City of Newcastle

Stockton Bight Sand Movement Study

Report for 2020/194Q

Report #: P19028_R4.00

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Executive summary

Stockton Beach is located on a sand peninsula immediately north of one of NSW's largest coastal rivers, the Hunter River. It is a highly dynamic coastal environment and has experienced numerous coastal erosion events requiring, the construction of a range of temporary (e.g. sandbagging) and permanent protection measures. While historical analysis of erosion at Stockton suggested a cyclic nature of beach erosion and recovery, in recent years erosion has progressed beyond the extents of historical cycles. The erosion is impacting beach amenity and coastal assets. In recognition the NSW Government has declared Stockton Beach a 'Significant Open Coast Location' or coastal erosion 'hot-spot'. The governments (local and state) are seeking a long-term solution to coastal management at Stockton Beach.

Coastal management strategies are often expensive and robust scientific knowledge is essential for effective coastal planning. To fully appreciate the dynamics at the southern end of Stockton Beach, an understanding of the entire sediment compartment is needed. A sand movement study of the entire Stockton Bight sediment compartment has been completed in accordance with the NSW *Coastal Management Act 2016*. This technical study forms a major part of Stage 2 investigations as outlined by the NSW Coastal Management Manual.

The report covers a 32km long beach (NSW's longest beach), the largest active dune system in Australia, one of the highest wave energy beaches in NSW and a beach that grades from highly developed in the south to natural along its central and northern sections. It is a beach that is impacted by waves, tides, river flows, wind and human modification, all of which vary alongshore. Combined, these present an extremely complex and dynamic natural system that within and through which, there is considerable sand movement.

The study adopts a data-driven approach. At its centre is an analysis of the Bight's sand budget, which maps historical sand volume changes in ten beach and three dune sediment cells. These are used to infer the rates and directions of sand movements. The most likely drivers for the observed sand volume changes are described based on observational data, previous literature, state-of-the-art numerical modelling and/or coastal processes knowledge. 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. Recommendations are made where this uncertainty could be reduced with improved data which would in turn would improve the quantification of the sand budget.

A quantified conceptual sand movement model was developed to link together the drivers and volumes of annual sand movement (see figure below). A net northerly longshore transport is fitted to explain the contemporary observations of sand volume changes. The southern Stockton Bight shows a net erosive trend while the northern area and dunes show a net gain in sand volumes. The pivot point of this trend was found approximately mid-way along the Bight where the shoreline turns more to the east. The highest annual net north-eastward sand transport rates were found adjacent to Fort Wallace which are gradually decreasing with alongshore distance in updrift and downdrift direction. Bypassing of sand around Birubi Point at Anna Bay was estimated to be around 44,000m^3/yr.

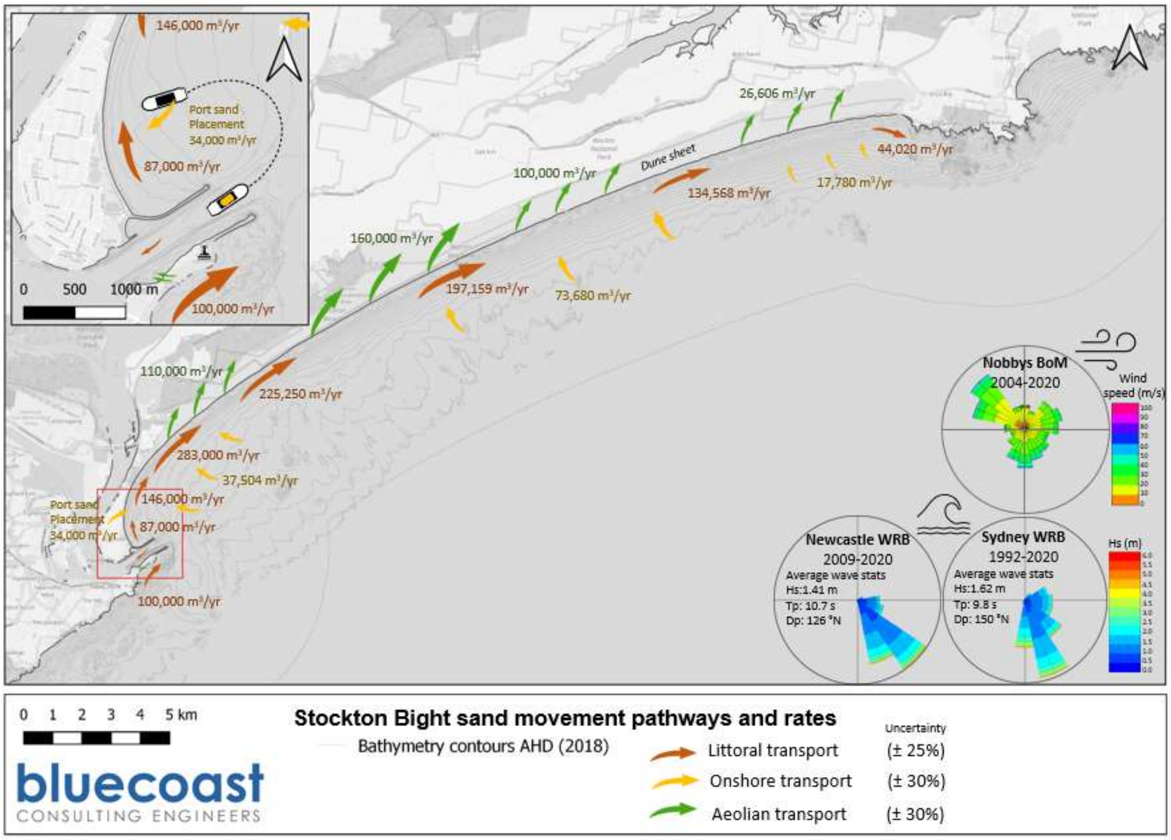

Figure showing the quantified conceptual model of sand movements in the Stockton Bight.

The most complex part of the system is the southern area around the river entrance, Nobbys Head and Stockton Beach area. Considerable attention has been paid to sand sources and sinks including the impact of the entrance training breakwaters, channel deepening and sand placements. Observations presented herein show a long-term deepening of the nearshore and a more recent realignment of the shoreline in the southern embayment between the northern breakwater and Fort Wallace. This agrees with the processes described herein that no natural sand bypassing from Nobbys Beach (northward) occurs and a net northward longshore transport or loss of sand occurs in the southern embayment of Stockton Beach. In contrast, previous literature (DHI, 2006) predicted a nodal point and divergent net sand movement directions with a net southward transport in the southern embayment. A nodal point and net southerly transport imply a depositional area in the southern corner against the northern breakwater or in deeper areas north of the northern breakwater. No significant depositional area is observed in the survey analysis and therefore the DHI (2006) conceptual model of sand movement in the southern embayment is not supported by the observations.

The observed deepening and realignment of the southern embayment is partly attributed to a significant reduction in the rate of sand bypassing the river entrance due to the construction of the breakwaters and deep navigation channel which, when combined represent a physical barrier to natural sand movement. The downdrift starvation of the southern embayment, until recently, is reasoned to have not been readily observable on the shoreline due to most change being attributed to the deepening of the nearshore and onshore sand supply to the Stockton shoreline from the relict ebb tide delta. The downdrift starvation is compounded by a second and more persistent pattern of coastal erosion/recession observed to the north of the southern embayment that is likely to be inherent to the Bight. The underlying cause of the inherent factors are reasoned to be the natural supply of marine sand to transgressive dune sheet. It is unclear if the clockwise rotation of the Bight is inherent or not.

Based on volumetric analysis of historical topographic and bathymetric surveys the long-term sand loss rate from the full coastal profile within the southern embayment of Stockton Beach (compartments 4 and 5 in Figure 50) is estimated as 112,000m^3/yr (±25%). This rate of sand loss is significantly greater than previously estimated and has implications for the on-going management of the coastal erosion issue at Stockton Beach. Without intervention the implications include chronic and worsening erosion which has already resulted in the loss of amenity and relocation of assets. There is a high potential for additional loss of amenity and assets. The scouring increases the risk of failure of the existing seawalls, wave overtopping of these seawalls and continued downdrift erosion as well as an increased risk of breakthrough of the peninsula.

The increased understanding of the Bight's contemporary sand budget and sand movements provides the basis for improved evidence-based decision-making in coastal risk management and planning along Stockton Beach. The work can also be used to increase the confidence in shoreline change forecasts under future climate and sea level rise scenarios.

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1 Introduction

1.1 General

The City of Newcastle (CN) is seeking to understand sand movements within the Stockton Bight coastal sediment compartment and has engaged Bluecoast Consulting Engineers to prepare a sand movement study of the entire Stockton Bight. This technical study forms a major part of Stage 2 of the Newcastle Coastal Management Program (CMP) for the high-risk coastal vulnerable area of Stockton Beach (see Figure 1).

The Newcastle CMP is being prepared in line with the Coastal Management Act 2016 (the Act) and the NSW Coastal Management Manual Part A (the Manual). In accordance with the Act, it takes a sediment compartment wide approach with the study area extending from Nobbys Head to Birubi Point.

