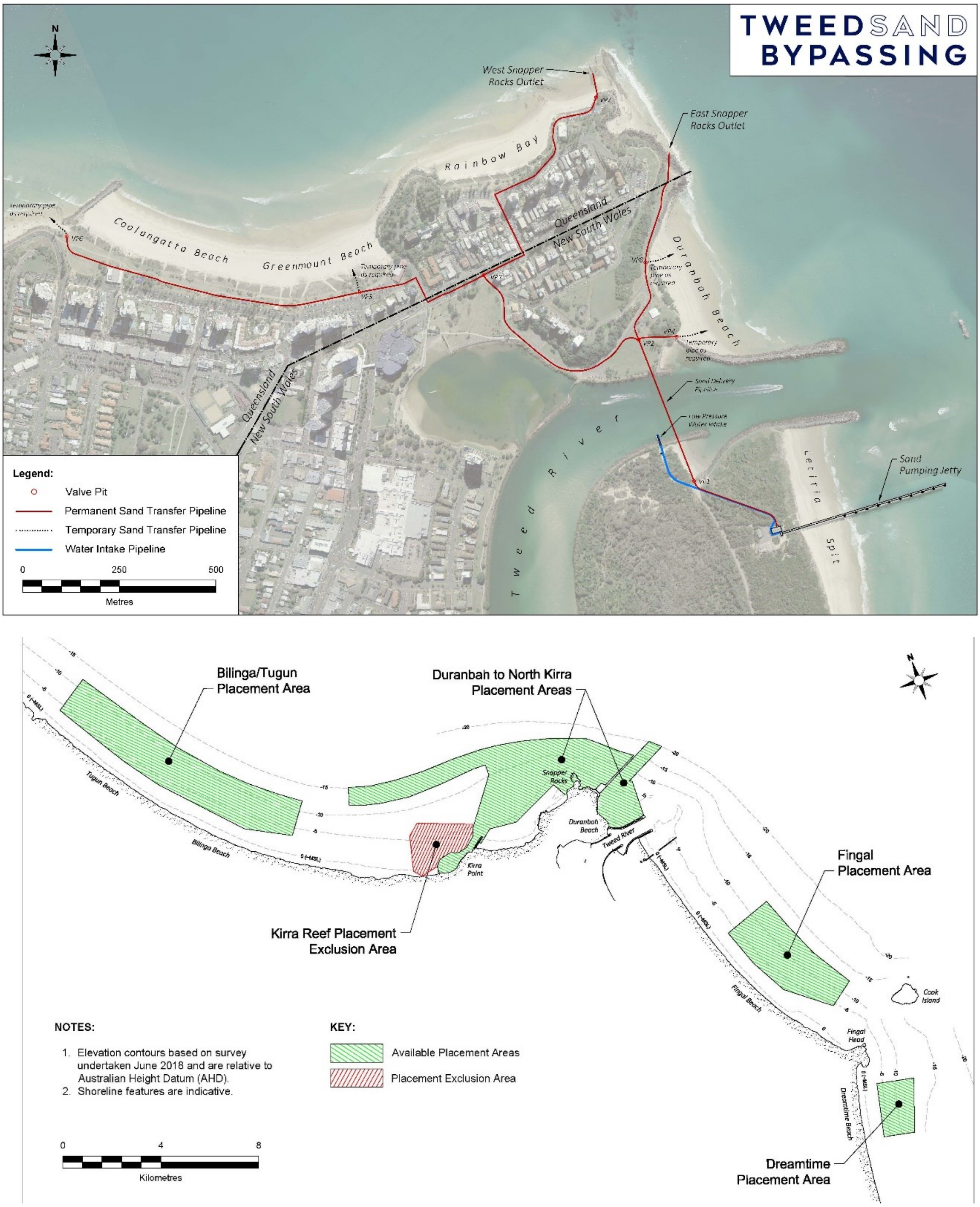

Figure 16: (top) TSB sand pumping extraction/delivery locations and (bottom) dredge material placement areas (source: TSB).

Figure 17: Annual and cumulative TSB dredging (top) and sand pumping (bottom) volumes.

4. Letitia Beach sand budget

4.1 Overview

This section provides an explanation of the key coastal processes that are relevant to TSB operations. A data-driven approach is adopted. At its centre is an analysis of the study areas' sand budget, which maps historical sand volume changes in ten beach, two river entrance, four dune and five offshore sediment cells (Section 4.2). These are used to infer the rates and directions of sand movements and provide the quantified conceptual sand movement model presented in Figure 18 with further details outlined in Section 4.3. Additional analysis results are provided in Appendix A.

The most likely drivers for the observed sand volume changes are described based on observational data, previous literature, available numerical modelling results and/or coastal processes knowledge. 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.

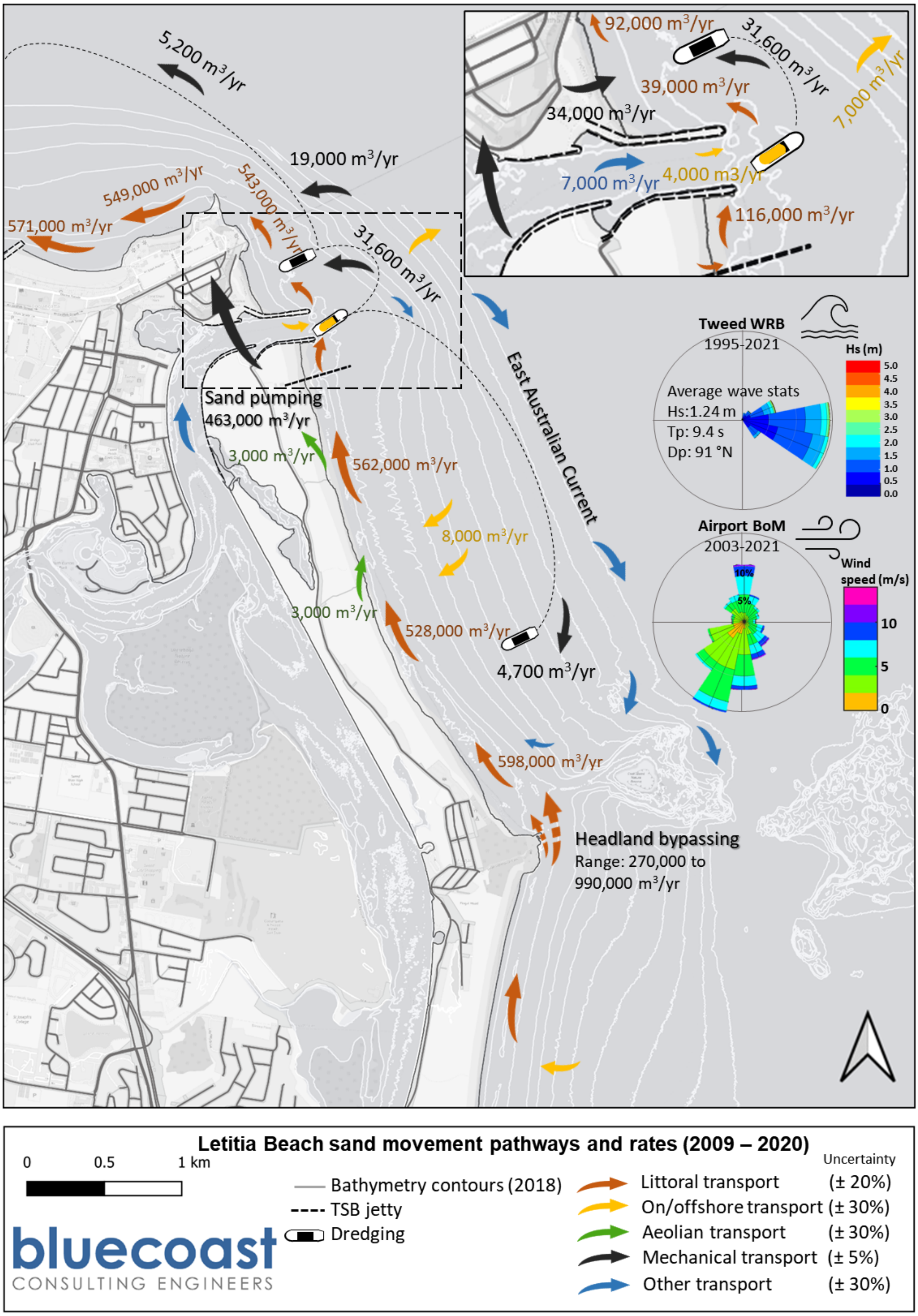

Figure 18: Quantified conceptual model of sand movements along Letitia Beach.

4.2 Current morphological trends

An assessment of available surveys, volumetric change analysis of the coastal profile as well as derivation and explanation of a sand budget for the coastal sediment cells between Fingal Head and Coolangatta is provided in this section.

The coastal profile can be divided into several zones, we will discuss the subaerial part (i.e., the land-based part above 0 m AHD) and the full coastal profile which includes the subaerial part and the subaqueous part (i.e., the part below the water approximated by 0 m AHD). The data used in the analysis is provided in Section 2.6.

4.2.1 Shoreline behaviour

Mean annual shoreline positions are available from Digital Earth Australia (DEA), a continental dataset that includes satellite derived shorelines along the entire Australian coastline from 1988 to 2019. The derived shoreline positions are shown in Figure 19. In consideration of TSB's operational periods outlined in Section 3.7, Figure 20 provides a comparison of selected mean annual shoreline positions. The shoreline position for pre-training wall extension (1962) was extracted from a 1960 survey and is also plotted in Figure 20. The initial shoreline adjustment along Letitia is also seen in the relative shoreline behaviour between years before and after the commencement on sand pumping in 2001, shown in Figure 20. The comparison of mean annual shorelines suggests:

- Following the extension of the Tweed River training walls the shoreline of Letitia Beach accreted. Accretion would have commenced in the north. By 1994 (immediately pre-TSB) a 190m seaward movement from the 1960 shoreline was observed in the north. This accretion in the north resulted in a clockwise shoreline rotation and by 1994 it appears the accretion extended along the entire beach (to a lesser degree at the southern end of the beach where shoreline position is predominantly subject to variation due to headland bypassing). It is noted that comparison of shorelines from the early to mid-1990s suggests that in 1994 the shoreline was relatively accreted compared to preceding and subsequent years. No noticeable accretionary trend was observed at the northern end of Dreamtime Beach because of the training wall extension.

- Following the 2001 commencement of sand pumping the accreted northern shoreline retreated by around 90 to 120m resulting in an anti-clockwise rotation of Letitia Beach. Letitia's shoreline behaviour in response to TSB appears to be a reversal of the accretion response (i.e., retreat commences in the north and propagates south as seen by the central bulge in 2001 shoreline in Figure 20). Additional landward realignment of the mean shoreline of around 15 to 30m is evident in the immediate jetty area since 2001.

- The initial shoreline adjustment occurred rapidly immediately after commencement of the sand pumping operations and extended southward with reducing effect in subsequent years until around 2004, when natural processes started to dominate again. By 2004 an anti-clockwise rotation of around 3 degrees of the mean shoreline alignment up to around 1,500m south of the jetty was evident (see inset map in Figure 20).

- By the end of the supplementary increment period in 2008 the shoreline appeared to have completed the anti-clockwise rotation cycle as since 2008 there was relatively minor change in the mean annual shoreline positions.

- The recent (2019) shoreline position along the northern section of Letitia Beach is approximately 30m seaward of the 1960 pre-training wall extension shoreline.
- At the southern end of the beach, a high interannual to interdecadal variability in shoreline positions over a cross-shore distance of around 50-100m is observed, with the most landward position occurring in 2013.

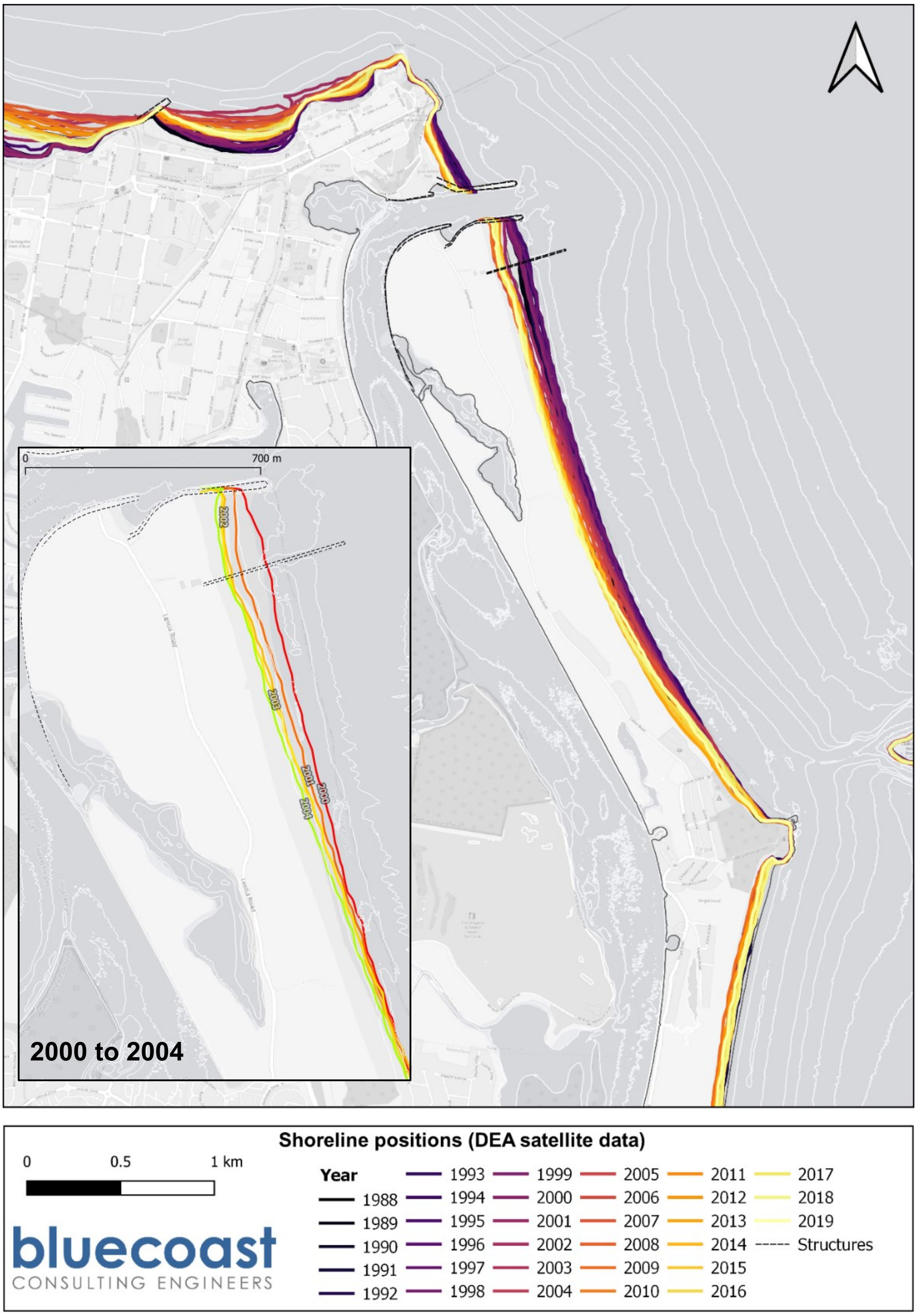

Figure 19: Mean annual Digital Earth Australia (DEA) satellite-derived shoreline positions at Letitia Beach.