Shifting Sands at Stockton Beach (Umwelt, 2002), Stockton Beach Coastal Processes Study Stage 1 (DHI, 2006) and the Stockton Beach - Coastline Hazard Study (DLWC, 1995) included assessments of sand movements but analysis was confined to the southern end of Stockton Bight within the CN LGA. The earlier Sediment Movement in Newcastle Bight (Public Works Department, 1977) study lacked the benefit of contemporary data. The Scoping Study (Stage 1) of the Newcastle CMP (CN, 2019a) identified sand movement patterns within the entire Stockton Bight, particularly changes to the subaqueous (under water) part of the coastal profile, as a key knowledge gap which was explored as part of Stage 2.

This report sets out the findings of the Stockton Bight sand movement study. The study uses a data-driven approach to quantify the pathways and rates of sand movement in the Bight and describes the underlying coastal processes driving the observed changes. Through informing Stages 3 to 5 of the CMP, the study ultimately seeks to inform sound coastal management at Stockton Beach.

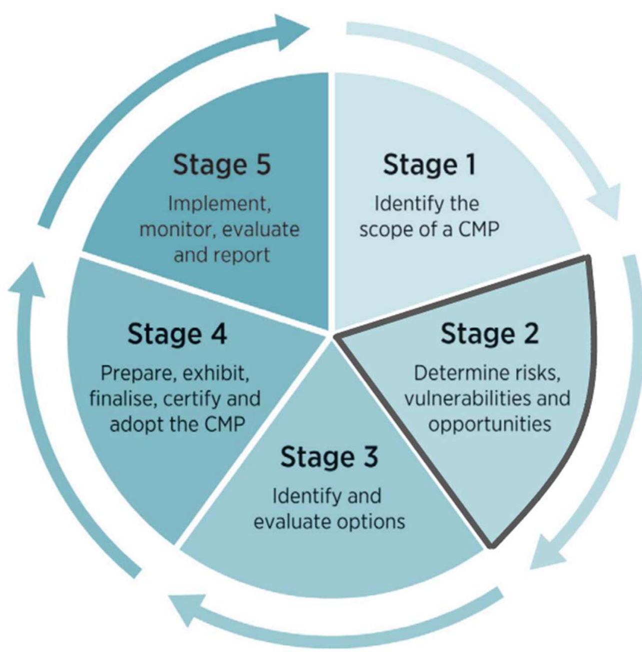


Figure 1: Stages in preparing and implementing the Newcastle CMP, this study forms a major component of Stage 2 (source: NSW Government).

1.2 Study objectives

The objectives of the Stockton Bight sand movement study are to:

- analyse and quantitatively describe the coastal processes and sand movement patterns within the Stockton Bight coastal sediment compartment, and
- analyse and describe changes to the subaqueous profile of the Stockton Bight sediment compartment.

1.3 Study context

Due to a time constraint imposed by Ministerial direction to complete the Stockton CMP by 30th June 2020, CN prepared a CMP specifically for Stockton Beach. The area included in the Stockton CMP is the area north of the Stockton Breakwater (northern training wall of the Hunter River) to Meredith Street, Stockton. Initial critical elements of the Bight study were brought forward to inform the Stockton CMP. These initial findings were documented in the supporting documents titled Sand Movement Study and Probabilistic Hazard Assessment. However, it was always the intention of CN that the full Bight sand movement study would be used to inform the Newcastle CMP. As outlined below, this report incorporates these initial findings and expands the analysis to cover the entire Stockton Bight coastal sediment compartment as encouraged by the *Coastal Management Act 2016*.

The Stockton CMP outlines a plan for mass sand nourishment to return amenity and access to the beach, while also establishing a sand protection buffer between the ocean and public assets. Acknowledging that the mass sand nourishment from offshore sources is currently not permissible without a permit a range of interim measures are also outlined in the program. These include interim sand nourishment from terrestrial (or other permissible) sources, construction of terminal protection structures to formalisation the existing sand filled geotextile bag emergency works located at the southern and northern end of both the Surf Life Saving SLSC and Mitchell Street seawalls, maintenance of existing seawalls and implementation of emergency actions as permissible and set out in the subplan (CN, 2020).

The NSW Deputy Premier formed the Stockton Beach Erosion Taskforce (the Taskforce) in June 2020. The Taskforce was established to drive the implementation of the sustainable long-term solutions to the coastal erosion issues for Stockton Beach within the framework of the CMP. Key areas of focus encompass investigation of options for sand sourcing including onshore and offshore sources, actions to mitigate loss of community amenity from engineering solutions and seeking the priority capital and operational funding required. Its membership consists of representatives from CN, the Worimi Aboriginal Land Council, Department of Planning, Industry and Environment (DPIE), Department of Regional NSW, Port of Newcastle, NSW Coastal Council and community representatives.

The Stockton CMP was certified by the Minister for Local Government on the 31st July 2020 and gazetted by CN on the 7th August 2020. It is the first CMP to be certified by the NSW Government. Following the completion of the Bight sand movement study the coastal management strategy and actions in the Stockton CMP will be reviewed during development of the Newcastle CMP. Opportunities to further enhance or improve coastal management of Stockton Beach will be identified (CN, 2020).

1.4 Study approach and scope of this report

Coastal management strategies are often expensive and robust scientific knowledge is essential for effective coastal planning. To fully appreciate the dynamics at the southern end of the Bight, an understanding of the entire sediment compartment is needed. This holistic approach to considering coastal processes on a compartmental basis is in accordance with the NSW *Coastal Management Act 2016*.

The report covers an extremely dynamic and active coastal sediment compartment. It includes NSW's longest beach, the largest active dune system in Australia, one of the highest energy beaches in NSW and a beach that grades from highly developed in the south to natural along its central northern sections. It is a beach that is impacted by waves, tides, river flows, wind and human modification, all of which vary longshore. Combined, these present an extremely complex and dynamic natural system that within and through which, there is considerable sand movement.

The study adopts a data-driven approach. At its centre is an analysis of the Bight's sediment budget, which maps historical sand volume changes in ten beach and three dune sediment cells. These are used to infer the rates and directions of sand movements. The most likely drivers for the observed sand volumes changes are described based on observational data, previous literature, state-of-the-art numerical modelling 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 noted with uncertainty quantified with error bars on some of the findings and recommendations made where these errors could be reduced with improved data which would in turn improve the quantification of the model.

The report is set out as follows:

- Section 2 provides background information including a critical review of previous literature on coastal processes in Stockton Bight, a timeline of key anthropogenic changes and a list of the existing data that has been utilised.
- A geological and geomorphic description of the Bight, including the sand dunes is provided in Section 3.
- The Bight's metocean conditions covering wave climate, water level variations, wind regime and river and tidal flows are set out in Section 4.
- Section 5 outlines the volumetric analysis of topographic and bathymetric surveys to establish observed historical changes in sand volumes as well as the Bight's sediment budget.
- Development and detailed explanation of a quantified conceptual sand movement model is provided in Section 6.
- Finally, Section 8 contains a summary along with recommendations.

The history of long-term sand loss from the coastal profile at Stockton Beach is considered a pivotal piece of information in understanding the patterns of sand movement within Stockton Bight.

1.5 Statement of assumptions and uncertainty

The approach developed herein is reasonable and valid for estimating the Bights sediment budget, sand movements and underlying coastal processes. However, it is important that decision-makers recognise the assumptions underlining the estimates as well as the inherent uncertainties. The key assumptions and uncertainties are outlined in Section 8. It is further recommended that CN:

- communicate the assumptions and uncertainties to the community and stakeholders
- seek to reduce the degree of uncertainty through on-going monitoring of the full coastal profile at Stockton, nearshore coastal processes (wave, currents etc) and sand movements.

2 Background information

2.1 Introduction

Stockton is the longest beach in NSW. It extends almost 32km from Birubi Point in the north to the mouth of the Hunter River in the south. It occupies Stockton Bight, also known as Newcastle Bight. For most of its length the beach is well exposed to the dominant southerly waves (mean significant wave height of 1.6m) and south to west winds. Marine sand had blown up to 3km inland, building the largest continuous mobile dune systems in the Australia (Newcastle City Council, 2014).

Prior to European settlement the entrance of the Hunter River was characterised by shallow depths with a central channel less than six metres. Survey information from 1816 (see Figure 2) shows large sand shoals present both within the river entrance and on a large ebb tide delta adjacent to the northern side off Stockton Beach. These extensive sand shoals, drying in places at low tide, extended around 900m off a low sandy beach. Wave breaking would have predominately occurred over these shallow shoals which are likely to have also had various tidal channels. The low sandy beach on the northern side was part of a Stockton peninsula formed by a thick layer of unconsolidated sand deposits. The southern side of the entrance consisted of bedrock cliffs, rocky reefs surrounding Coal Island and patches of open water between Signal Hill and Coal Island (now Nobbys Head). In its natural state, the river entrance and particularly the northern side was a highly dynamic environment responding to waves, storms, tides and river flows including floods.

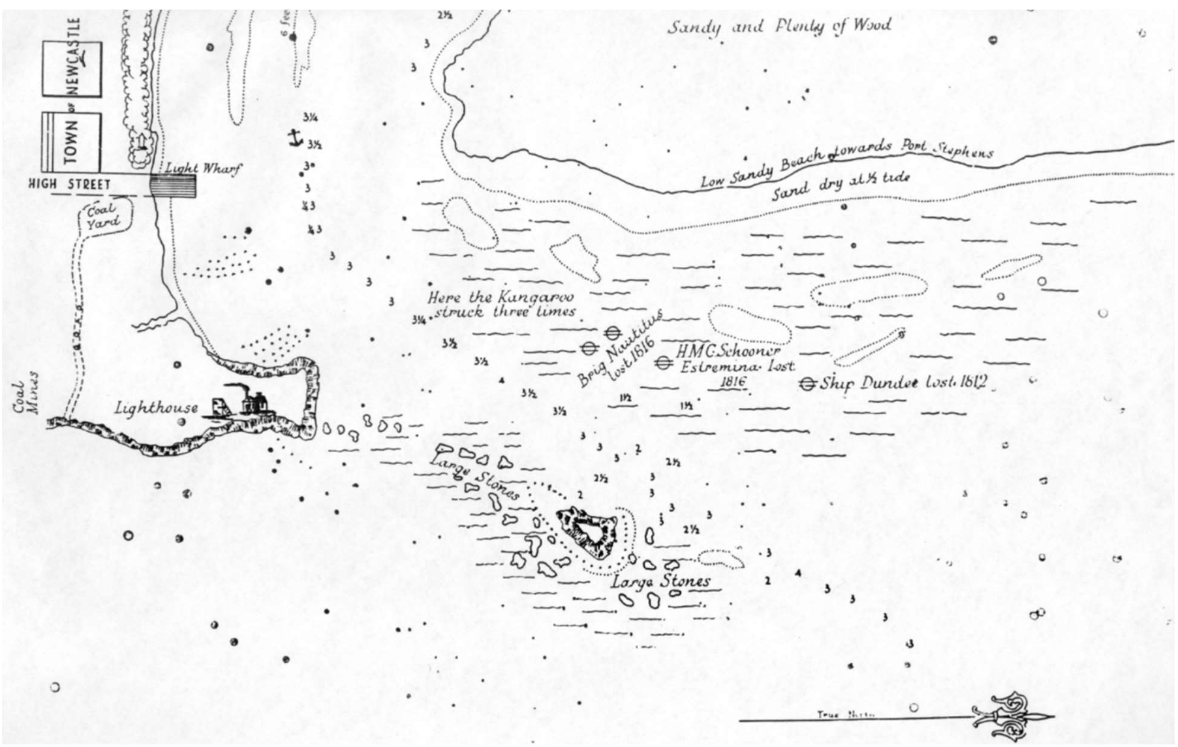


Figure 2: Hydrographic survey from 1816.

Large cyclical episodes of erosion/accretion have been prominent in the history of Stockton Beach. In the 1940s to early 1950s parts of Dalby Oval were lost and extensive erosion in front of Mitchell Street required rock to be routinely dumped as ad-hoc protection. Residents remember the beach growth of the 1960s when a beach backed by wide vegetated dunes existed seaward of Mitchell Street between the

War Memorial and Corroba Oval and sand banks were present in the nearshore. More serious erosion returned in the 1970s. During this period, the former extension of Mitchell Street north that joined up to Griffith Avenue and the circular road around the oceanside of the War Memorial were claimed by erosion. The fourth, most seaward Hunter Water treatment pond was destroyed by erosion during the May/June 1974 event. Following this beach recovery was observed with a relatively wide beach in the 1980's and early 1990's, for example, the Mitchell Street seawall that was completed in the late 1980s and it remained largely buried behind the beach, not taking its first waves until March 1995. This was during the extended swell activity and erosion resulting from Tropical Cyclone Violet.

Recently, the erosion has progressed beyond the extent of historical cycles. The present-day shoreline along Stockton Beach is at its most landward (receded) alignment since the breakwaters were constructed (see Section 6.1.6). The on-going coastal erosion has required the construction of a range of temporary measures (e.g. sandbagging and beach scraping) as well as relocation of assets like the caravan park cabins. Recognising this, the NSW Government has declared Stockton Beach a 'Significant Open Coast Location' or coastal erosion 'hot-spot'. The recent erosion, photos of which are shown in Figure 3 to Figure 6, leaves several CN assets at risk and has required a significant and on-going emergency response effort by CN. The erosion has been reported extensively in the media.

Figure 3: Cabins being removed from the caravan park due to beach erosion following a large wave event in February 2020.

Figure 4: Erosion scarp and failing emergency coastal protection works following an east coast low around the 15th July 2020 (source: CN).

Figure 5: Emergency coastal protection works underway in preparation for a second east coast low in late July 2020 (source: M. Bardsley).

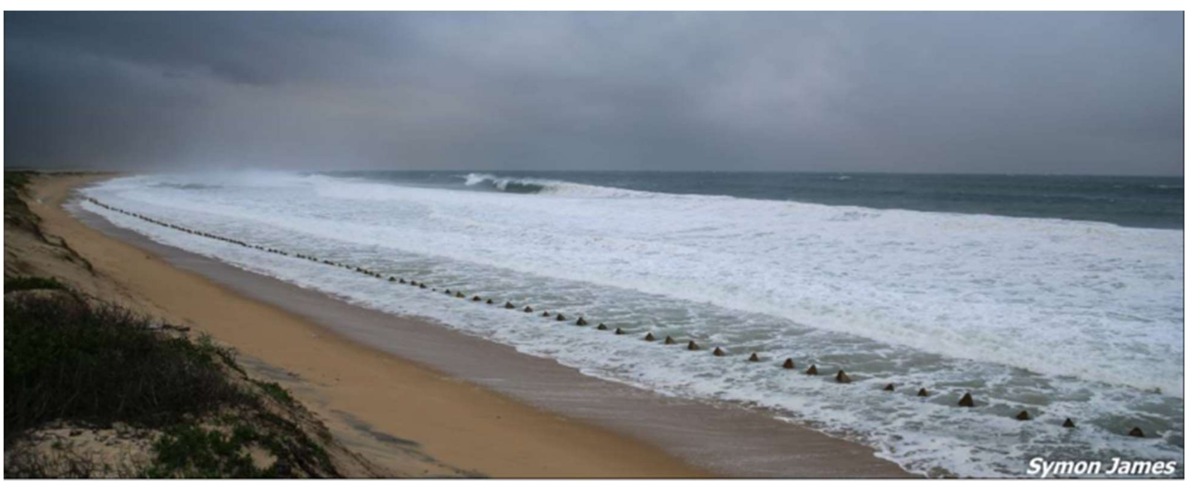


Figure 6: World war II tank traps uncovered by erosion north of the Hunter Water site (source: Symon James).

2.2 Historical timeline of human modifications

Stockton Beach and the adjacent Hunter River has been continually modified over the course of European settlement. Modifications that have impacted the beach response include the construction of the Hunter River breakwaters, capital and maintenance dredging of the navigation channel, seawall construction, beach nourishment, beach scraping and temporary, emergency and permanent protection works. Due to the Hunter River breakwater construction and navigation channel dredging the Hunter River entrance is now a formalised harbour entrance, preventing its natural migration. A summary of the key anthropogenic influences on the coastal processes at the study site is given in this section.

1818 The construction of the Macquarie Pier linking Nobbys Head to the mainland is commenced. Figure 7 shows depictions of Nobbys Head before Macquarie Pier was constructed. It is important to note the open water that formally existing between Signal Hill and Nobbys.