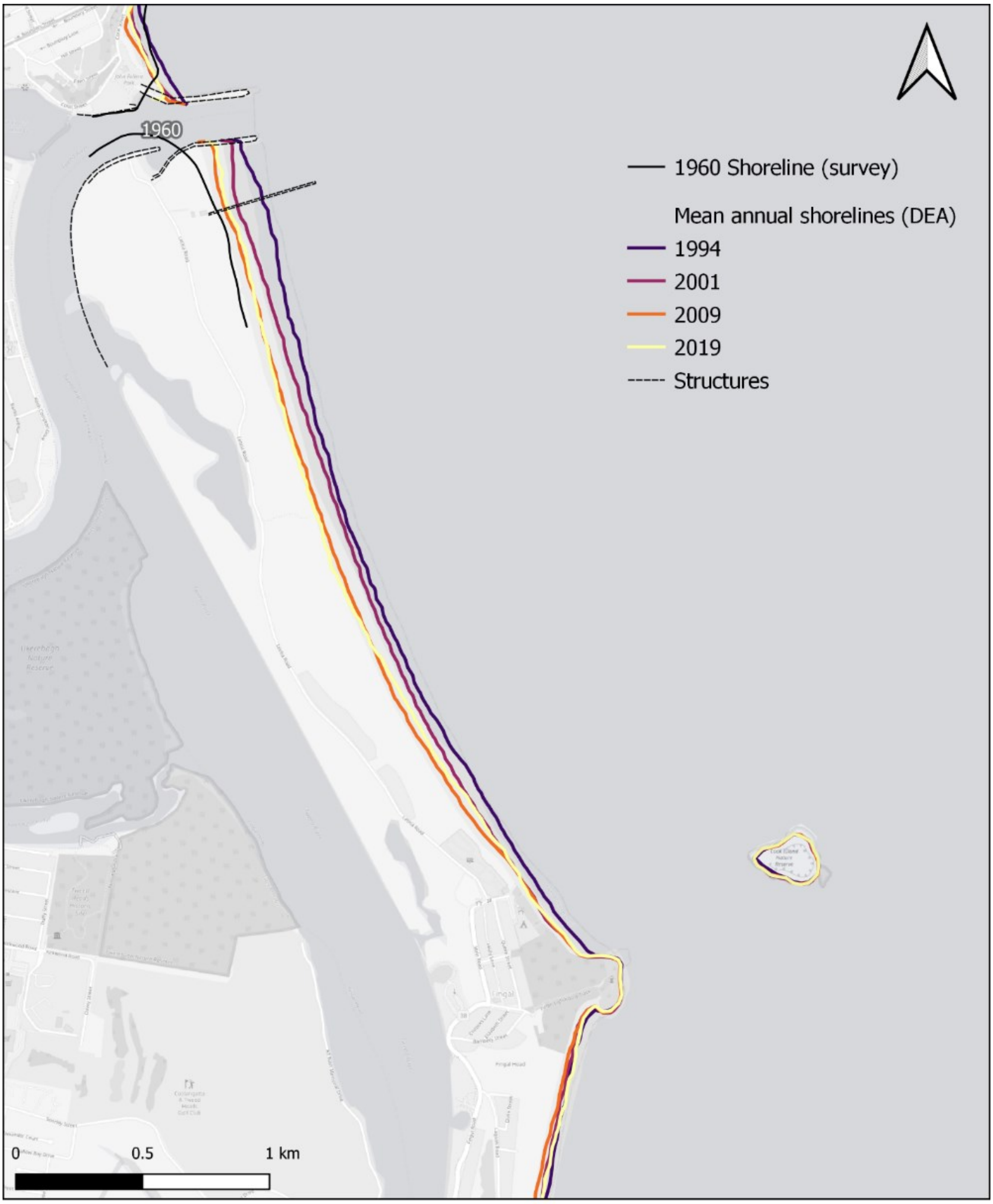

Figure 20: Comparison of selected shoreline positions over the TSB operational period.

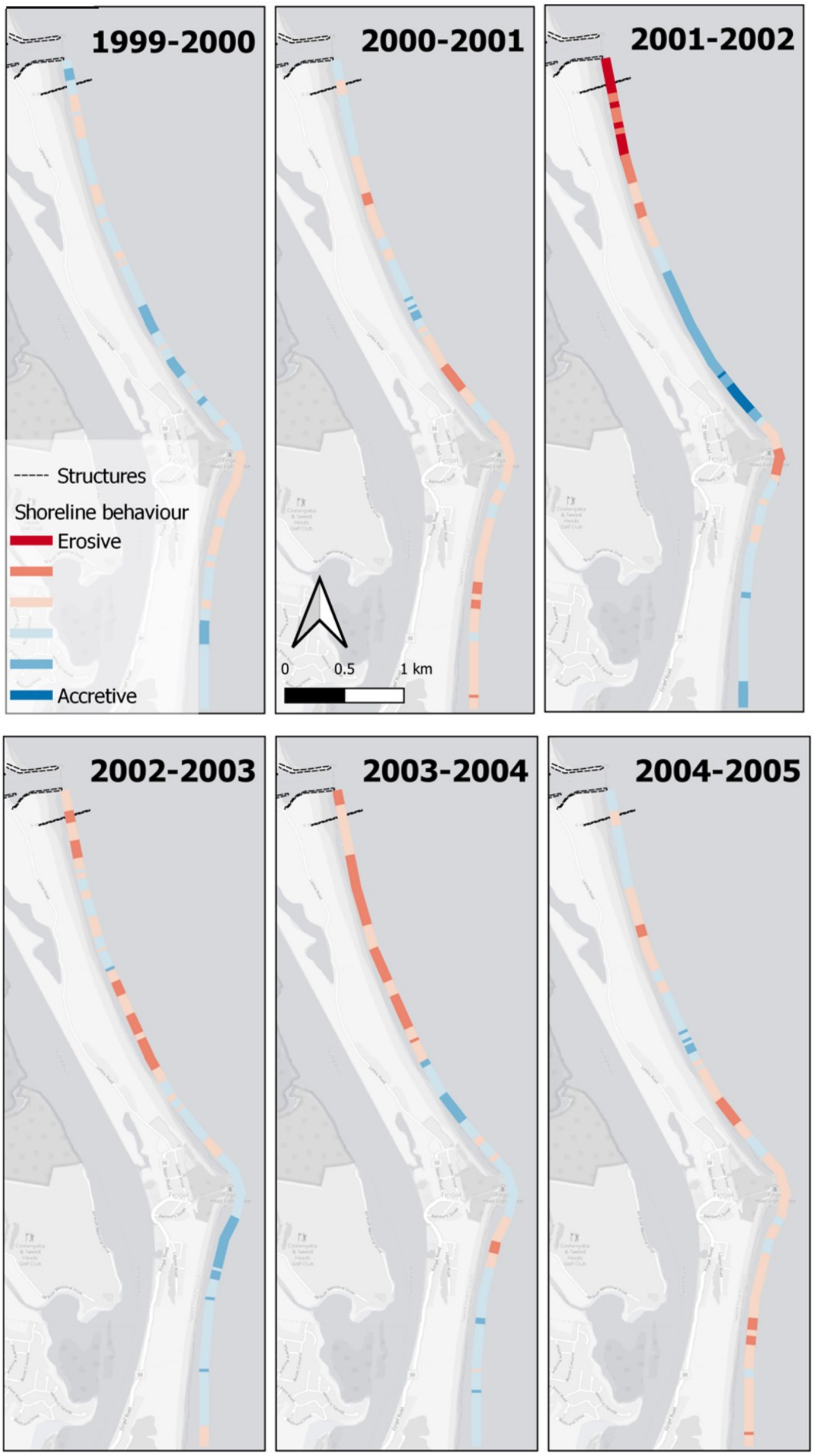

Figure 21: Annual shoreline behaviour (DEA) around commencement of sand pumping in 2001.

4.2.2 Volumetric change

Beach profiles

Beach profiles from the NSW photogrammetry database (DPIE, 2020) were analysed to examine subaerial (above 0 m AHD) sand volume changes along Letitia Beach. The analysis covered the available profiles (see Figure 23):

- Letitia Beach: 18 profiles at 200m spacing across five blocks each with 11 surveyed dates between 1972 and 2021 (referred to as 'Tweed Entrance blocks' 1 to 5 in the database)
- Dreamtime Beach (north): 13 profiles at 200m spacing across two blocks each with 11 surveyed dates between 1947 and 2021 (named 'Kingscliff blocks' 7 and 8 in database)

Figure 22 presents a timeseries of calculated average subaerial beach volumes for the Letitia Beach and Dreamtime Beach profiles. Additional plots of the historic beach profiles are provided in Appendix A for selected profiles.

The subaerial beach volume along Letitia increased up until 2000, with the northern end of Letitia Beach reaching a subaerial volume of around 340,000m^3. Between the 2000 and 2007 (over the supplementary increment period), the subaerial beach volume at the northern end of Letitia decreased by 89% to 38,000m^3. For the central part of Letitia Beach, however the erosion response was dampened (lower rate) and delayed by around 2-years[3]. After the supplementary increment phase, there was less variability in the subaerial beach volumes and trends align more closely with observed trends at Dreamtime Beach.

Linear regression analysis of the subaerial beach volumes was undertaken over selected periods:

- long-term trends were examined using data from 1994 to 2020 (since start of TSB operations)
- initial TSB operations and supplementary increment phase trends were examined using data from 1994 to 2008
- the post- supplementary increment phase trends were examined using data from 2009 to 2020.

The alongshore variability of the calculated rate of change is presented in Figure 24. These align with the observed beach volumes described above.

[3] Beach profile present snapshots in time. The sparse temporal nature of the data, particularly pre-2004 can mask the true timing of change in beach behaviour. This has been interpreted from the 5-year delayed upper beach erosion response in the Letitia South.

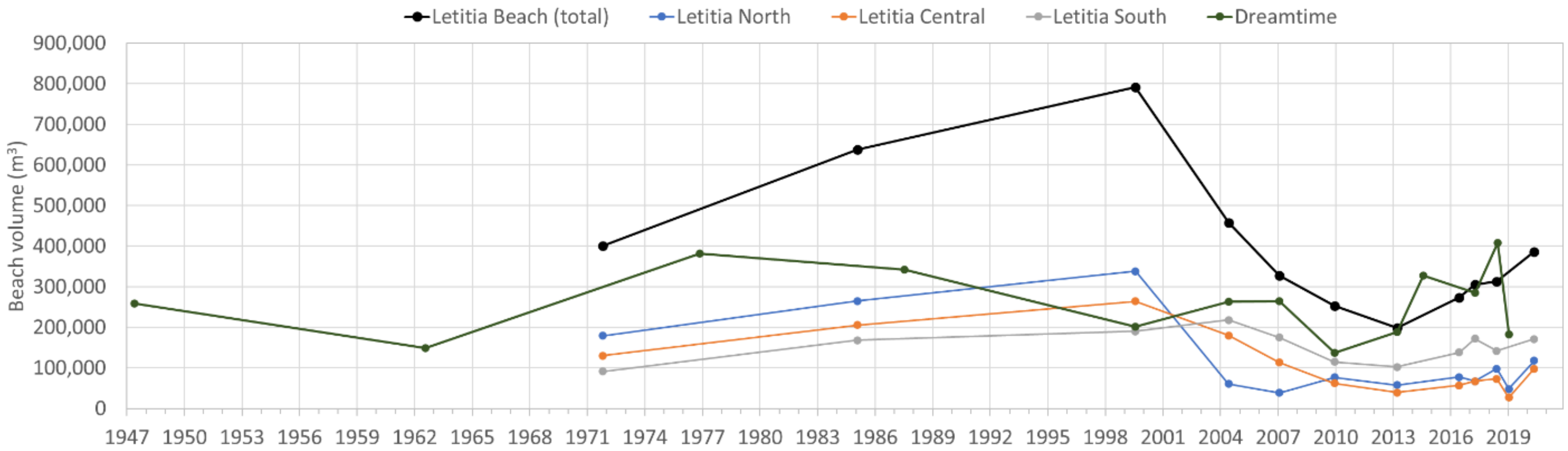

Figure 22: Timeseries of subaerial beach volumes for Letitia Beach and Dreamtime.

Figure 23: NSW photogrammetry profiles and blocks used along Letitia Beach and Dreamtime Beach.

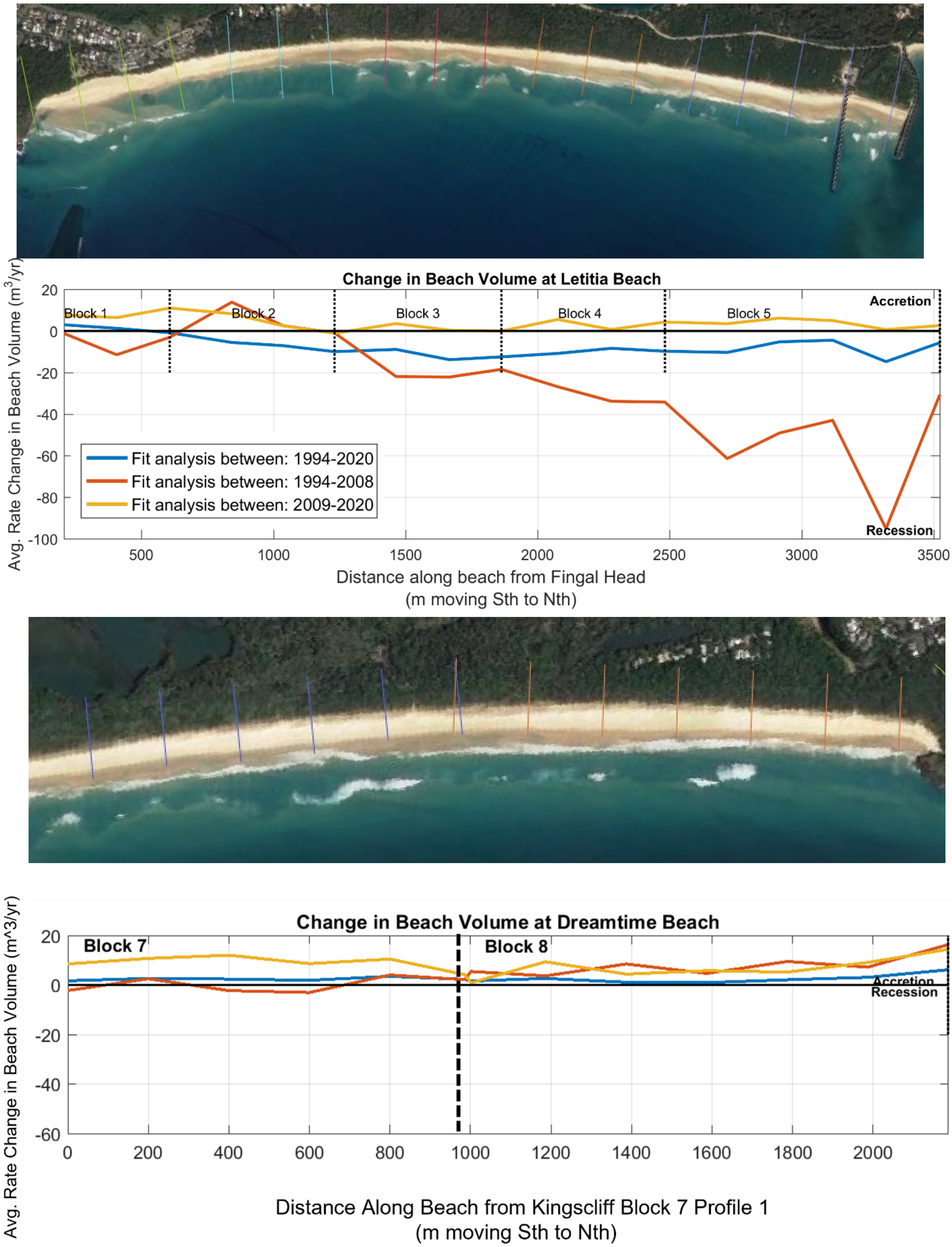

Figure 24: Rate of change in beach volume across all photogrammetry blocks along (top) Letitia Beach and (bottom) Dreamtime Beach.