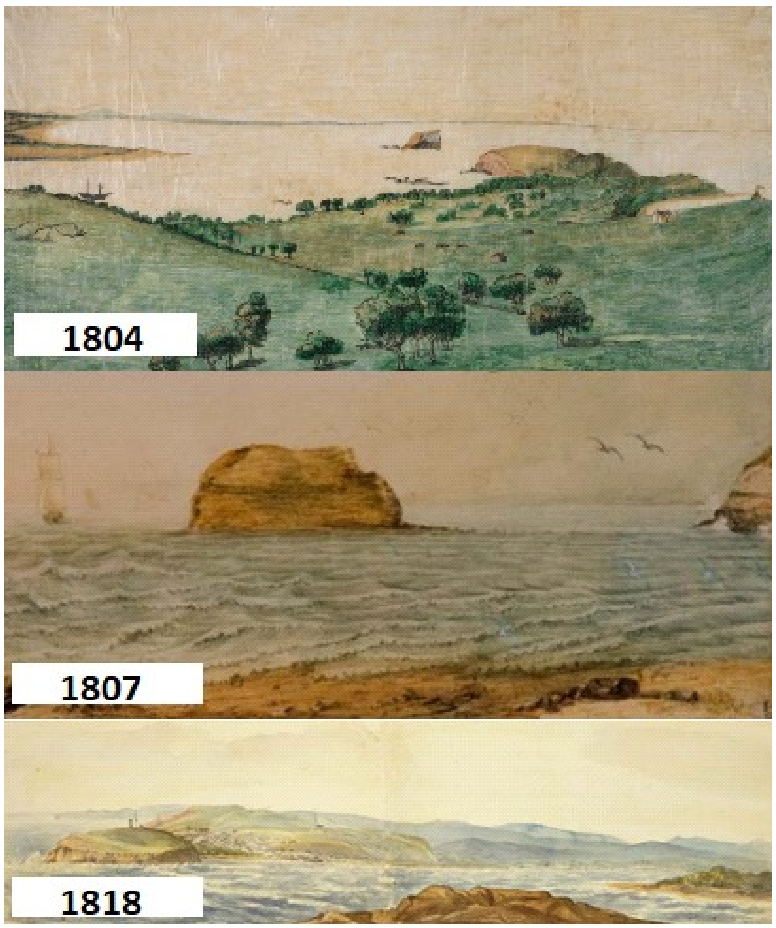
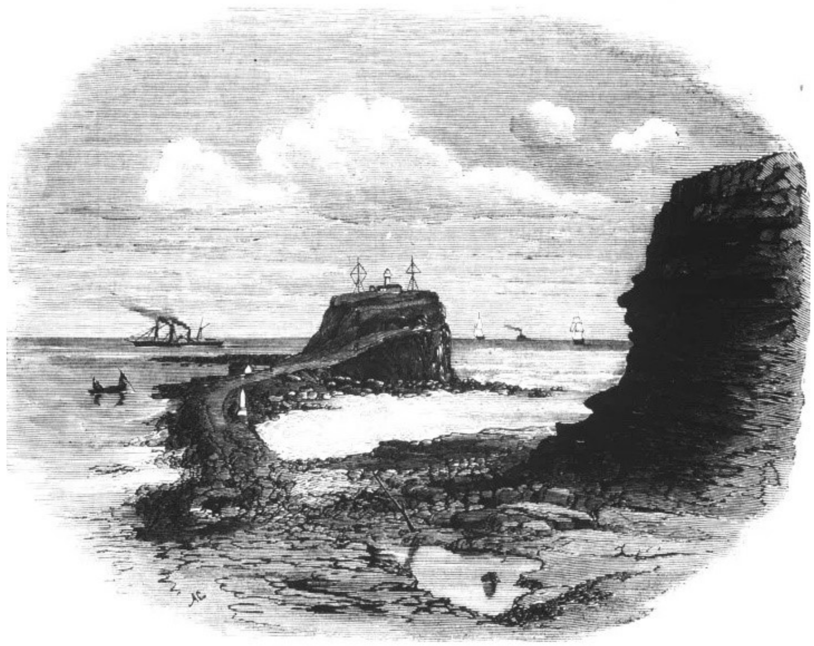


Figure 7: Nobbys Head and Signal Hill depicted in 1804 and 1807 (from the mainland) and 1818 (from atop of Nobby Head) before being connected to the mainland (Source: Dunn, 2020 & Hunters Living Histories, 2010)

1846 Construction of Macquarie Pier was completed, as depicted in Figure 8*: Nobbys Head and Macquarie Pier* , but continually breached by storms and wave action.



THE NOBBY ROCK, NEWCASTLE.

Figure 8: Nobbys Head and Macquarie Pier connecting it to the mainland at Signal Hill in 1871 (Source: Hunters Living Histories, 2017).

1859 Continuous dredging began using ladders dredges to remove mud, sand and surface rock.

Figure 9: Newcastle Harbour and Stockton, looking north in 1873. A ladder dredge (circled in blue) is illustrated in the centre of the harbour (Source: Hunters Living Histories, 2017).

1861 Work began on Pirate Point breakwater at the tip of Stockton peninsula (or sand spit) on the northern side of the entrance channel. Work was completed by 1866.

1875 The first breakwater extension beyond Nobbys Head continuing from Macquarie Pier was started. Work was completed by 1883. Over the years sand has accumulated in front of Macquarie Pier and the southern breakwater, creating Nobbys Beach as shown in Figure 10.

Figure 10: Macquarie Pier and the extension of the southern breakwater beyond Nobbys in 1887 (right) showing the build-up of sand in front of Macquarie Pier and the Southern Breakwater in 1998 (source: WBM, 1998).

1875 Extension to Pirate Point breakwater (northern breakwater) which was completed by 1896.

1888 ‘Berbice’ ran aground at Stockton Tuesday 5th June 1888, this shipwreck was one of a series of wrecks that have occurred in the entrance area of the Hunter River.

Figure 11: ‘Berbice’ wreck at Stockton 1888 and its position opposite the Stockton surf club in a 2017 aerial (Source: Hunters Living Histories, 2018).

1896 Work completed on Pirate Point breakwater.

1898 Work began on the new northern breakwater. The structure was later known as Shipwreck Walk in recognition of the wrecked vessels that were incorporated into the construction.

1914 Dredging at the entrance of the harbour increases depths to 24 feet 6 inches (~7.5 metres).

Figure 12: Newcastle Harbour entrance (looking south) with the completed northern breakwater and extension of the southern breakwater past Nobbys Head with Nobbys Beach and Horseshoe Beach to the west and east of Macquarie Pier looking south in 1934 (source: Hunters Living Histories, 2014).

1942 Tank traps were placed along Stockton Beach and other placed around Newcastle to fortify against invasion during World War II.

Figure 13: World War II Tank traps on Stockton Beach (source: Hunters Living Histories, 2014).

1952 A Dutch dredge carried out contract dredging 2,000,000 cubic yards (~1.5M cubic metres) of material.

1955 Almost 3,500,000 tons (~2.3M cubic metres[1]) of silt and sand was removed from Newcastle Harbour and the lower reaches of the Hunter River.

1962 Between 1962 and 1966 approximately 450,000 cubic metres of rock and 620,000 cubic metres of soft sediment were dredged. While most of the material was disposed offshore some of the dredged sand was placed on Stockton Beach via a pipeline (DHI, 2006).

1974 The ‘Sygna’ storm caused widespread erosion along the east coast, including the Newcastle beaches. The large swell caused the ship ‘Sygna’ which was anchored 4 km offshore to run aground parallel to the beach. After several failed salvage attempts only the bow section was recovered but the stern remains, at the time it was the largest shipwreck in Australia’s history (CoastalWatch, 2007).

Figure 14: The ‘Sygna’ ran aground at Stockton Beach in the 1974 storm event (source: CoastalWatch, 2007 and Wikipedia contributors, 2020).

1977 A contract was awarded for works required to deepen the harbour approaches to 17.7 metres and the harbour channels to 15.2 metres. Works were completed by 1983 and included the removal of approximately 2 million cubic metres of rock and over 8 million cubic metres of sand and clay was dredged from the main entrance to the port and dumped offshore for a total cost of $103,300,000 (NPC, 2014). A special harbour levy of $1 per tonne on overseas exports of coal and interstate imports of iron ore was used to fund the cost of channel deepening.

1989 The rock revetment at Mitchell Street (Figure 15) was constructed. This structure protects shoreward assets and property for approximately 600m of shoreline in the southern Stockton embayment.

Figure 15: Stockton Beach in (left) August 1998 looking south of Mitchell Street seawall and (right) Mitchell Street seawall at Stockton Beach July 1998 (Source: WBM, 1998).

[1] Conversion from tons to cubic meters using the density factor used in the 2013 NPC dredging report of 1.4 t/m^3.

1996 A geotextile sandbag wall was also constructed in front of the SLSC club which was the first modern geobag structure in NSW.

Figure 16: Construction of Geotextile seawall in front of the SLSC (Source: Carley, 2017).

2005 Maintenance dredging of 153,000 cubic metres of sand from the harbour entrance areas using TSHD Brisbane with the sand dumped offshore (DHI, 2006).

2007 A storm event on the 8th June 2007 led to the 'Pasha Bulker' running aground on Nobbys Beach. The Panamax bulk carrier was successfully refloated and moved offshore.

Figure 17: 'Pasha Bulker' grounded at Nobbys Beach in the June 2007 storm (source: Wikipedia contributors, 2020).

2009 Newcastle Port Corporation (NPC), begin placing clean sand of marine origin in the nearshore of Stockton Beach. This sand required dredging as part of their routine dredging operations to maintain the navigation channel. Due to the shorter sailing distance the practice offered operational and economic benefits to the port relative to disposal offshore.

2016 The rock revetment fronting the SLSC was constructed. This structure protects shoreward assets for approximately 145 m of shoreline in the southern Stockton embayment.

2019 A 100 metre seawall of very large geotextile container is built on Stockton Beach to protect Hunter Water land from coastal erosion (Figure 18).

Figure 18: Construction of sea wall in front of the Hunter Water site (Source: Newcastle Herald, 2019).

Given their relevance to sediment budgets at Stockton Beach, the human modifications above has been summarised into Figure 19. The beach nourishment volumes placed at Stockton Beach nearshore area during recent years are discussed in Section 4.1.1.

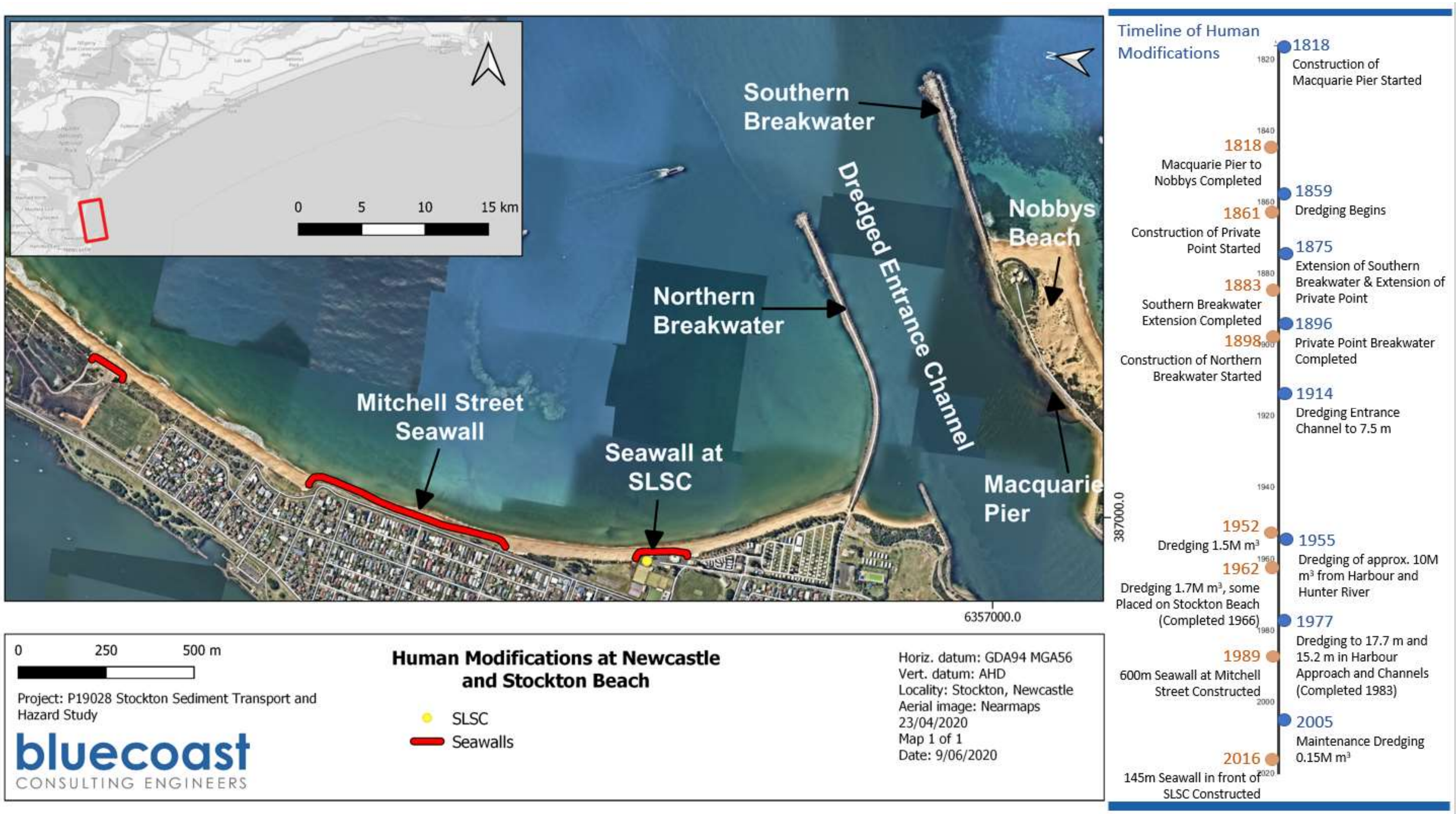


Figure 19: Timeline of notable human modifications at Stockton.

2.3 Introduction to coastal processes

The section provides a general overview of coastal processes. Section 4 presents a site-specific description of the coastal environment along Stockton Bight 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 (MLS) mark, in the intertidal swash zone, and in the deeper 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 three primary sources, offshore (swell), locally generated wind-waves (sea) and waves associated with low pressure systems. 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 from 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. Wind driven current can also occur due to wind set-up as currents are generated from gradients in water levels during strong onshore winds pushing surface waters against the coastline. The rate at which the wind increases in speed also affects water level elevation, with rapid wind speed acceleration leading to larger maximum water levels at the shoreline.
- **Nearshore currents** - generated from differences in waves, tides, water levels and winds and the interactions between the processes.
- **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 and winds as described above. Transportation in the nearshore zone is comprised of alongshore and nearshore transport which act concurrently and interact together.

- **Longshore sand transport** (also known as littoral drift) occurs across the surf zone due to waves approaching the beach from an oblique angle which generates radiation stresses, driving currents along the shore. The direction of sediment transport along the coast is dependent on the prevailing wave direction (i.e. transport north could occur during a south-easterly wave direction). Longshore sediment transport occurs inshore of the surf zone 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.

2.4 Summary of literature review

Stockton Bight has been the subject of numerous studies to assess coastal processes relevant to this sand movement study. A non-exhaustive list of the key previous studies used to inform this study is presented below along with a summary of the most up-to-date process understanding. In addition, the previous literature is referred to throughout this document wherever relevant to do so.

- The NSW Department of Public Works carried out an investigation called Littoral Drift in the Vicinity of Newcastle Harbour Entrance (PWD, 1966). The investigation used radioactive sand tracing to obtain information of the littoral drift in the vicinity of Newcastle Harbour entrance. The investigation was undertaken over a 3 to 4-month period in the winter of 1966. Based on sand tracing results the annual rate of sand bypassing the southern breakwater was 98,000m^3/yr (or 128,000 cubic yards) and the northern breakwater was 23,000m^3/yr. This second measure was determined from tracer placed on a growing shoal that was in the harbour entrance at the time.
- A major investigation of sand movement in the Bight was undertaken by the Public Works Department and reported in PWD's 1977 report. The report was undertaken as part of an overall feasibility study into the construction of an alternate deep-water port to augment existing harbour facilities at Newcastle. It was proposed to excavate this harbour in the area behind the beach of

Newcastle Bight and to connect it to the ocean with a dredged channel through the beach. For this purpose, an assessment of sediment movements in the area was required. Geology, surveys, calculation of gross and net littoral drift rates and analysis of windblown sand movements were used to infer a sediment budget for the Bight. The study found a closed sediment compartment (no movement around headlands, no contribution from the Hunter River or onshore sand supply) with high gross longshore transport but no net longshore transport and windblown losses that were assumed to account for the shoreline recession rates observed.

- Following the guidance set out in the 1990 NSW Coastline Management Manual the Stockton Beach - Coastline Hazard Study was prepared by the then Department of Land and Water Conservation in 1995 (DLWC, 1995). The report presents a comprehensive review of shoreline and sub-aerial beach volumes based on historical survey and photogrammetry data available at the time. Most relevant findings/observations to the present study are:
    - Overwash around Pembroke Street occurred in 1945 and 1952 and newspaper reports make mention of a “gap in the sandhills”, which is assumed to mean sand dunes. This area is noted as being almost directly inshore of the ‘Oyster Bank’. While not a finding of the 1995 report, regular overwash of this nature suggests an open coast barrier that is not in equilibrium with the wave climate (i.e. the low sandy beach barrier that was present prior to European settlement was in equilibrium with the lower swash zone wave climate afforded by the extensive sand shoals formed by the relict ebb tide delta).
    - The introduction of the southern breakwater produced a strong seaward realignment of the shoreline south of the SLSC.
    - Episodic storm erosion and recovery was observed in the sub-aerial beach with the most landward shoreline positions in 1952, 1946 and 1995.
    - Using the definition of long-term shoreline recession set out in the 1990 Coastline Management Manual[2] the study found no long-term recessional trend in the shoreline. That is, based on the sub-aerial data (i.e. upper beach above 0m AHD) only where there was no observable erosion trend.

  Importantly, the report did not examine changes in the sub-aqueous part of the coastal profile (i.e. below 0m AHD) using data that was available at the time. Had this data been examined for long-term changes across the full coastal profile, an erosional trend would have been identified.

- Stockton Beach Remedial Action Plan that was prepared by WBM Oceanics Australia in 1996.The interim protection works recommended in the plan, a geotextile sandbag revetment around the Surf Life Saving Club, were implemented.
- Hazard Definition Study prepared by WBM Oceanics Australia in 1998 was the first stage of the coastal management process. The study defined the hazards along the coastline and the coastal hazard lines which gave the projected landward limits of erosion for various planning periods.
- CN issued the Newcastle Coastline Management Plan (NCMP) for the 2000 Emergency Response and Interim Action Plan prepared by WBM Oceanics Australia. The plan recommends a comprehensive and detailed set of actions that covers the entire coastline of Newcastle.
- Shifting Sands at Stockton Beach, a 2002 study from Umwelt Pty Ltd. The study involved the digitisation of historical navigation charts around the Stockton Bight and calculation of the sand volume changes in the southern embayment. This study was the first to correctly identify the long-

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[2] This definition assumes that a net loss of sand across the active coastal profile (i.e. top of dune to depth of the limit of active sand movements) is evidenced by a progressive landward shift of the average long-term position of the shoreline (as defined by a contour on the sub-aerial beach). Coastal erosion is herein defined as the permanent loss of sand from the system (i.e. full coastal profile) and this is not assumed to be the same as variations in the shoreline.

term trend of deepening in the southern embayment. The 2003 Newcastle Coastline Hazard Definition Study was issued by CN from the Coastal Management Study and Plan undertaken by Umwelt Pty Ltd. The document was used to guide the sustainable management of the coastline. The study identified that the erosion at the study site is progressively worsening with analysis showing significant volumes of sand being lost from the beach and nearshore zones over the 10 years prior. The study also stated that additional investigations were required, which led to the 2006 and 2009 studies from DHI.