Full coastal profile

An assessment of the change in the sand volumes within the study area was undertaken adopting the 20 analysis cells shown in Figure 25. The extents and division of the cells were defined in consideration of previous assessments, survey extents, observed processes and morphology.

To determine the changes across the full coastal profile (i.e., subaerial and subaqueous part) from dune to around -14mAHD[4], the sand volume relative to the 2021 survey was calculated for all available surveys with sufficient extents. Maps of the 2021 survey and changes in seabed levels relative to 2021 for selected earlier surveys are shown in Figure 26 to Figure 28. Where survey coverage allowed, changes in the seabed (sand) volume were calculated for each cell. The sand volume changes for all cells are provided in Appendix A.

A timeseries showing the change in sand volume along Letitia Beach (south, central and north), Dreamtime Beach and Coolangatta is shown in Figure 29. A timeseries showing the total sand volume change along the entire length of Letitia Beach is shown in Figure 30.

In agreement with the subaerial beach volume observations and previous studies the following was observed:

- A long-term trend of accretion from 1960 to 1994 is evident across the full coastal profile along northern and central Letitia Beach. No subaqueous survey data was available for the southern end of Letitia and Dreamtime Beach prior to 1994 for this analysis.
- With commencement of TSB operations in 1994 the sand volume along northern and central Letitia began decreasing.
- In combination with TSB sand pumping operations at the Letitia jetty (commenced in 2001) the receding trend rapidly accelerated.
- Following completion of the supplementary increment phase in 2008, the sand volumes at the northern end of Letitia were found to fluctuate around a new equilibrium volume. At the central section of Letitia Beach, this new equilibrium volume was reached by 2011. Overall, for the entire length of Letitia the survey data suggests that a new equilibrium volume was achieved between 2008 and 2009.
- The sand movements at the southern end of Letitia are less controlled by the TSB operations and the beach volume fluctuates over short- and long-term cycles owing to headland bypassing.

[4] A series of offshore cells between -14mAHD to -20mAHD were included in the analysis, however due to limited survey coverage these were considered separately as presented in Appendix A.

Figure 25: Analysis cells from Fingal Head to Coolangatta.

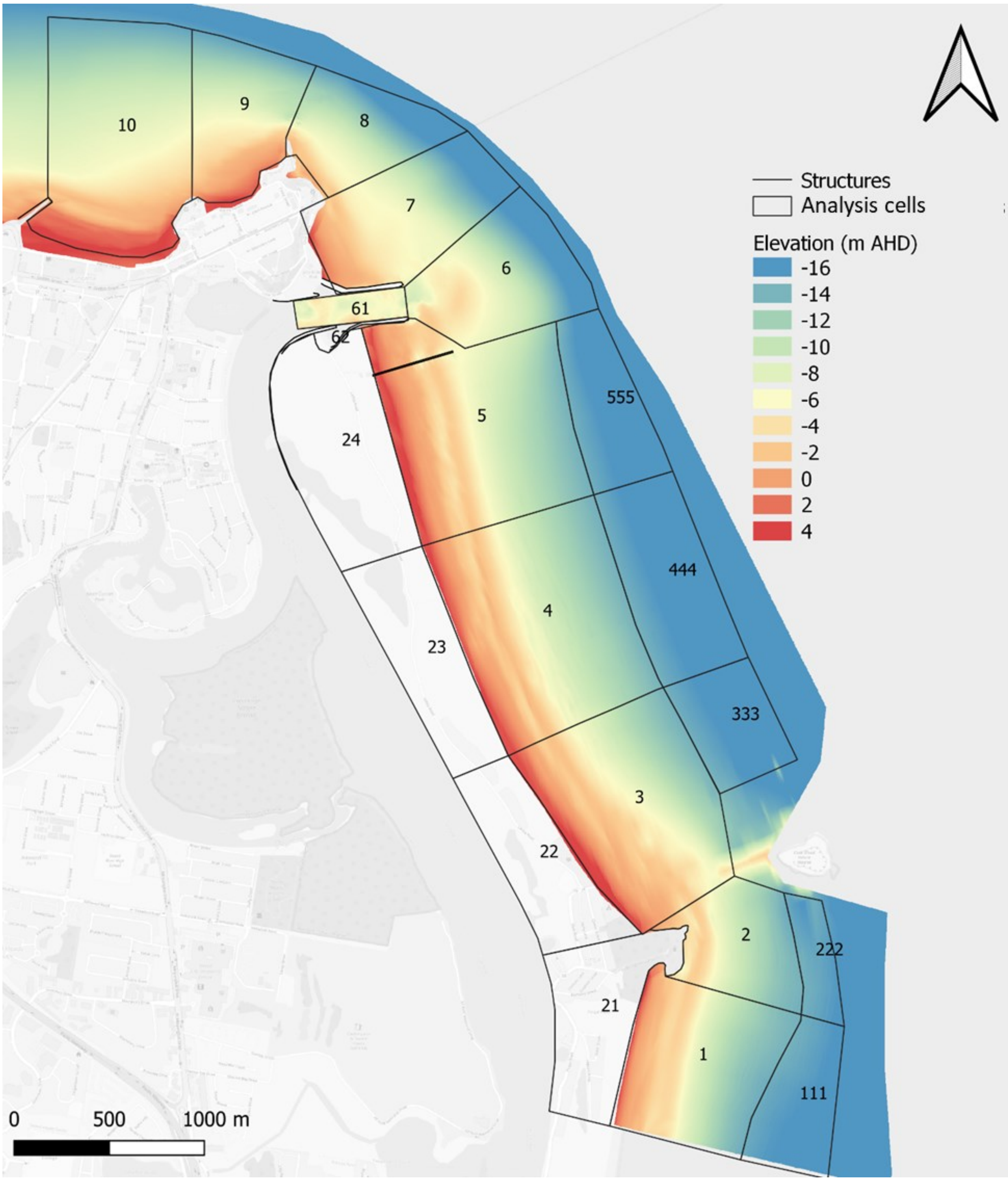

Figure 26: Map of combined topographic and bathymetric survey from June 2021.

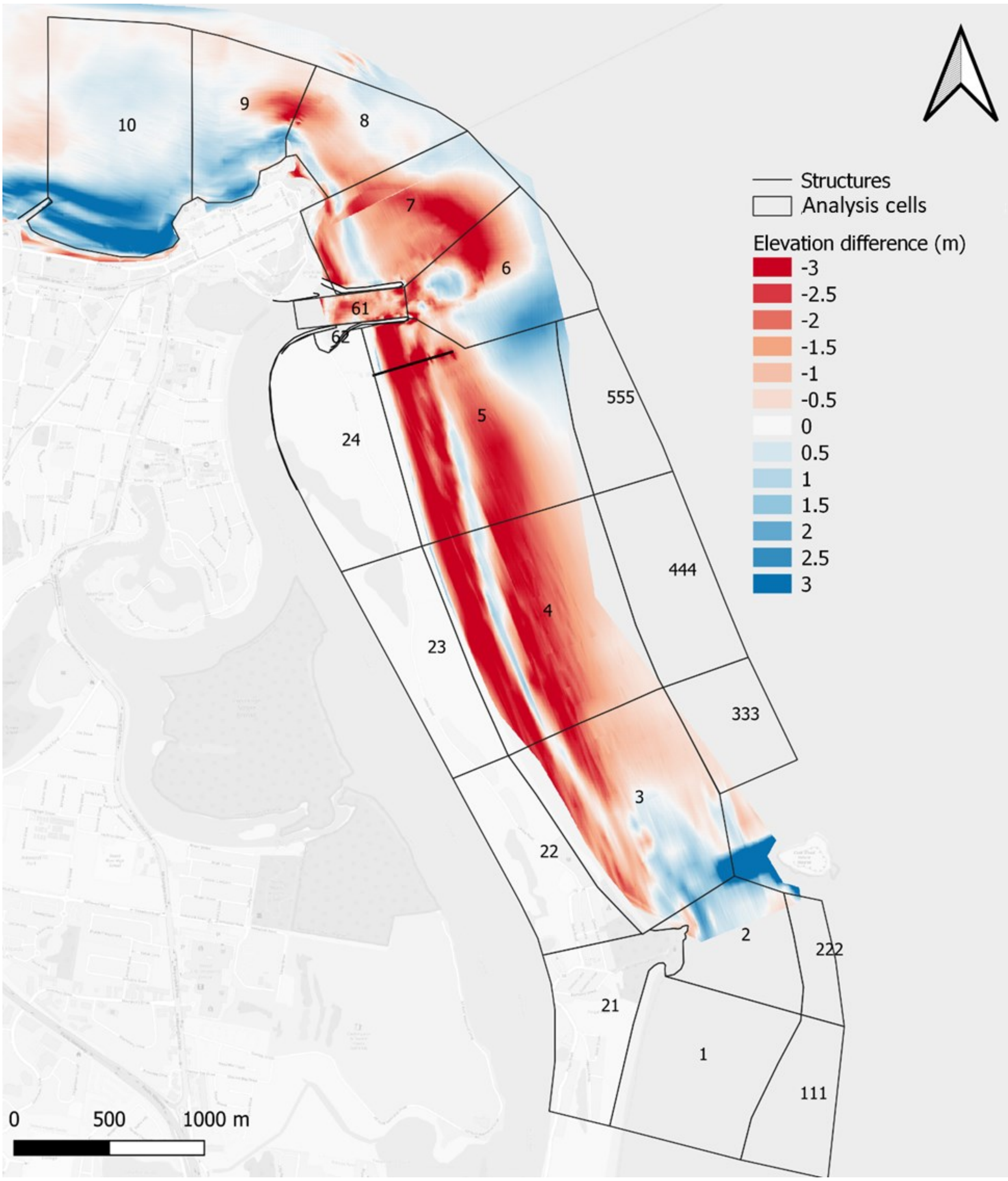

Figure 27: Map of surveyed elevation difference between 1994 and 2021 (red colours show erosion).

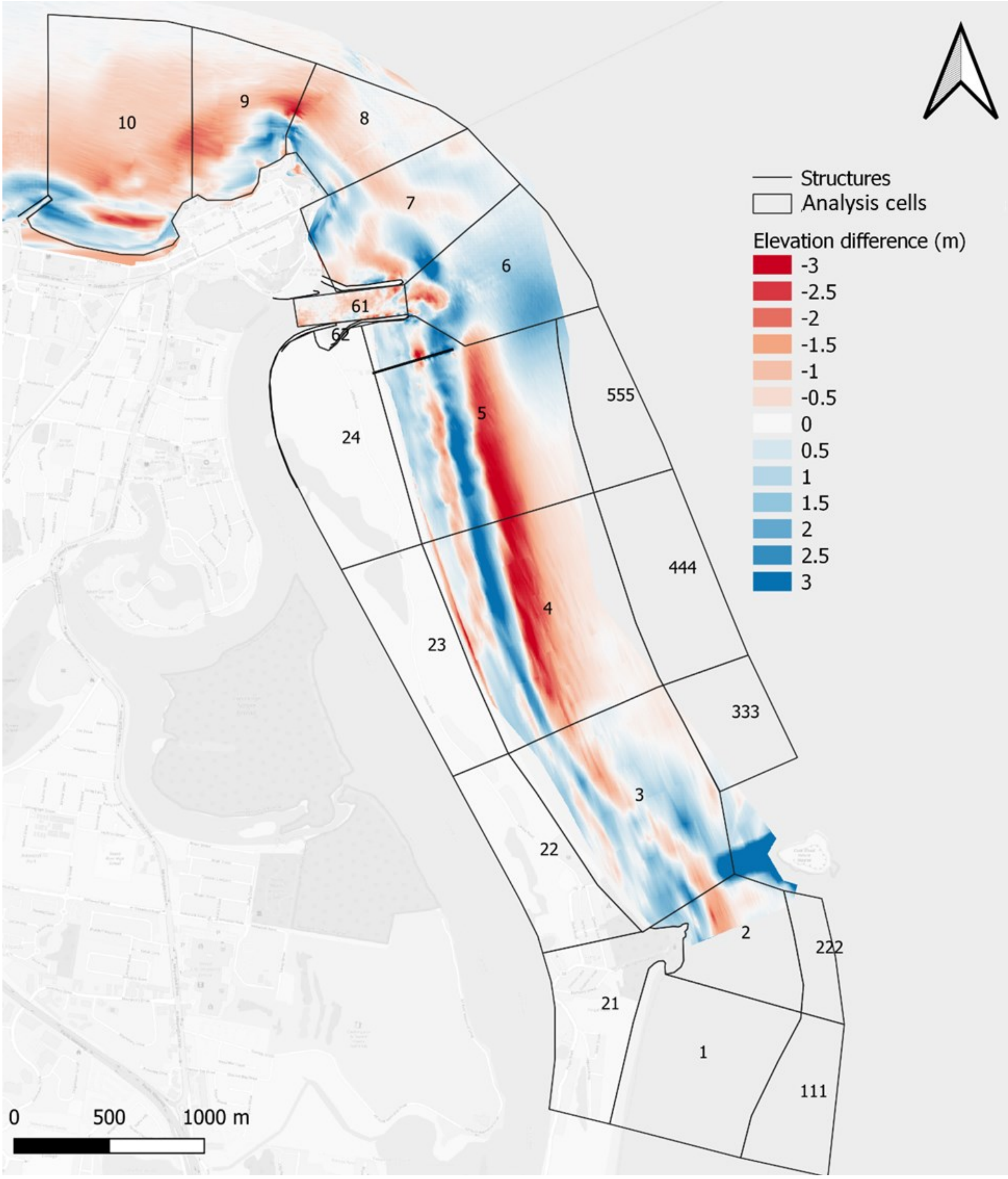

Figure 28: Map of surveyed elevation difference between 2009 and 2021 (red colours show erosion).

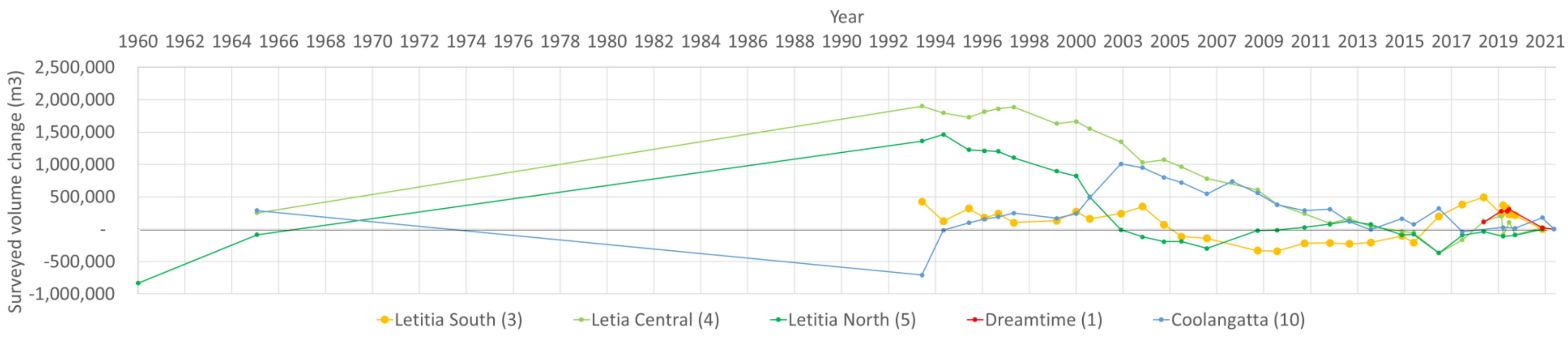

Figure 29: Long-term sand volume change at Letitia Beach (cells 3, 4 and 5), Dreamtime Beach and Coolangatta Beach.

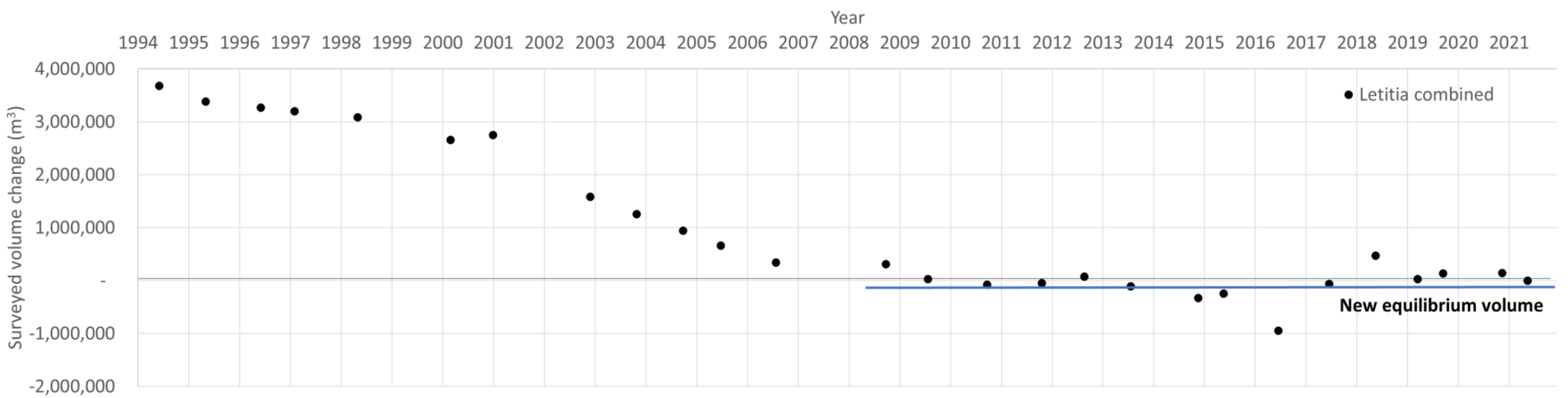

Figure 30**: Long-term sand volume change at Letitia Beach (cells 3, 4 and 5 combined) over the TSB operational period between 1994 and 2021.**

4.2.3 Contemporary sand budget

A sediment budget aims to provide conceptual and quantitative sediment transport pathways and magnitudes within complex coastal systems. Here, the sand sources and sinks of the study area between Fingal Head and Coolangatta have been assessed for a series of coastal cells to determine transport rates between the cells. In this study the sediments considered are sand and the included sediment transport are littoral processes, aeolian transport, fluvial transport and anthropogenic changes such as dredging, dredge material placement and sand pumping.

Sand transport rates and directions between the defined coastal cells vary from year to year and with seasonal changes in the metocean climate. Adopting a historic analysis over a sufficient period can provide long-term averages and net sand transport pathways. Typically, net sand transport rates derived from survey data are obtained from the longest possible observed period to reduce the influence of cyclic behaviour. However, the considerable changes in the management of the coastline over the past two to three decades at the Tweed River entrance and Letitia Beach need to be considered when assessing changes. An analysis period that is most representative of the contemporary sand budget and behaviour of Letitia Beach was required. As suggested in previous assessments (e.g., BMT, 2020; Jacobs, 2017) and confirmed in the results presented herein, Letitia Beach reached a new dynamic equilibrium shortly following completion of TSB's supplementary increment phase in 2008. Hence, the period since 2009 was considered for the derivation of contemporary sand transport rates.

To capture the uncertainty in the derived volumes from survey analysis a typical range of uncertainty has been considered as follows:

- ±5% for mechanical transport rates based on SCADA (pumping system hardware and software system) data and dredging records
- ±20% for littoral transport rates based on error estimates in BMT (2020)
- ±30% for aeolian transport based on limited available LiDAR topography data
- ±30% for on/offshore transport and fluvial transport based on literature

The progressive transport rates between cells were estimated using a sediment budget approach by:

- Assuming that the total sand volumes are consistent with all observed inputs, outputs and observed changes within the coastal system, while recognising potential errors in survey data and uncertainties in unsurveyed areas (see Section 5.2).
- Assessing the progressive surveyed changes in sand quantities for each cell (where possible) between 2009 (i.e., when a dynamic equilibrium was reached along Letitia Beach following adjustment to initial TSB operations) and 2020 (i.e., last full year of available data).
- Adopting a sand capture efficiency of the Letitia jetty of 25% of the longshore transport based on the *Reassessment of Long-term Average Annual Net Sand Transport Rate 2020* (BMT, 2020), i.e., the combined sand pumping volume and sand leakage make up the longshore transport rate at the jetty.
- Known dredge material placement quantities, sand pumping quantities and onshore sand transport based on regional literature values of 1-2m^3/m/year (Patterson, 2013).

- Minimal fluvial sand sources, aeolian transport and offshore losses, in line with previous assessments (BMT, 2020; Jacobs, 2017).

Based on the above approach, inputs and outputs are applied in consideration of the change in volume for neighbouring cells describing the sand transport into and out of each cell. The sediment budget and net cell changes within the study area are presented in Table 7.

Table 7: Sand budget for study area between Fingal Head and Coolangatta based on estimated accumulation/erosion rates and literature (error bands outlined above apply to all rates).

Cell	ID	Net volume change (m^3/year)	Net (northward) littoral transport (m^3/year)	Other source [+ive] or sink [-ive] (m^3/year)	Data source/ comment
Dreamtime	1	-	**598,000**	+598,000 (inflow)	Volume change not considered due to lack of long-term data
Fingal Head	2	-	**598,000**	-	Volume change not considered due to lack of long-term data
Letitia South	3	71,745	**528,000**	+2,320 (onshore supply)	Survey
Letitia Central	4	-23,200	**562,000**	+2,400 (onshore supply) +3,214 (dunes) +4,700 (dredging)	Survey
Letitia North	5	-18,462	**115,854**	+2,400 (onshore supply) -3,282 (dunes) -463,417 (pumping)	Adopted as 25% sand leakage at jetty (BMT, 2020). The total sand transport north from Letitia is then this littoral rate plus the transfers under TSB operations (pumping + dredging).
Tweed Entrance	6	19,837	**39,000**	+3,932 (channel scour) -60,489 (dredging)	Survey, Assumed offshore losses and river supply balance each other out (BMT, 2020)

Cell	ID	Net volume change (m^3/year)	Net (northward) littoral transport (m^3/year)	Other source [+ive] or sink [-ive] (m^3/year)	Data source/ comment
Duranbah	7	13,192	**92,000**	+31,567 (dredging) +33,628 (pumping)	Survey
Snapper Rocks East	8	-2,364	**543,000**	+18,963 (dredging) +429,789 (pumping)	Survey
Rainbow Bay	9	-5,617	**549,000**	-	Survey
Coolangatta	10	-22,121	**571,000**	-	Survey

4.3 Quantified conceptual sand movement model

Informed by the rates and directions of sand movements from the sand budget analysis the following sections provide a detailed description of the most likely drivers of the sand transport rates adopted in the quantified conceptual sand movement model.

4.3.1 Net and gross longshore transport

South-east Australia is exposed to dominant south-east swell that is obliquely aligned to the coast and experiences moderate energy (and variable) wave climate. This obliquity drives the east Australian sand transportation system shown in Figure 31 (left). Figure 31 (right) shows the seasonality of the three dominant wave modes along the northern NSW to south-east QLD coast, i.e., east, east-south-east to south-south-east and south-east to south-south-east waves. As discussed in Section 3.6, large scale climatic drivers result in longer term variability of the regional wave climate. This seasonality and wave climate variability also controls the magnitude and direction of longshore sand transport along Letitia Beach and headland bypassing around Fingal Head (da Silva, 2021a).

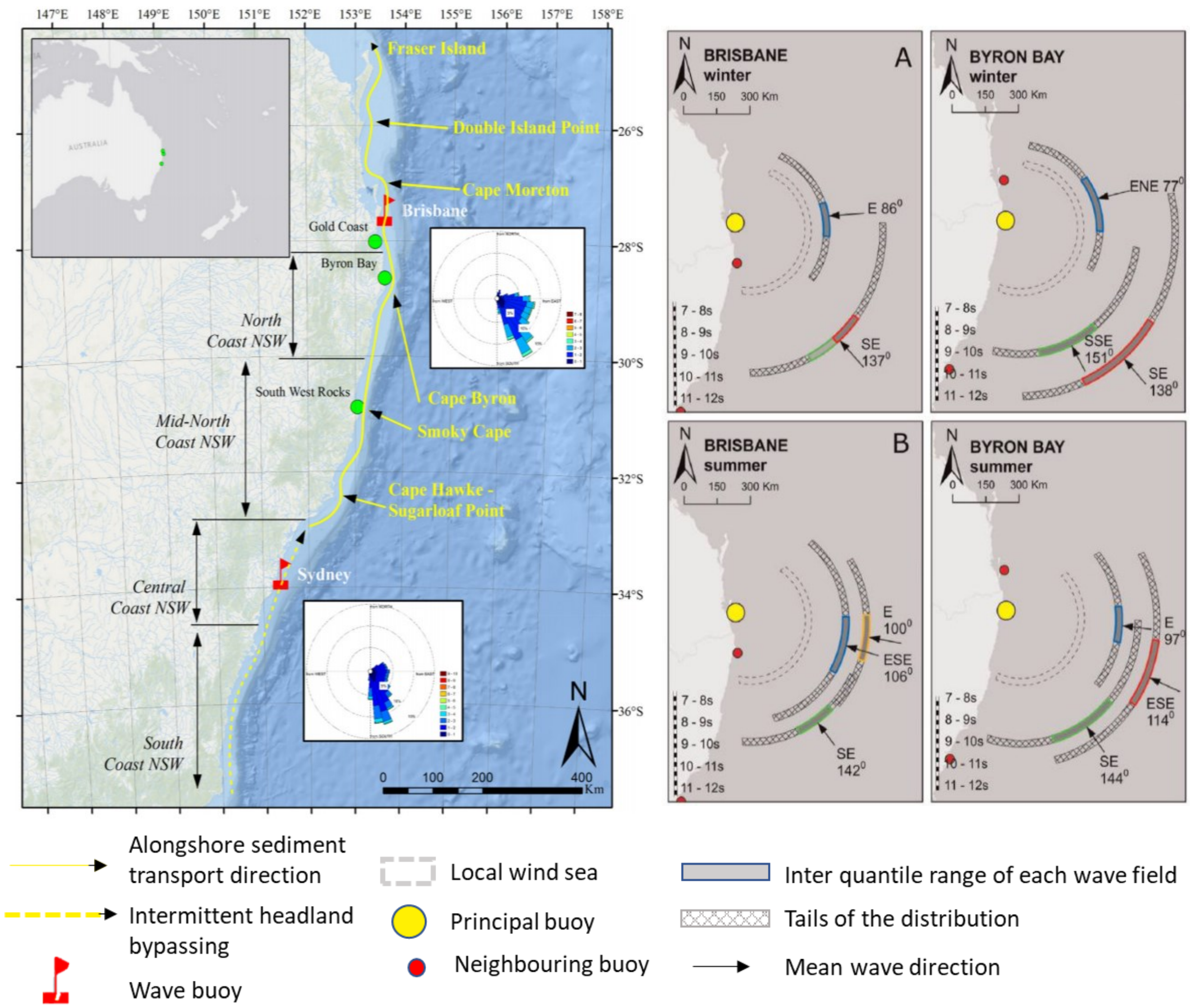

Figure 31: (left) East Australian sand transportation system (source: Goodwin et al., 2020) and (right) main wave modes observed at Brisbane and Byron WRB (source: Mortlock and Goodwin, 2015).

Note: (left) Solid yellow line in the north indicates the area of more continual northward littoral transport, headland bypassing and drift aligned beaches. The dotted yellow line in the south indicates swash aligned embayed beaches either closed or with intermittent bypassing.

Due to its east to north-north-east coastline alignment, Letitia Beach experiences predominantly northward longshore sand transport. The long-term net northward sand transport rates derived from the sand budget analysis herein suggest that these range from 528,000m^3/year at the southern end of Letitia Beach to 562,000m^3/year near the jetty. These rates are representative for the contemporary (since 2009) morphology and climate experienced at Letitia Beach. Prior to 2009, longshore sand transport rates were considerably higher and were found to gradually reduce (BMT, 2020) as the shoreline of the central and northern sections of Letitia Beach were undergoing an anti-clockwise realignment due to the initial TSB operations.

Previous studies estimated that approximately 73% of the gross transport sand occurs in water depths of less than 4m and approximately 91% in depths of less than 8m (Hyder et al., 1997). Jacobs (2017) suggest that considerable southward longshore transport occurs from time to time during more northerly wave directions. In contrast, Cardno (2009) suggest that due to the orientation of the northern section of Letitia Beach, there is limited southward directed sand transport during such periods. Preliminary numerical modelling undertaken by Cardno (2009) suggested that during periods with northerly wave directions most sand transport would be onshore directed for low to medium wave energy conditions. Longshore sand transport rates derived from survey analysis as well as theoretical estimates from empirical calculations undertaken in BMT (2020) are shown in Figure 32. The estimated longshore sand transport rates suggest that there is minimal southward movement (negative rate) along Letitia Beach.

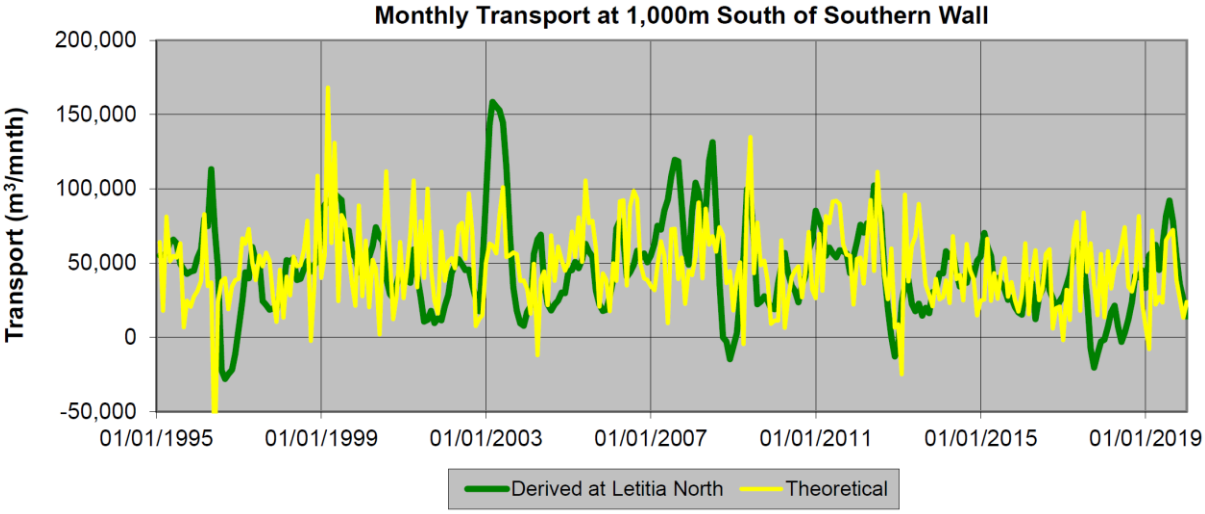

Figure 32: Monthly longshore sand transport at Letitia Beach derived from survey data analysis and theoretically derived from wave data (source: BMT, 2020).