- An analysis of the coastal erosion process at Stockton Beach was undertaken by DHI in 2006 as Stage 1 of the Stockton Beach Coastal Processes Study. Results of numerical modelling of waves and currents and the resulting sediment transport at Stockton Bight was used to provide predictions of ongoing beach response and shoreline changes. The study gave annual longshore transport rates in the southern Bight ranging from 20,000 to 55,000 m^3/yr with longshore transport rates at Nobbys Head estimated as 33,000 m^3/y. The 2009 DHI Coastal Zone Management Study Report (Stage 2 of the Coastline Management Study) followed the 2006 Stage 1 report. It identified and suggested a preferred management option for Stockton based on findings from Stage 1 and modelling of the annual average and long-term shoreline responses for the various options. The assessment of management options identified that nourishment was needed in all options with capital beach nourishment volumes ranging from 410,000 m^3 to 515,000 m^3 and maintenance nourishment of up to 30,000 m^3/yr.
- A review of the environmental impacts of the maintenance dredging and placement of dredged material off Stockton was undertaken by Worley Parson in 2009. The document was prepared to provide the necessary approvals for the proposed dredging which involved the removal and disposal of up to 100,000 m^3 of maintenance dredge material over a placement area identified in in the nearshore of Stockton Beach. Sediment sampling and testing was undertaken during the assessment.
- Beach nourishment was incorporated into all management options identified by DHI 2009. Following this WorleyParsons was engaged by CN to review potential sources for nourishment. The Stockton Sand Scoping Study (Worley Parsons 2011) and Stockton Beach Sand Scoping and Funding Feasibility Study (Worley Parsons, 2012) identified the potential sources of sand for beach nourishment and provided a method and cost estimate of the works. Grain size analysis of sediment samples from Stockton Beach and offshore sources were tested. It was recommended that the spoils from maintenance dredging be used in ongoing sand nourishment.
- Regional NSW (2020) provided a desktop study of the marine sand bodies within the area that may be suitable for nourishment at Stockton Beach. The report issued in May 2020 reviewed previous offshore sediment sampling investigations. The study recommended an extensive offshore sampling program as little is known regarding the extent, thickness, continuity and uniformity of the material.

Both the DHI (2006) and Worley Parsons (2012) reported conceptual models of sand movements in the southern Stockton Bight area, see Figure 20. DHI's sand movement pathways were largely based on numerical modelling. Worley Parson's model was based on a synthesis of existing literature and therefore reproduce similar pathways to DHI's earlier work.

Overall, these models were explained by wave-driven currents along the coastline and that are influenced by the port structures which diffract waves from the southeast around the tip of the breakwater. The net northward rate of littoral drift transport from south of Nobbys Head was estimated to be 33,000 m^3/yr, with some of this sediment being deposited at the offshore sand lobe and the remainder bypassing Nobbys Head towards Stockton Beach with some deposited into the entrance of Hunter River (DHI, 2006).

A nodal point, or area where the net sand movement changes direction, was predicted at the northern end of the Mitchell Street seawall. Here the longshore transport splits in two directions northward and southward and this was assumed to be an underlying cause of the major erosion observed at the location of the nodal point (DHI, 2006). The analysis estimated an annual average net northward transport of 55,000 m^3/yr in the area north of the old Hunter Water treatment ponds for the period from 1992 to 2004.

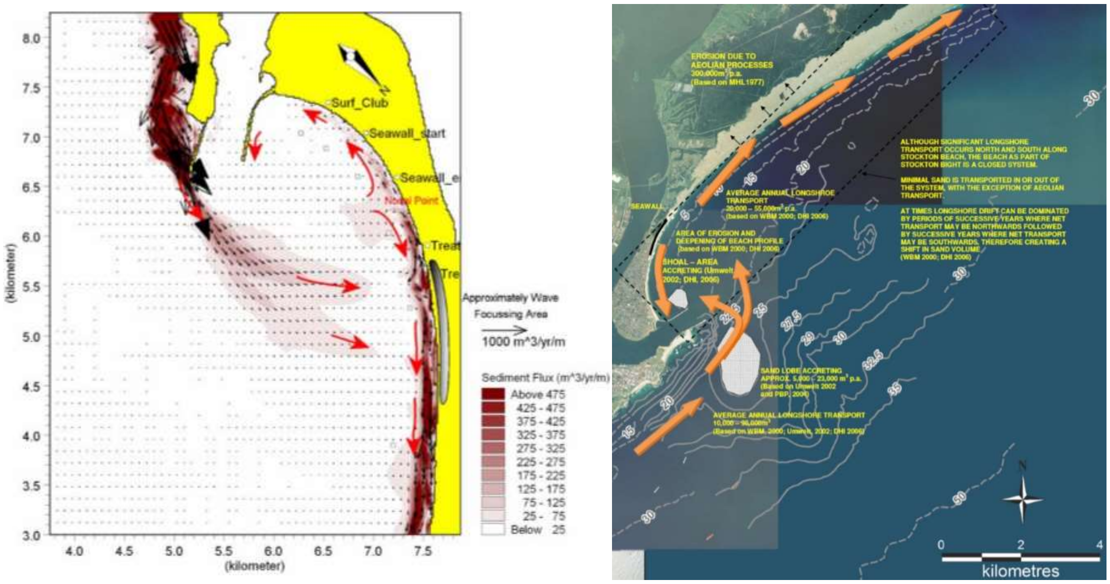

Figure 20: (right) Predicted annual sand movement for the southern Stockton Bight based on a typical yearly condition from 1992 to 2005 (source: DHI, 2006) and (left) conceptual model of sand movement along southern Stockton Bight (source: Worley Parsons, 2012).

2.5 Data used in this study

2.5.1 Existing data

This study follows a data driven or evidenced based approach using data kindly made available for use in the study. A summary of the extensive datasets used in the study is presented in Table 1. The locations for metocean instruments are displayed in Figure 30 (see Section 4.1).

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

ID	Description	Source	Dates
Topography and bathymetry	Coastal LiDAR (LADS) at 5 m resolution	DPIE	2011-13, 2018
	High-resolution topography (UAV/drone) and bathymetry (jetski) surveys from sand placement trial	CN	2019 and 2020
	Beach profile data (photogrammetry)	DPIE	1952 – 2020
	Hydrographic surveys from assorted periods and coverage extents	DPIE, Umwelt, CN, PoN	1816 - 2018
	Satellite Derived Bathymetry (SDB)	Bluecoast/Eomap	2010 and 2012
	CoastSat extracted shoreline positions from publicly available satellite imagery	CoastSat (Vos et al 2009)	32+ years from mid-1970's - present
Aerial imagery	High resolution, rectified aerial imagery	Nearmap	2020
	High resolution aerial images collected during CN UAV survey of Stockton Beach	CN	Various dates in 2019 and 2020
Water levels	Water levels from Stockton Bridge at a 15-minute measurement period	MHL	1984 - 2020
	Water levels from Sydney at a 15-minute measurement period	MHL	1987 – 2020
Waves	Measured wave heights, directions periods and directional spreading at Sydney and Crowdy Head directional WRB at a 1-hour sampling period	MHL	1992-2020 2011-2020
	Measured wave heights, directions and periods at Newcastle WRB at a 10-minute sampling period	PANSW	2009-2020
	Measured wave heights, directions and periods at Stockton and Worimi at a 30-minute sampling period	DPIE	Dec 2019-July 2020
	Measured wave heights, directions and periods at Stockton at approx. 13 m water depth.	Royal HaskoningDHV	Dec 2019-Feb 2020
	CAWCR hindcast of modelled wave heights, directions and periods offshore of Stockton at an hourly sampling period	CSIRO	1979-2020
Currents	ADCP measured currents at Stockton at 8 m water depth over four deployments offshore of the SLSC seawall.	Royal HaskoningDHV	Dec 2019 and Jan 2020
	ADCP measured currents at 8 m water depth offshore of Mitchell St seawall.	MHL	2001

ID	Description	Source	Dates
Winds	Measured wind speeds, directions at atmospheric pressure at 10 m for Newcastle Nobbys and Williamstown RAFF at three hourly, half hourly and one-minute sampling periods	BoM	1979-2020 (1 min since 2004 and 1999 respectively)

2.5.2 Satellite Derived Bathymetry

Due to the importance of repeat bathymetric survey to the development of the Bight sand budget and a lack of repeat survey coverage over the northern Bight, project specific bathymetric data was generated for this study using satellite derived bathymetry techniques. Standard satellite imagery can be used to derive shallow water bathymetry data (~water depth <30m) using physics-based algorithms and image processing techniques. These techniques have been deployed and validated world-wide over the last 15 years.