Note: Negative values indicate southward movement (and vice versa).

Figure 33 compares satellite-derived shorelines for periods characterised with high occurrence of waves from a more northerly to easterly direction (La Niña period) compared to periods with dominant south-easterly (El Niño period) wave conditions as consistent with low rates of southward sand movement. If considerable southward longshore sand transport occurs after extended northerly conditions, noticeable sand accretion on the northern side of Fingal Head would be expected (as seen in other NSW embayment's that 'rotate' with temporary changes in the prevailing wave climate, e.g., at Collaroy-Narrabeen). The reverse behaviour is observed during periods of dominant south-easterly wave conditions, with sand accumulating against Fingal Head. It is therefore assumed, that due to the general east-north-east coastline orientation of Letitia Beach there is no strong linkage between ENSO and the direction of sand movements. In contrast, there appears to be a strong linkage with ENSO at Dreamtime Beach, with a general east-south-east coastline orientation.

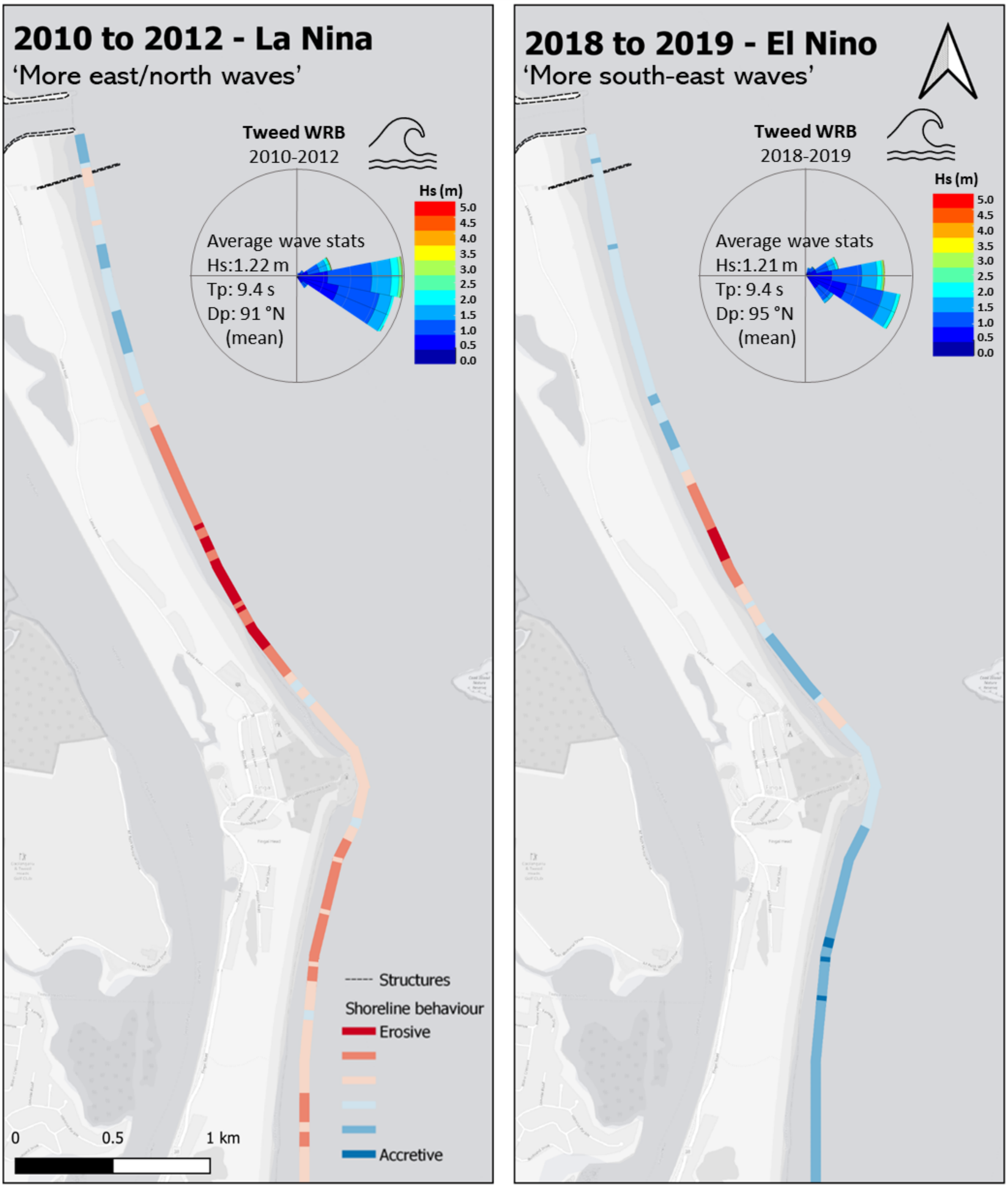

Figure 33: Relative change in mean annual shoreline position (DEA) for dominant (left) La Nina and (right) El Nino periods.

4.3.2 Headland bypassing

Sand supply to the southern end of Letitia Beach is predominantly controlled by intermittent headland bypassing processes around Fingal Head. As summarised in Section 2.5, Silva et al. (2021a) undertook a detailed assessment of sand movements around Fingal Head. A timeseries of surveyed elevation differences in the vicinity of Fingal Head between June 2018 and January 2020 is shown in Figure 34. During this period hundreds of thousand cubic metres of sand was observed moving around Fingal Head by sandbar-driven bypassing during a high energy wave event (Tropical Cyclone Oma). A second bypassing mode was observed during low energy wave conditions as a gradual widening of the upper beach on the updrift side (Dreamtime Beach) eventually resulted in sand leaking around Fingal Head to Letitia Beach.

It was found that sandbar-driven bypassing is typically initiated during late summer/autumn and requires seven to ten months to be completed. The gradual sand leaking bypassing mode was found to occur mainly during late spring to early summer months. Based on the survey differences assessed for the sand budget analysis herein, the long-term average net sand supply into Letitia Beach was 598,000m^3/year between 2009 and 2020. However, it is noted that headland bypassing occurs over various time scales and the annual range of sand supply around Fingal Head was estimated to be around 270,000 to 990,000m^3/year (BMT, 2020).

Large scale climatic variability linked to ENSO, PDO and IPO was 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) was seen to result in upper beach erosion at Dreamtime Beach, reducing the sand availability for sand bypassing around Fingal Head. At the same time, high energy wave events during extreme La Niña periods also arrive from a more easterly wave direction, reducing the northward longshore transport potential due a reduced wave obliqueness in respect to the coastline orientation. Conversely, extended El Niño dominance results in the opposite effect.

The key consideration for the sand budget at Letitia Beach is that during periods of reduced sand supply around Fingal Head the predominantly northward sand transport along Letitia Beach is maintained. Therefore, the sand supply to the central and northern section of Letitia is also maintained, resulting in a deficit of sand at the southern end (i.e., more sand moving north out of the southern end of Letitia than is being supplied from the south by headland bypassing). This temporary sand deficit then results in a reduction of beach width and natural cycles of upper beach erosion at the southern end of Letitia Beach. This natural cyclic process is evident (over multiple timescales) in the observed shoreline behaviour and volumetric survey assessment presented in Section 4.2. Interannual variability in shoreline positions up to 30m and cell volumes changes of over 100,000m^3 was observed at the southern end of Letitia.

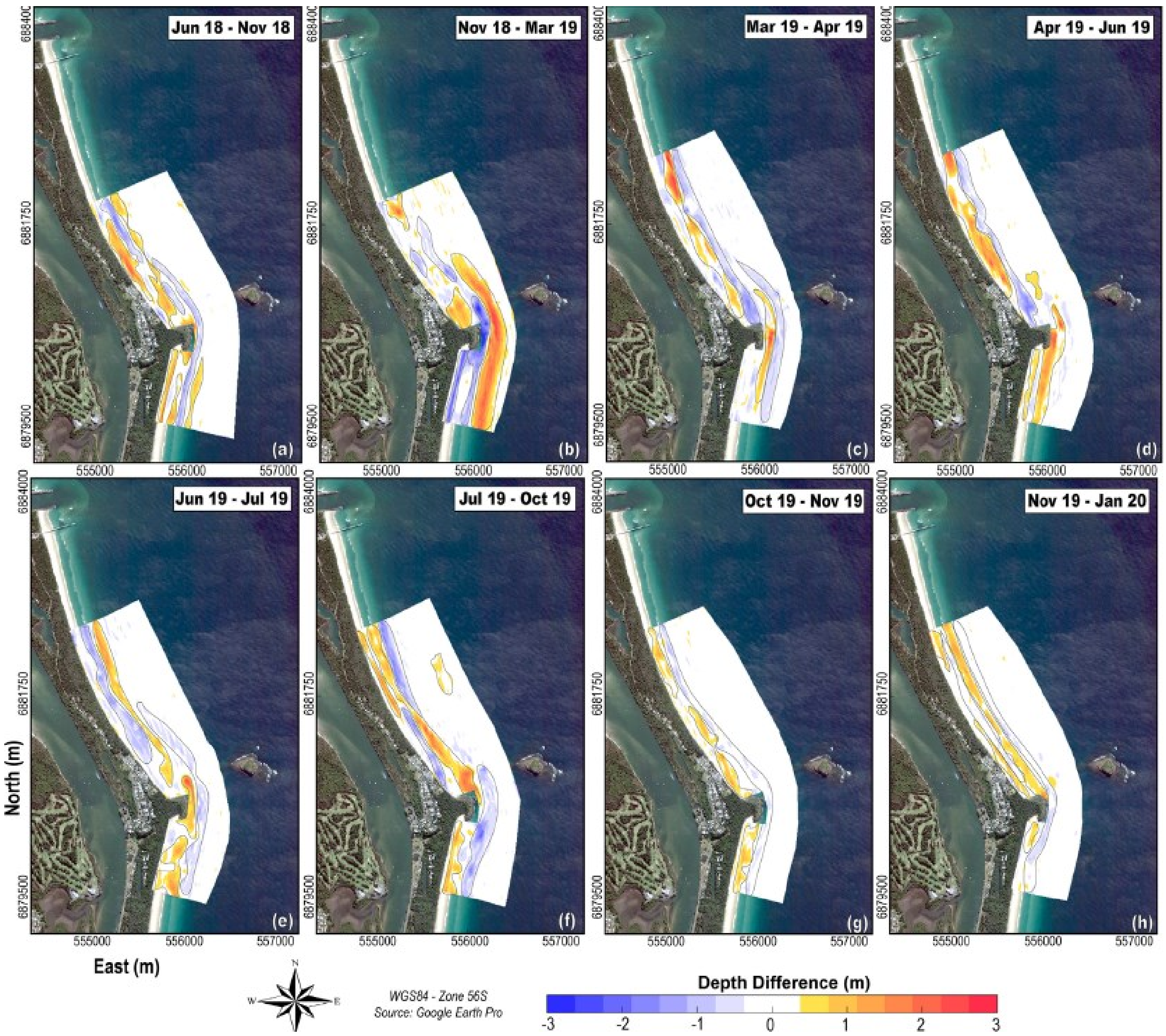

Figure 34: Timeseries of surveyed elevation differences between June 2018 to January 2020 around Fingal Head (source: Silva et al., 2021a).

4.3.3 Cross-shore transport

Three distinct cross-shore sand transport processes act along the open coast in the vicinity of the Tweed River entrance:

- Offshore directed sand transport due to beach erosion during high energy wave conditions (event based – typically days) followed by onshore sand transport and beach recovery (typically months) during lower wave energy conditions. The amount and depth of cross-shore transport is a function of the size, duration and direction of the waves and the tidal conditions with higher water levels (i.e., spring tides or elevated by storm surge) causing more erosion and larger quantities of cross-shore exchange. However, this storm driven offshore/onshore exchange typically occurs in depths less than 25m and more often in depths less than 10m. Harley et al. (2021) suggests extreme storms can also have a positive contribution to the nearshore sand budget by exchanging sediment between the lower and upper shoreface. Hence, single (or sequence of) large storm erosion events can result in a net increase in sand volume across the active profile.

- Offshore directed sand transport during major flood events depositing sand from the river entrance area in deeper water.
- Onshore directed transport from nearshore deposits such as the ebb tidal shoals, flood deposits and (minimal) relict inner-shelf Holocene sand deposits.

A dominant bar and trough system frequently migrating from the shoreline to around 200m offshore (around 0 to -5mAHD) and back is observed at Letitia Beach (Silva et al., 2021b). As described above, this process is linked to the prevailing wave energy and resulting storm erosion and subsequent beach recovery. The active part of the coastal profile along Letitia Beach was previously identified to extend to a depth around -14mAHD (Strauss et al., 2013). The active profile is where variability in profile elevation is observed due to cross-shore and longshore sand transport. Comparison of cross-shore coastal profiles showing the observed variability south at the jetty (ETA8.5) and at the southern end of Letitia (ETA4) are presented in Figure 35.

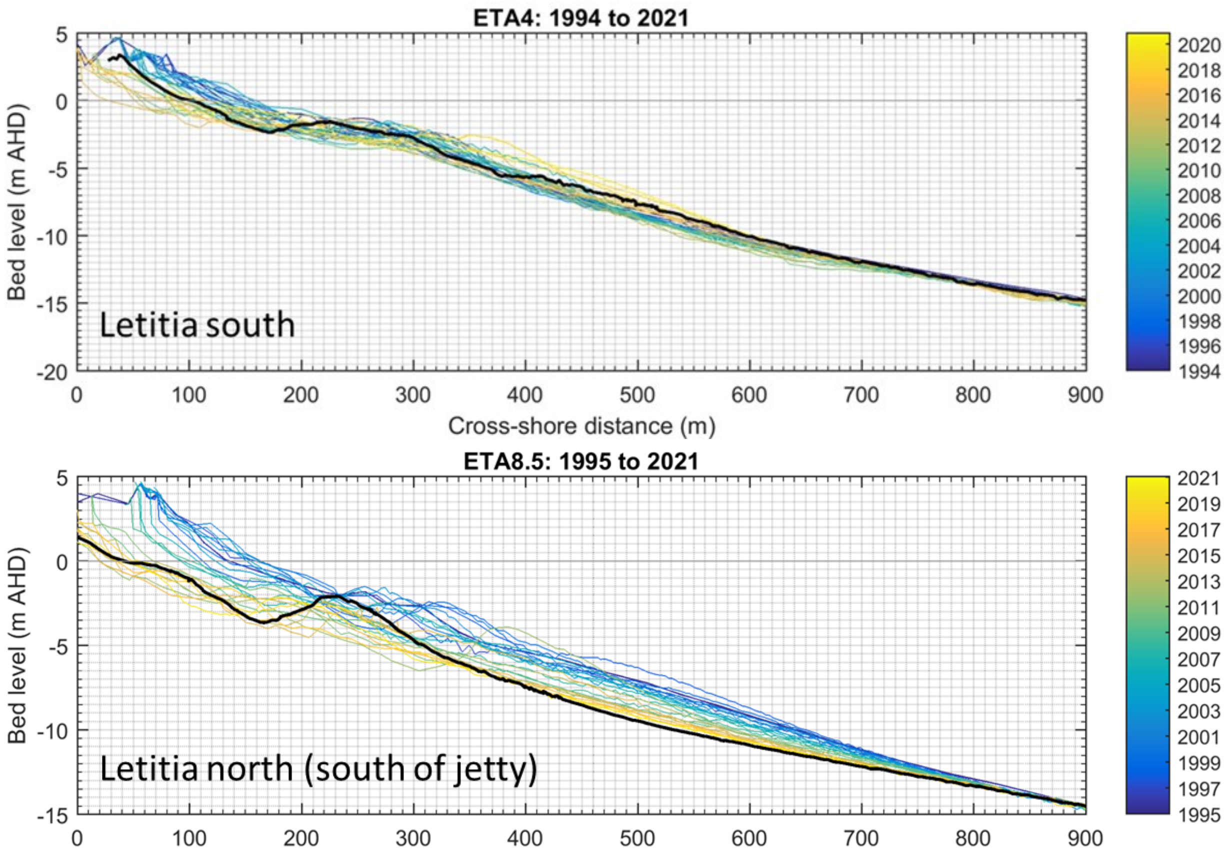

Figure 35: Cross-shore profiles derived from ETA surveys at Letitia Beach.

Note: 2021 survey is shown in black.

Available beach profile surveys from 2008 to 2021 (annual or more frequent) were analysed to determine shorter-term fluctuations in beach profiles. The period after 2008 is selected to minimise the influence of net profile changes attributed to the initial shoreline re-adjustment following commencement of TSB operations (see Section 4.2). Figure 36 shows the profile surveys for three representative beach profiles: Letitia south (ETA4), Letitia centre (ETA7) and

Letitia north (ETA8.5). Since 2008, an inter-annual shoreline fluctuation[5] of around 67m, 56m and 37m is observed at Letitia south, centre and north, respectively. The volume fluctuation above 0m AHD between the 5th and 95th percentile profiles is 80m^3/m, 60m^3/m and 73m^3/m for Letitia south, centre and north, respectively. Most of the changes are observed as a result of onshore-offshore migration of the sand bar and occurrence of sand slugs.

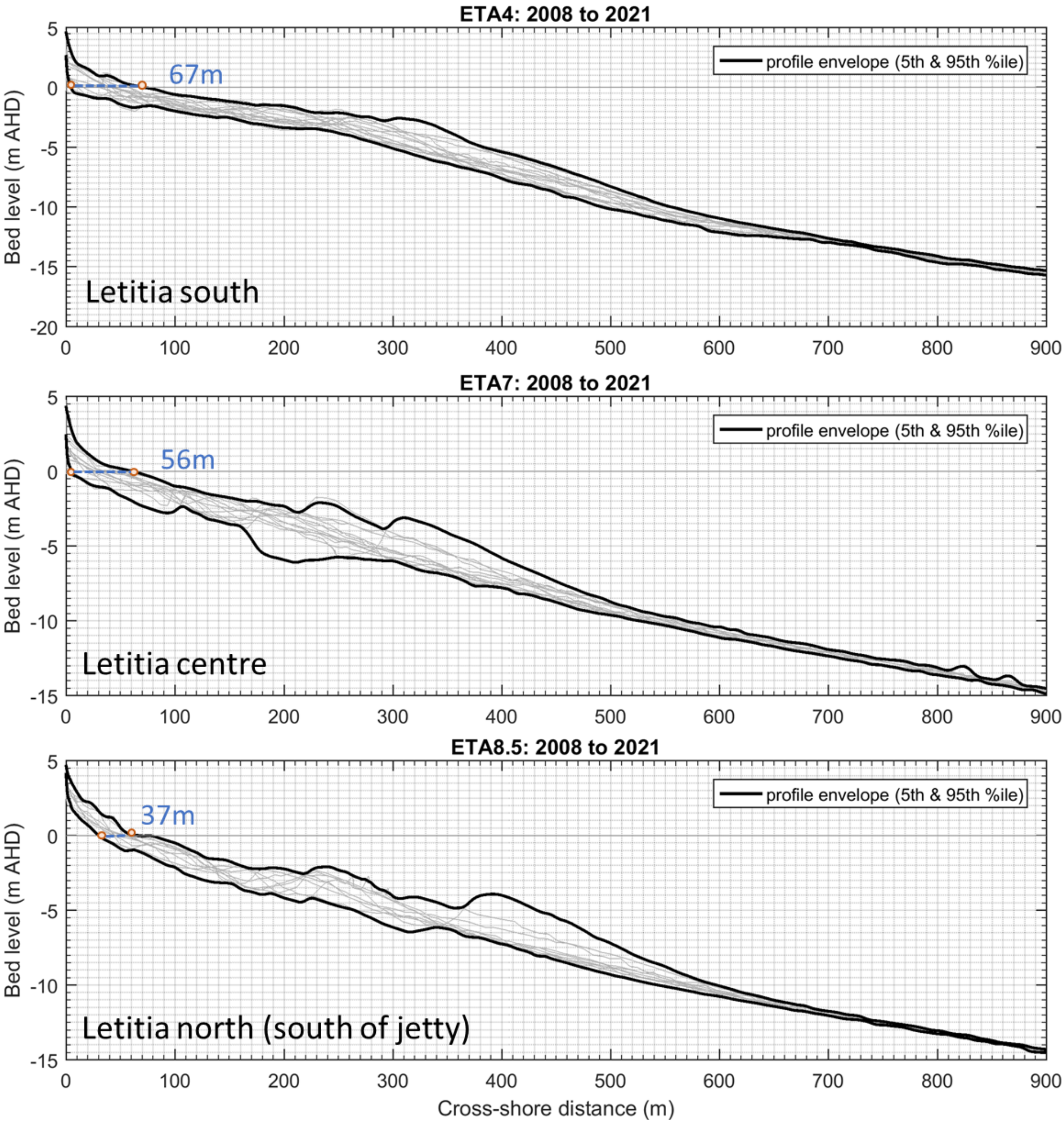

Figure 36: Inter-annual beach profile envelope along Letitia Beach. Distance between 5th and 95th percentile shoreline position is shown in blue.

[5] Changes in shoreline position were defined based on the position of the 0m AHD elevation contour (approximately mean sea level).

Coastal Studies (2008) found that due to the depression in the seabed elevations underneath the Letitia jetty, a topographically defined rip current is initiated and maintained. This rip current is fixed in location and induces additional offshore directed sand transport that can lead to more severe shoreline erosion locally (Short, 1985). Coastal Studies (2008) estimated that around 10-20m of shoreline setback would be expected in the lee of the jetty over and above that of the normal coastal processes.

Offshore sand transport in the vicinity of the river entrance due to major flood events has been assessed in Jacobs (2017). A 1 in 20-year river flood in 2017 as a result of Tropical Cyclone Debbie was observed to have scoured the estuary shoals and deposited approximately 150,000m^3 of sand between the tip of the training walls and the entrance bar. Following such flood events, the sand is reworked by tidal and wave-driven currents returning some of the sand into the river and adjacent beaches. Offshore losses beyond the limit of the sand budget calculation cells adopted herein were assumed in the order of 7,000m^3/year based on BMT (2020). Onshore transport of sand from this depth is expected to occur over much longer timescales than the onshore sand transport from nearshore storm bars. Onshore transport of flood deposits from water depths greater than ~20m were assumed to be minimal and not significant for the contemporary sand budget for this project.

Based on review of the shape of the coastal profiles along Letitia and Dreamtime Beach (see Figure 37), there is no apparent evidence for the presence of a significant shelf sand body (SSB) within the surveyed extents. SSBs can provide a considerable source for onshore sand transport in some locations along NSW due to a disequilibrium to the profile morphology (Kinsela et al., 2015). Based on regional coastline evolution modelling by Patterson (2013), it is estimated that there remains some onshore sand supply from relict Holocene sand deposits on the lower shoreface at a rate of around 1-2m^3/m/year.

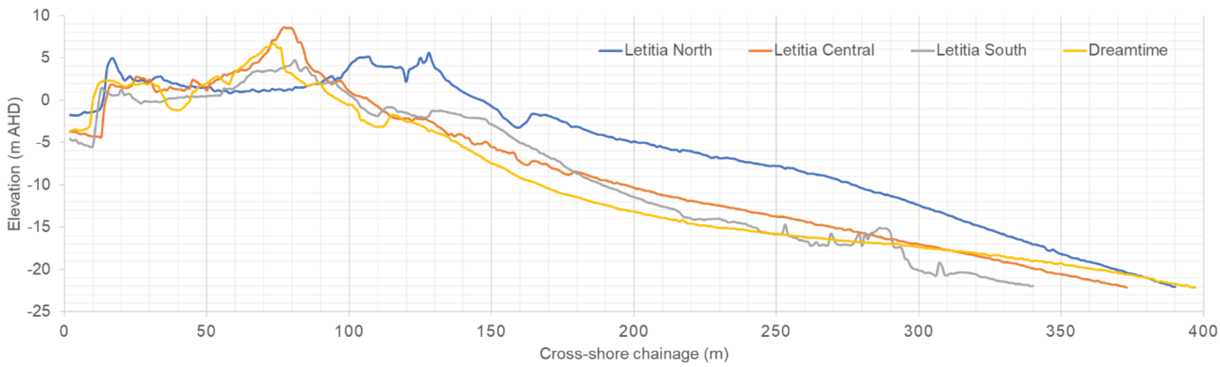

Figure 37: Comparison of coastal profiles along Letitia Beach and Dreamtime Beach based on 2018 LiDAR.

4.3.4 Sand transfers (pumping and dredging)

Since adjustment of the TSB operations to align more closely with the natural sand transport rates at Letitia in 2008, the average annual mechanical transport rates were:

- 463,000m^3/year between 2009 and 2020 via pumping
- 60,500m^3/year between 2009 and 2020 via dredging (although, effectively no dredging was undertaken between 2009 and 2015).

Most of the pumped sand has been delivered to the Snapper Rocks East outlet at Point Danger while on average 33,600m^3/year was delivered directly onto Duranbah Beach. Around half of the dredged sand was taken from the river entrance to the Duranbah placement area (i.e., average of 31,600m^3/year). As of 2019, a total of 56,000m^3 and 62,900m^3 of dredged sand was delivered to the Fingal and Bilinga/Tugun placement areas, respectively (or an annual average of 4,700m^3/year and 5,200m^3/year over the 2009 to 2020 period). Additional small-scale dredging and nourishment from other sources, including from the river have been undertaken. Due to the relatively small volumes and one-off occurrences these were not considered in the sand budget analysis.

A comparison of cell volumes relative to 2021 calculated for the Tweed River entrance bar, the river entrance (between the training walls) and the northern section of Letitia Beach is presented in Figure 38. The following observations are made from this comparison:

- A rapid reduction in the Tweed River bar cell volume is evident because of the large-scale dredging undertaken during Stage 1 TSB operations.
- Between the completion of the Stage 1 dredging in May 1998 until March 2000 infilling of the dredged area occurred at approximately 330,000m^3/year.
- Since commencement of regular dredging and sand pumping in April 2000 and May 2001, respectively, a gradual increase has occurred on the bar at an average long-term rate of around 32,500m^3/year. During periods of higher combined dredging and sand pumping activity the Tweed River bar volume remained relatively constant (e.g., between 2000 to 2003 and 2016 to 2021).
- A gradual reduction in the cell volume at Letitia North was observed during the initial Stage 1 dredging, followed by a rapid volume reduction upon commencement of the sand pumping in May 2001 until around 2004.
- The cell volume within the river entrance (between training walls) maintained relatively constant throughout the TSB operational period.

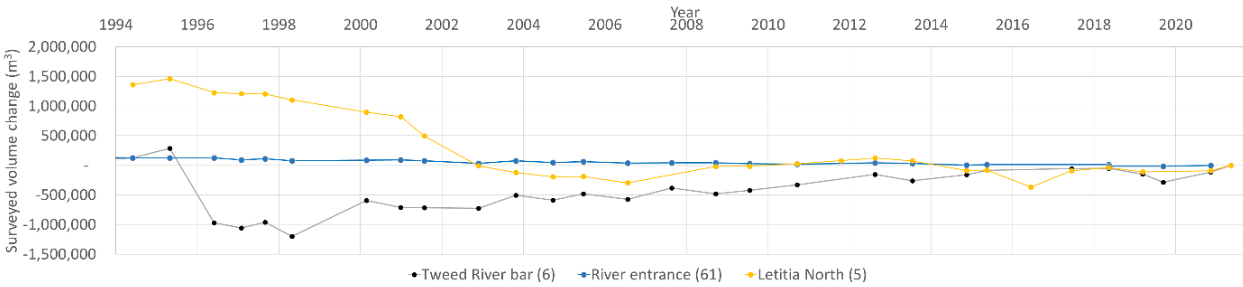

Figure 38: Timeseries of surveyed volume changes relative to 2021 for cell 6, 61 and 5.

4.3.5 Aeolian transport

Aeolian sand transport volumes were estimated to be relatively small in comparison to other transport processes in the study area. While the dune area along Letitia Beach has significantly increased following stabilisation of the entrance in the late 1890s and 1960s (see Figure 39), there is no significant expansion of the dune system in recent times. The aerial photographs from the 1960s show large areas of the sand spit were still unvegetated. Prior to establishment of dune vegetation due to sand spit stabilisation by the river training works aeolian sand transport was likely considerably higher along Letitia Spit and Fingal Head. The higher aeolian sand transport experienced back then would have significantly contributed to the present-day topography of the sand spit (e.g., dune building) and resulted in sand losses to the Tweed

River. The aerial photograph from 1966 shows dune overpassing at Fingal Head, essentially connecting Dreamtime Beach and Letitia Beach landward of Fingal Head. There is no evidence of similar events in more recent times as the aeolian sand transport pathways are effectively stopped by the vegetation.

Comparison of available LiDAR data from 2009, 2013 and 2018 was undertaken for a series of profiles (see Figure 40) and spatially as part of the sand budget analysis (see Appendix A). The analysis suggests a minor net increase in the dune volume of around 3,000m^3/year at the northern end of Letitia Spit (cell 24) while the same volume was lost from the dunes along the central part of Letitia Spit (cell 23).

1962 **1966** **2010** **2021**

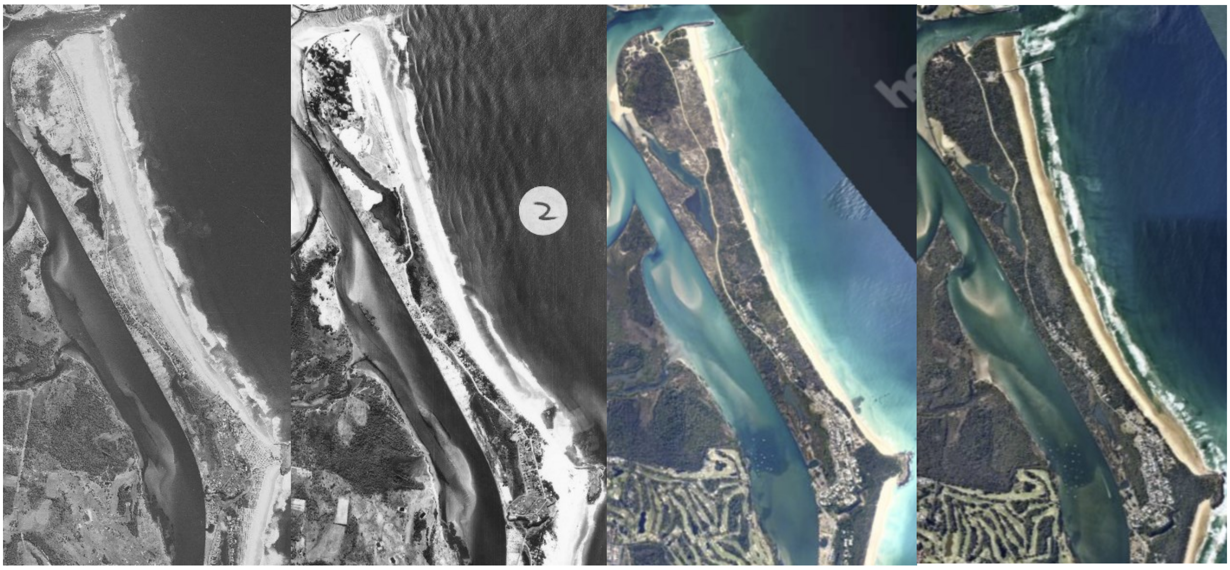

Figure 39: Aerial imagery showing gradual stabilisation and vegetation of dunes at Letitia Spit (source: NSW Government and Nearmap).