High resolution (2 metres) satellite imagery captured on the 31st December 2010 and the 24th August 2012 was purchased from EOMAP. The 2010 dataset covered the northern end of Stockton Bight and the 2012 dataset had a larger coverage with the stretch of coast between Newcastle and the northern end of Stockton Bight. Prior to purchasing the imagery, a visual review was undertaken to assess the quality for this purpose. The water clarity, imagery extent and water surface texture as well as no cloud cover provides an excellent opportunity for bathymetry conversion in the northern Bight. However, due to persistent poor water clarity in the southern most Bight accurate bathymetry could not be derived in the southern areas.

The nearshore morphological features in the study area are well represented in the 2012 bathymetry data. Maps showing the quality controlled SDB for the selected date are presented in Figure 21 and Figure 22.

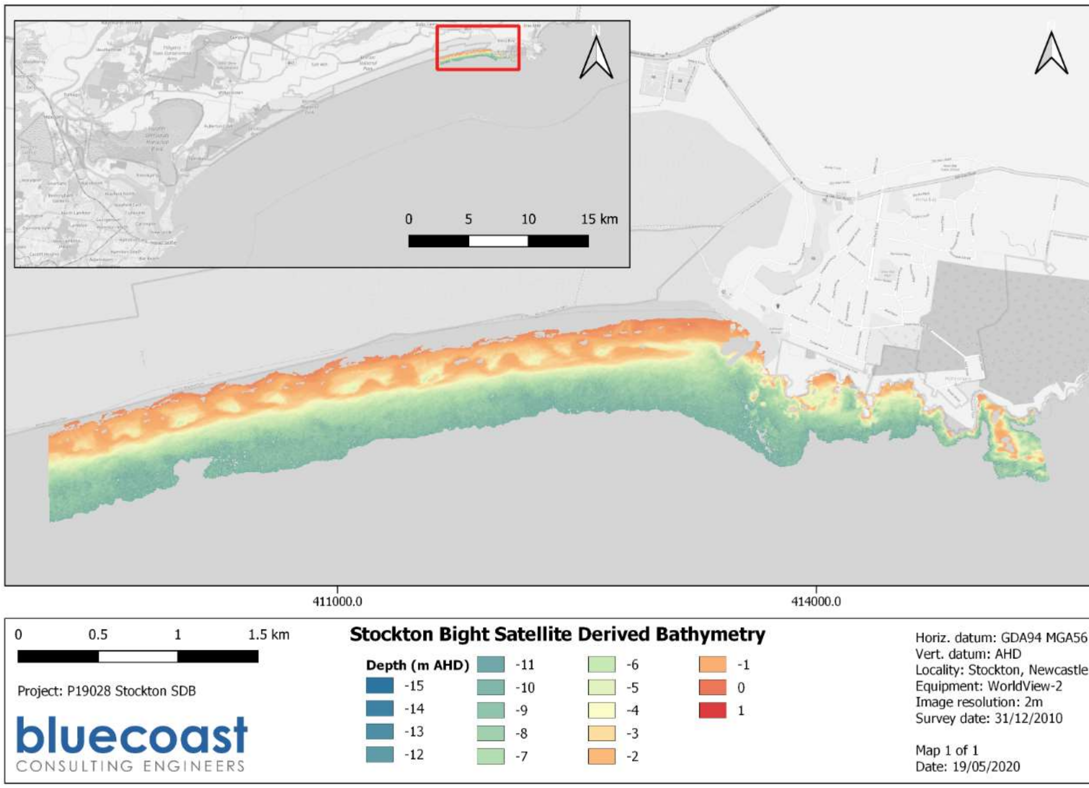

Figure 21: Map showing SDB at northern Stockton Beach on 31st December 2010.

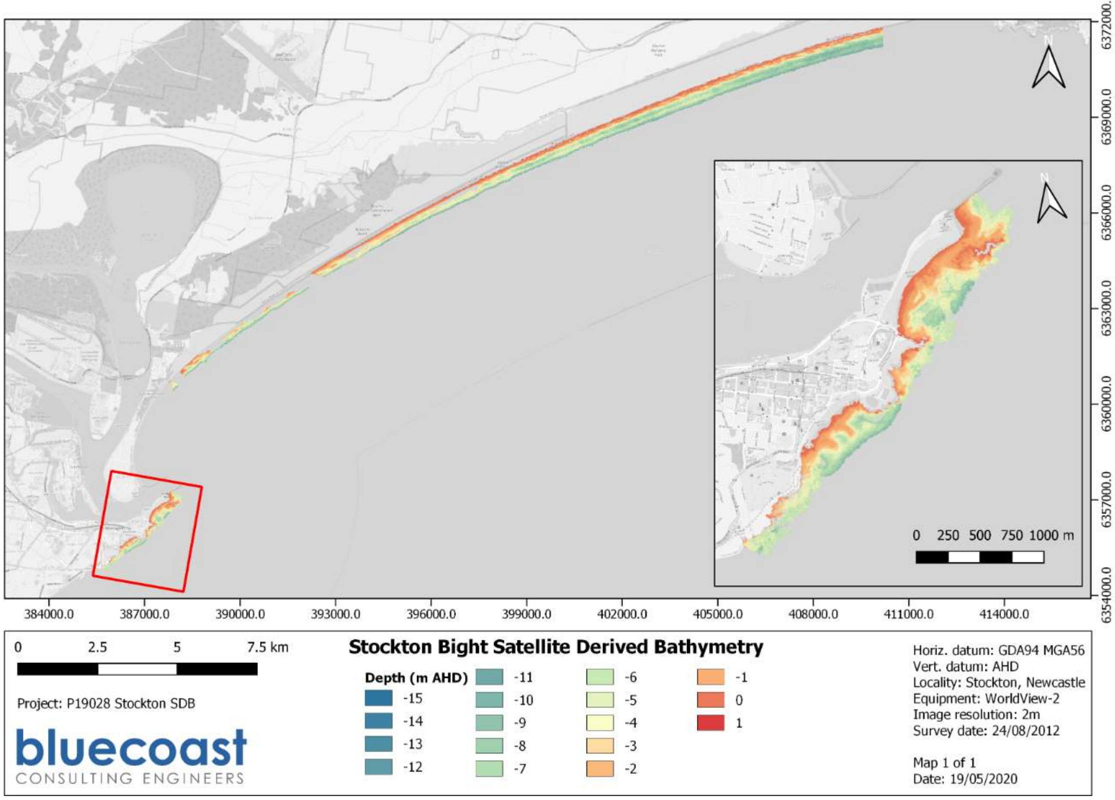

Figure 22: Map showing SDB at Stockton Bight and Nobby Beach on 24th August 2012.

3 Geological and geomorphic description

3.1 Introduction

Stockton Bight is a 31.8 km stretch of coastline in the Newcastle-Port Stephens area. It extends between the mouth of the Hunter River in Newcastle and Birubi Point in the north and is backed in part by Port Stephens, a drowned river valley. This section sets out a description of the local geology, seabed and dunes for the Bight as well as a description of the geotechnical and geophysical data available.

3.2 Local geology

3.2.1 Subaerial geology

The local geology of the Newcastle-Port Stephens area is a bedrock embayment filled with late Quaternary age marine, estuarine and fluvial sediments (Gordon and Roy, 1977). Figure 23 displays the location of two sandy barriers comprised of marine and aeolian deposits. The Pleistocene Inner Barrier (red and orange areas in Figure 23is above the current day sea level and was deposited during the last interglacial period and comprised of foredune ridges and longitudinal dunes (Cheng, 1978). The longitudinal dunes were formed from reworked foredune ridges during the last glacial period and are up to 30m height and 1-2km in length and are stabilised by vegetation. The Holocene Outer Barrier (green and yellow areas in Figure 23 shows sharp relief stabilised with vegetation (Cheng, 1978). It has undergone four phases of evolution. A regressive foredune ridge plain still visible in the north and south (light green), followed by three separate phases of dune transgression, The first two are now vegetated (dark green) with the present phase still active (yellow mobile sand). The transgressive dunes have buried most of the foredune ridges and the mobile dunes consist of a foredune, deflation basin and a field of mobile transverse dunes extending along most of the bight. These are described in detail in Section 3.4. The fluvial deposits are in tidal creeks and flats such as the Hunter River add a limited supply of sand sized sediment to the coast. Nobbys headland is an artificial tombolo at the entrance to the Hunter River in the south that was connected to the mainland via a breakwater in 1818 (see Figure 18).