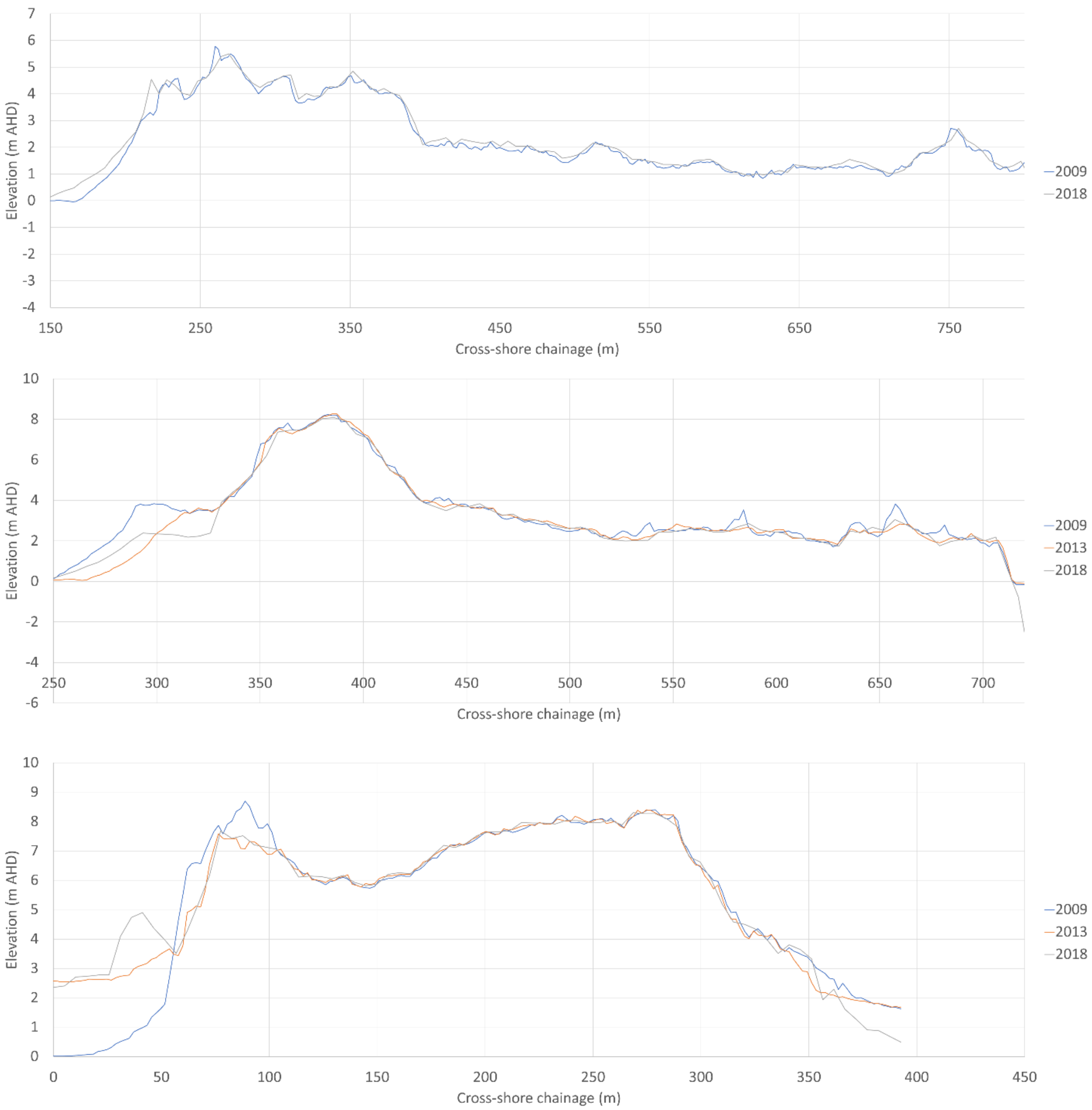

Figure 40: Comparison of dune profiles across Letitia Spit at the (top) Letitia North, (centre) Letitia South cells and (bottom) across Fingal Head (south to north).

4.3.6 Fluvial transport

The Tweed River does not supply significant quantities of terrestrial sourced sand to the coast/ocean. The river has acted as a sink for marine sand up until the late 1900s as the flood shoals adapted to the initial construction and extension of the training walls (Jacobs, 2017). It is unclear what quantities of sand are permanently moving into the estuary, if any, as it is regularly removed by dredging or by the action of floods. Jacobs (2017) suggests that since commencement of TSB sand pumping in 2001 a net sand supply from the river to the entrance is observed. BMT (2020) estimated that the net supply from the river is approximately 7,000m^3/year (equivalent to offshore losses in the vicinity of the entrance).

The sand budget analysis undertaken herein (Appendix A) suggests that approximately 4,000m^3/year of sand is lost from the river channel between the training walls.

4.3.7 East Australian Current

Previous studies have highlighted the importance the EAC on nearshore currents and sand transport within the Letitia embayment (Hyder et al., 1997). At the Tweed River entrance, it was found that the EAC generally flows in a southeast direction and the magnitude and location depends on the state of the tide as well as seasonal variability in the current. During ebb tide, this southeast current was observed just beyond the entrance bar with measured average speeds up to 0.4m/s (Helyer et al., 2011). This southeast current is expected to occasionally create clockwise circulation cells through the Letitia embayment. Such current circulation gyres create a northward flowing current along the shore which may enhance northward sand transport (Helyer et al., 2011). This reversed longshore current was identified in measured current profiles along Letitia in 2010 (see Figure 41).

In comparison to wave-driven longshore sand transport, the relative magnitude of the EAC is considered minimal. While the magnitude and rates of sand movement due to the EAC are not fully understood its effect is captured in the net transport rates derived from the sand budget analysis presented herein.

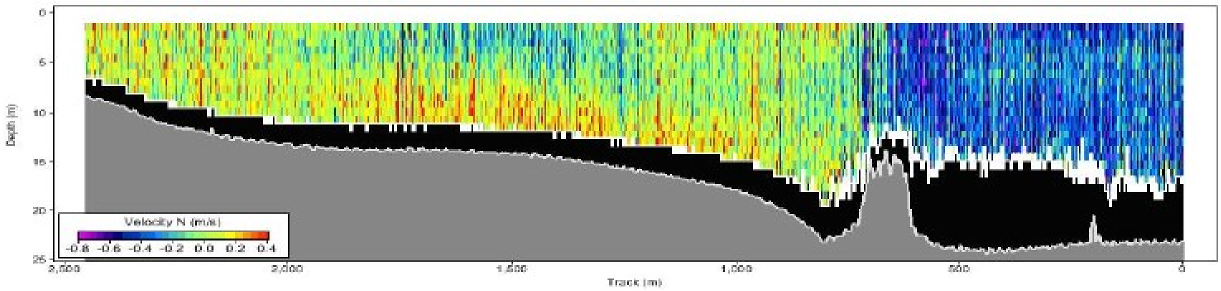

Figure 41: North-south current speeds measured between Fingal Head and Cook Island on 20 December 2010 (source: Helyer et al., 2011).

Note: Green/red colours show northward flowing current and blue/purple colours show southward flowing current.

4.4 Future projected morphological trends

SLR induced shoreline recession can be estimated based on the concept that sea level rise will lead to erosion of the upper shoreface, followed by re-establishment of the original equilibrium profile (Bruun, 1962 and 1983). This profile is re-established by shifting it landward and upward. It is noted that the application of this concept is a highly simplified method to estimate SLR recession and its use in complex coastal processes areas such as Letitia Beach which is in proximity to the Tweed River entrance is challenging. The Tweed River entrance and lower estuary may also accumulate marine sand as a morphological response to SLR (BMT, 2020), hence reducing the active sand budget of adjacent beaches.

As described in Section 3.6, the directionality of the modal wave climate is well correlated with large-scale climate drivers such as ENSO. The modal wave conditions have a greater influence on shaping the long-term planform geometry and beach orientation than storm event conditions which have a larger influence on coastal stability. Climate change is likely to force a continued poleward expansion of the tropics which would maintain a strong coupling between the southeast Australian shelf and ENSO (Allen et al., 2014). The poleward expansion of the tropics impacts storm type distribution, wave direction, headland bypassing and regional longshore transport. Although the issue has been studied extensively, there is no consensus on exactly how a warming climate will influence ENSO (Mortlock and Goodwin, 2016).

While there is also no consensus on exactly how a warming climate will influence tropical cyclones, a continued expansion of the tropics would lead to a poleward shift in storm type, with more tropical origin storms than extra-tropical storms with a southern origin. Such an evolution would result in a significant reduction of the net northward littoral sand transport that predominate on the north coast of New South Wales and efficiency in headland sand bypassing for headland-bay beach cells such as Letitia Beach (Goodwin et al., 2016). Goodwin et al. (2016) predicted a reversal in the direction of tropical storm driven longshore transport rates at the Central Coast by ~150% and a 30% reduction in net northward longshore transport from extra-tropical storms.

The observed morphological response at Letitia Beach to extended periods of low headland bypassing around Fingal Head shows significant landward translation of the shoreline position at the southern end of the beach. Likewise, an increase in high energy wave events linked to tropical storms arriving from more easterly directions would likely result in more frequent beach erosion along Letitia Beach. This in turn could be offset (to some extent) by sand exchange with the lower and upper shoreface during extreme wave events (Harley et al., 2021). An overall reduction in the northward longshore transport rates along Letitia Beach would likely result in a reduced supply to the TSB jetty at the northern end of the beach. During such periods sand pumping volumes may require adjustment to the reduced supply to avoid shoreline retreat adjacent to the jetty. However, the implications of reduced mechanical sand transport to the Gold Coast beaches would need to be considered.

5. Summary and recommendations

5.1 Summary

The report assesses the historic behaviour of Letitia Beach, a 3.6km long east-north-east facing beach in northern NSW. The Letitia embayment extends from Fingal Head on its southern end to the southern Tweed River training wall in the north and it’s beach is impacted by waves, tides, ocean currents, river flows, wind and human modification, all of which vary alongshore. Combined, these present an extremely complex and dynamic coastal 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 project areas’ sand budget, which maps historical sand volume changes in ten beach, two river entrance, four dune and five offshore sediment cells. These are used to derive 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, previous numerical modelling studies and/or coastal processes knowledge. 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. A quantified conceptual sand movement model was developed to link together the drivers and volumes of annual sand movement. A net northerly longshore transport is fitted to explain the contemporary observations of sand volume changes.

In agreement with previous studies, a long-term trend of accretion from 1960 to 1994 is evident across the full coastal profile along northern and central Letitia Beach. With commencement of

TSB operations in 1994 the sand volume along northern and central Letitia has been decreasing. In combination with TSB sand pumping operations at the Letitia jetty commenced in 2001, this trend was rapidly accelerated. Following completion of the supplementary increment phase in 2008, the sand volumes at the northern end of Letitia were found to fluctuate around a new equilibrium volume. At the central section of Letitia Beach, this new equilibrium volume was reached by 2011. The sand movements at the southern end of Letitia are dominated by natural beach volume fluctuations over short- and long-term cycles.

Due to its east to north-north-east coastline alignment exposed to east through south-east waves, Letitia Beach experiences predominantly northward longshore sand transport. The long-term net northward sand transport rates derived from the sand budget analysis herein suggest that these range from 528,000m^3/year from the southern end of Letitia Beach to 562,000m^3/year near the jetty. Sand supply to the southern end of Letitia Beach is predominantly controlled by intermittent headland bypassing processes around Fingal Head. Large scale climatic variability linked to ENSO, PDO and IPO was shown to result in interannual to decadal differences to the frequency and magnitude of headland bypassing. The key consideration for the sand budget at Letitia Beach is that during periods of reduced sand supply around Fingal Head the predominantly northward sand transport along Letitia Beach is maintained. Therefore, the sand supply to the central and northern section of Letitia is also somewhat maintained, resulting in a deficit of sand at the southern end (i.e., more sand moving north than coming in from around Fingal Head in the south). This sand deficit then results in a reduction of beach width and potentially upper beach erosion at the southern end of Letitia Beach. This natural cyclic process is evident (over multiple timescales) in the observed shoreline behaviour and volumetric survey assessment results. Fluctuations in the position of the shoreline up to around 70m linked to storm erosion and headland bypassing variability were observed.

Projected changes in the wave climate and sea level rise are expected to affect sand supply and morphological trends along Letitia Beach. With a projected anti-clockwise rotation in the mean wave direction a reduction in headland bypassing and net northerly sand transport is expected. This has considerable impacts on the sand supply into Letitia Beach and may result in increased variability in shoreline positions, particularly at the southern end. Further, the sand supply to the TSB jetty may be reduced, potentially requiring balancing sand pumping volumes with downdrift impacts to Gold Coast beaches.

5.2 Key assumptions and uncertainties

The approach adopted herein is reasonable and valid for estimating the coastal processes that are expected to be relevant to TSB operations and the associated effect on sand movements at Letitia Beach. However, it is important to recognise the assumptions underlining the estimates as well as the inherent uncertainties. It is recommended that these are considered when informing TSB operations and are communicated to the community and stakeholders. The key assumptions and uncertainties are outlined below:

- Analysed meteorological, coastal data and hydrographic surveys are representative of prevailing conditions at the time and some are influenced by anthropogenic changes to the coastal environment.
- Comparative volumetric analysis of available survey data has been used to estimate the sediment budget and the rates of sand movement. These estimates are therefore subject to the accuracy of these surveys as well as spatial and temporal gaps in the survey coverage.

- While the availability of regular surveys for the entire project period provided an excellent opportunity for this type of assessment, there remains some uncertainty in the accuracy, particularly for the older pre-TSB survey data. Nevertheless, due to the scale of processes within the study area identified from survey analysis, differences due to survey errors are considered minimal. The observed survey differences display a consistent pattern of large differences in discrete areas rather than small differences over large areas. Several surveys with quality and coverage issues were excluded from the analysis.
- Where limited survey was available for sections of the sediment cells, survey analysis was undertaken over shorter time periods which may result in higher uncertainties in estimated long-term averages. Where no data was available, literature values were adopted and/or justified assumptions were made.
- Uncertainty remains around projections for climate change impacts, specifically on a local scale.

5.3 Recommendations for future monitoring and management

It is further recommended to undertake on-going monitoring of key coastal and estuarine processes and sand movements to reduce the degree of uncertainty identified herein. As a minimum, the following monitoring recommendations are made:

- Continue Dreamtime Beach topographic and bathymetric surveys – recent TSB surveys have included this section of coast which provide valuable insights into the sand supply to Letitia Beach. Changes in headland bypassing frequency and magnitude may lead to significant impacts on the sand budget at Letitia Beach. Therefore, continuous monitoring with a view to build a long-term data set of the sand budget is recommended.
- Ongoing assessment of sand supply – undertake regular review of relevant data and targeted monitoring to understand current trends in sand supply to Letitia Beach and potentially forecast headland bypassing quantities for incorporation in TSB operations and management of Letitia Beach.
- Monitor/ assess potential changes to wave climate – undertake regular review of the measured regional wave conditions to identify any potential trends in the wave climate due to climatic cycles and/or climate change. Identification of such trends early will allow for proactive management of Letitia Beach.

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Appendix A: Sand budget analysis

Photogrammetry beach profiles

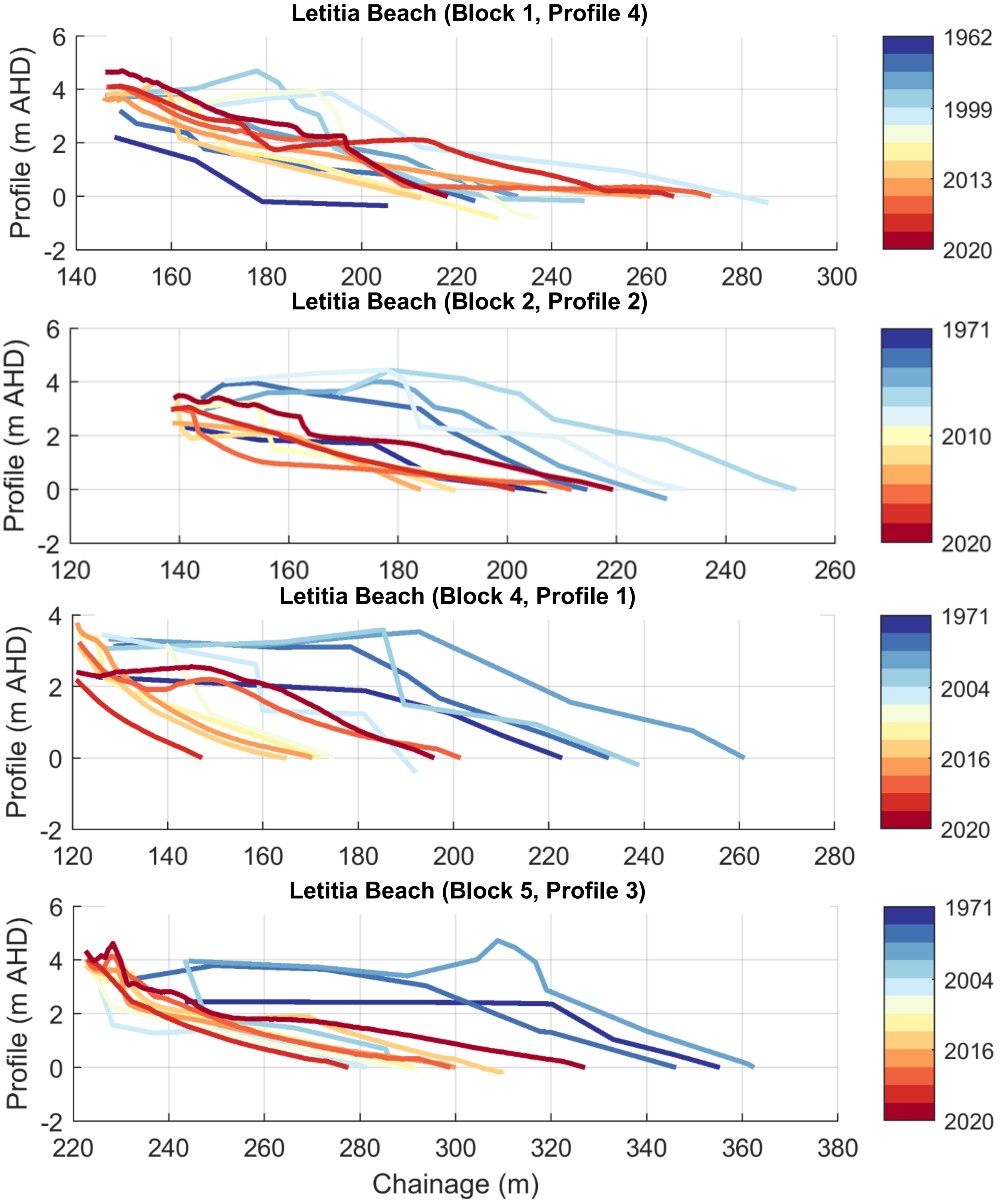

Figure 42: Selected photogrammetry profiles at Letitia Beach (top to bottom – south to north).

Volumetric analysis

$$\Delta V = LST_{IN} - LST_{OUT} + ON_{IN} + TSB_{IN} - DUNE_{OUT} - TSB_{OUT}$$

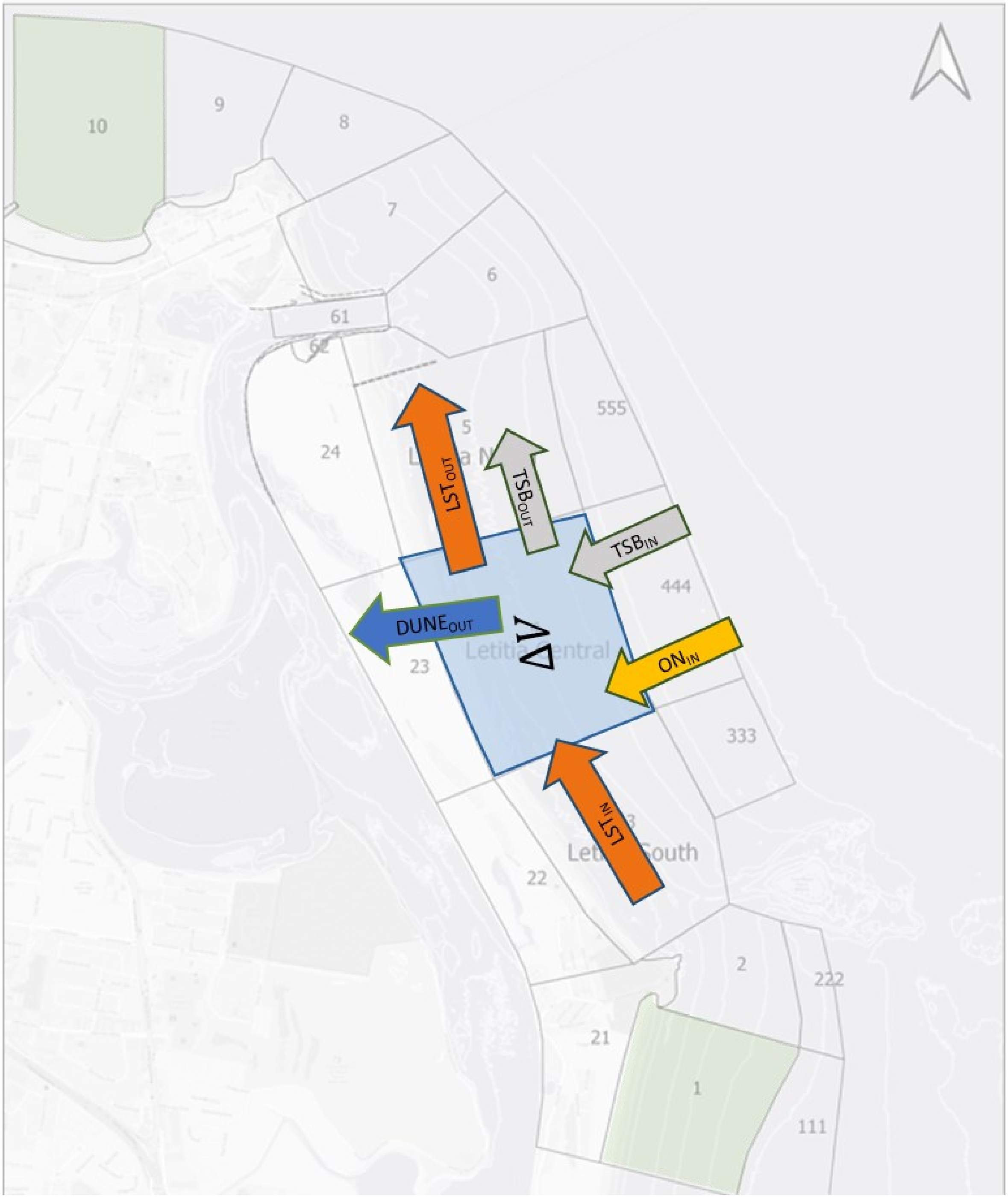

Figure 43: Volumetric analysis methodology.

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Table 8: Calculated volume difference in cubic metres (m^3) to 2021 baseline survey for key beach analysis cells.

	Cells										Letitia Beach (total)
	1	2	3	4	5	6	7	8	9	10	
Area (m^2)	***637,916***	***348,808***	***873,190***	***1,030,041***	***981,379***	***496,622***	***536,399***	***353,408***	***417,639***	***905,875***	***2,884,610***
Dec-60	-	-	-	-	-832,880	-1,336,464	221,645	-	-	-	-
Jan-66	-	-	-	250,845	-85,779	-1,104,198	-	392,165	404,852	287,649	-
Jun-94	-	-	426,834	1,898,936	1,359,968	126,256	607,417	115,718	-77,943	-707,829	3,685,738
May-95	-	-	126,238	1,796,354	1,460,859	286,273	700,019	146,292	31,329	-14,664	3,383,451
Jun-96	-	-	318,885	1,728,136	1,224,705	-970,119	273,683	116,136	204,698	97,646	3,271,726
Feb-97	-	-	179,006	1,813,846	1,209,697	-1,058,872	3,619	183,690	214,522	157,356	3,202,549
Sep-97	-	-	238,987	1,861,099	1,202,555	-961,231	40,161	84,513	156,089	189,421	-
May-98	-	-	100,828	1,884,325	1,104,483	-1,197,947	-33,591	244,651	238,670	246,768	3,089,636

	Cells										Letitia Beach (total)
	1	2	3	4	5	6	7	8	9	10	
Mar-00	-	-	131,816	1,630,304	896,147	-591,171	161,445	128,321	166,196	167,844	2,658,267
Jan-01	-	-	270,175	1,663,935	820,004	-711,834	88,362	331,426	157,950	239,484	2,754,113
Aug-01	-	-	158,538	1,550,352	495,916	-716,957	67,459	212,886	402,076	491,795	-
Dec-02	-	-	243,176	1,349,245	-9,115	-727,138	-13,403	277,353	376,104	1,007,653	1,583,305
Nov-03	-	-	350,528	1,030,133	-119,851	-503,428	115,506	208,302	380,592	951,405	1,260,811
Oct-04	-	-	71,454	1,071,397	-193,604	-590,041	-61,583	225,660	236,017	800,274	949,248
Jul-05	-	-	-112,678	962,831	-188,755	-482,604	-160,289	192,192	178,060	719,663	661,399
Aug-06	-	-	-140,247	782,288	-296,425	-572,699	-65,937	221,133	249,930	545,389	345,615
Sep-07	-	-	-	-	-	-384,415	-386,682	167,066	313,873	739,719	-
Oct-08	-	-	-276,686	608,206	-19,911	-482,680	-96,311	88,126	157,445	558,762	311,609
Aug-09	-	-	-331,869	382,288	-16,173	-421,564	-103,041	57,921	153,946	378,389	34,246
Oct-10	-	-	-341,506	237,755	26,233	-328,418	-187,607	25,935	79,737	287,339	-77,519

	Cells										Letitia Beach (total)
	1	2	3	4	5	6	7	8	9	10	
Nov-11	-	-	-216,377	91,657	76,866	-	-283,146	-28,769	134,769	308,012	-47,853
Sep-12	-	-	-210,275	165,687	124,359	-152,443	-102,287	-6,165	121,174	117,258	79,771
Aug-13	-	-	-226,462	43,507	74,699	-259,342	-87,971	9,893	73,224	-4,697	-108,255
Dec-14	-	-	-205,159	-32,934	-87,736	-157,094	-199,144	24,755	20,166	162,220	-325,829
Jun-15	-	-	-104,461	-56,332	-81,003	-82,875	-229,905	-83,727	-8,575	72,905	-241,795
Jul-16	-	-	-205,644	-367,855	-367,845	-	-	-	79,266	319,011	-941,344
Jul-17	-	-	199,760	-165,994	-91,373	-54,511	79,629	13,307	3,301	-41,191	-57,607
2018^	109,096	74,380	384,314	122,668	-36,830	-51,945	81,429	-	-	-	470,152
Mar-19	277,727	194,499	493,840	207,481	-	-	-	-	-	-	-
Apr-19	-	72,070	230,004	-88,462	-110,993	-151,024	-95,203	-30,246	41,395	27,485	-
Jun-19	276,328	251,229	369,013	-	-	-	-	-	-	-	-
Jul-19	305,400	197,618	319,084	107,344	-	-	-	-	-	-	-
Oct-19	-	72,004	228,121	-87,243	-	-287,819	-116,555	29,725	152,692	14,769	140,878
Dec-20	22,694	2,675	214,497	24,898	-91,758	-114,502	-84,071	-3,715	55,986	178,771	147,637
Jun-21	-	-	-	-	-	-	-	-	-	-	-

Note: ^Specific survey date for 2018 LiDAR data was not available

Table 9: Calculated volume difference in cubic metres (m^3) to 2018 baseline LiDAR survey for dune analysis cells.

Year	Dune cell			
	21	22	23	24
AREA (m^2)	*430,120*	*415,949*	*448,508*	*635,000*
Mar-09	-	8,620	29,463	-30,313
Sep-13	-1,699	18,616	27,236	-14,905
2018^	-	-	-	-

Note: ^Specific survey date for 2018 LiDAR data was not available

Table 10: Calculated volume difference in cubic metres (m^3) to 2021 baseline survey for offshore and river analysis cells.

Year	Offshore cell					Tweed River cell
	111	222	333	444	555	61
AREA (m^2)	*296,351*	*127,290*	*280,663*	*496,139*	*329,893*	*90,503*
Dec-60	-	-	-	-	-	369,423
Jan-66	-	-	-	-	-	
Jun-94	-	-	-	-	-	123,917
May-95	-	-	-	-	-	125,560
Jun-96	-	-	-	-	-	123,074
Feb-97	-	-	-	-	-	91,923
Sep-97	-	-	-	-	-	108,484
May-98	-	-	-	-	-	76,272
Mar-00	-	-	-	-	-	86,159
Jan-01	-	-	-	-	-	91,135
Aug-01	-	-	-	-	-	74,189
Dec-02	-	-	-	-	-	32,215
Nov-03	-	-	-	-	-	76,160
Oct-04	-	-	-	-	-	46,577

Year	Offshore cell					Tweed River cell
	111	222	333	444	555	61
Jul-05	-	-	-	-	-	59,697
Aug-06	-	-	-	-	-	35,946
Sep-07	-	-	-	-	-	40,545
Oct-08	-	-	-	-	-	43,618
Aug-09	-	-	-	-	-	29,653
Oct-10	-	-	-	-	-	15,192
Nov-11	-	-	-	-	-	-
Sep-12	-	-	-	-	-	43,737
Aug-13	-	-	-	-	-	29,822
Dec-14	-	-	-	-	-	3,309
Jun-15	-	-	-	-	-	12,113
Jul-16	-	-	-	-	-	-
Jul-17	-	-	-	-	-	-
2018^	25,698	-7,561	52,242	108,094	36,118	14,628
Oct-19	-	-	-	-	-	-15,618
Dec-20	21,112	5,975	5,576	-4,497	-2,963	-14,386
Jun-21	-	-	-	-	-	-

Note: ^Specific survey date for 2018 LiDAR data was not available. Further, visual inspection suggests that the accuracy of the LiDAR data for the deeper part of the coastal profile (-14 to -20mAHD analysed here) is doubtful, hence this was excluded from the sand budget analysis.