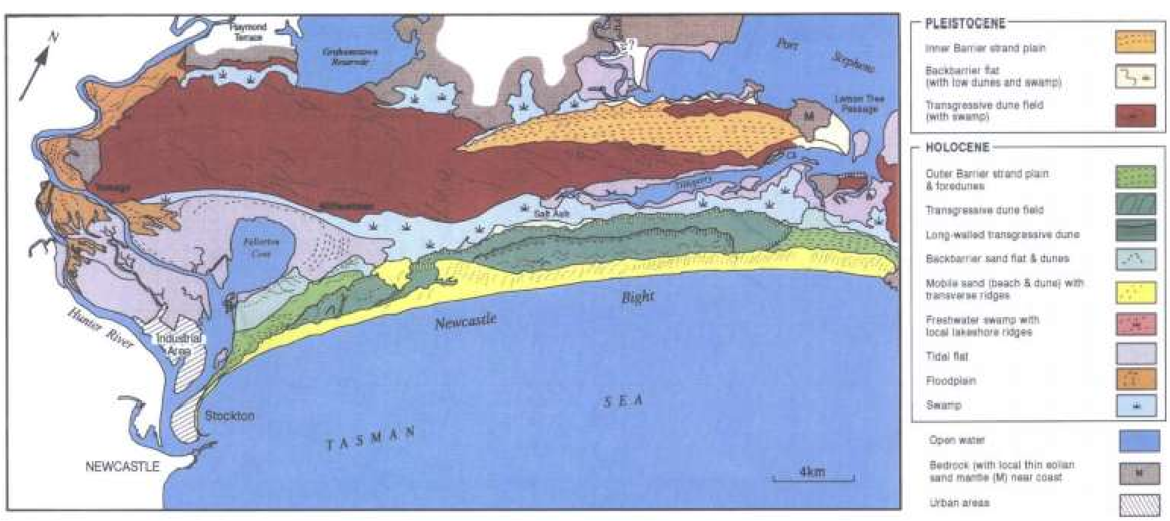

Figure 23: Geomorphology of the Newcastle-Port Stephens area (Source: Thom et al., 1992).

3.2.2 Submarine geology

Based on the work of Boyd, Ruming and Roberts (2004) the continental shelf and slope along the eastern seaboard can be classified into a variety of morphological units based on detailed analysis of geometry and slope. These units include a succession of shore-normal zones (shoreface, inner plain, inner and mid-slope, outer plain and continental slope) and a number of local regions (mounds, lobes, tongues, depressions, deltas and bedrock). Sediments are generally siliciclastic in composition on the inner margin and carbonate-rich on the outer margin, reflecting carbonate production at low sea-levels on the outer shelf/continental slope and terrestrial sediment input to the inner shelf. Fine-grained sediments are rare on the shelf north from Port Stephens and occur draped across the inner and mid-slope further south. Outer shelf carbonate sediments are coarse grained with a patchy distribution related to winnowing by the East Australian Current. The East Australian Current also produces erosional depressions and southward prograding sediment tongues and lobes where it separates from the shelf off Port Stephens. The margin character varies markedly from south to north in terms of fine-sediment distribution, depth to the shelf break and width of the outer shelf.

Stockton Bight is characterised by a steep nearshore out to 20m depth followed by 5-10km of gently sloping inner shelf out to 40-45m depth (Norman et al., 1992). Roy and Crawford (1980) characterised the inner continental shelf at Stockton Bight into four main zones, all parallel to the shoreline. In Figure 24 the four zones are defined as: the nearshore slope, the inner shelf plain, the inner shelf slope and the outer shelf plain. The characteristics of these zones from the shoreline out have been defined as:

- The upper part of the nearshore slope that extends from the rear of the beach to the 15-30m depths includes the beach and the offshore bar and trough systems. The beach is gently sloping along most of the bight with steeping slopes towards the centre. In the southwest of the Bight there is a single offshore bar and, in the northeast, a well-developed double bar system (Figure 20; Roy and Crawford, 1980).
- Seaward of the outer bar, the lower portion of the nearshore slope zone slopes steeply seaward. Once the slope reaches a depth of 15m in the south, 20m in the centre and 30m in the north, the slope terminates where it aligns with the rock headlands at both ends of the Stockton Bight (Roy and Crawford, 1980).
- The inner shelf plain is a gently seaward sloping zone that terminates at approximately 45-50m depth. Bedform features along the shelf are characterised as gently undulating dune of 1-2m high and 1-1.5km wide. Rock reefs are present at either end of the Bight. South of the southern end of the Bight rock protrusions and a rock platform are located south of the river entrance (Roy and Crawford, 1980).
- The inner shelf slope below 45-50m depth and out to 120m is relatively steep with large bedforms present. Four terraces evident along the slope can be interpreted as wave formed features with more irregular bathymetry at the north end of the Bight which may indicate submarine continuation of the headland (Roy and Crawford, 1980).

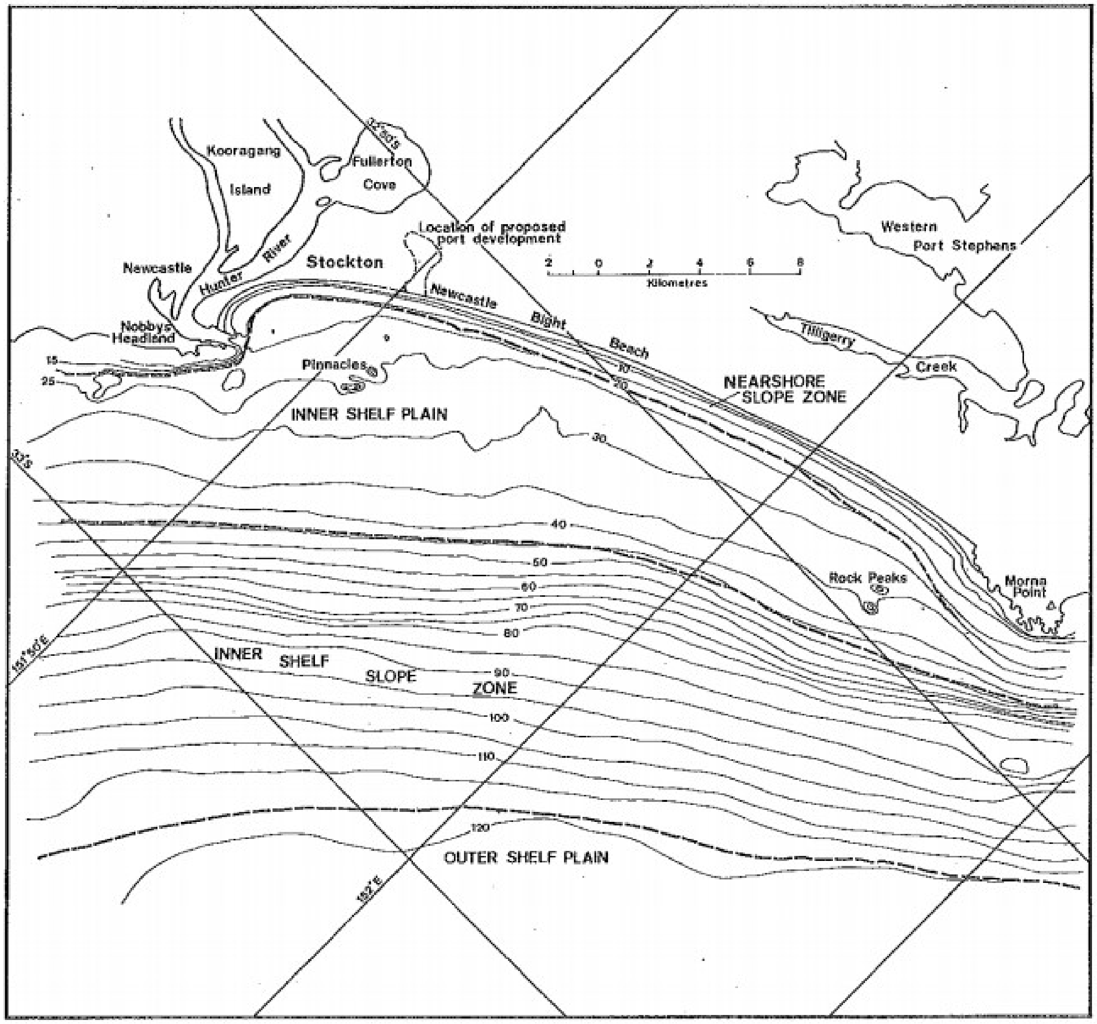

Figure 24: Bathymetry and geomorphology of the Stockton Bight (source: Roy and Crawford, 1980).

On the inner continental shelf offshore of Newcastle (in depths between approximately 20 – 60m) there are two main types of marine sands deposited, the inner shelf sand sheet (ISSS) and shelf sand bodies (SSB), as described in Roy (2001). The ISSS is a thin and extensive fine to coarse grained, shelly, iron stained sand while the SSB are thick but discrete bodies of sand consisting of slightly shelly, uniform fine to medium grained sand and are predominately found around rocky headlands (Roy, 2001). Regional NSW (2020) identified the ISSS at Newcastle as well as the lobe and spoils ground offshore of Nobbys Head as being comprised of medium-grained, quartzose sand. An extensive offshore sediment sampling program was suggested in the report as little is known about the thickness and continuity of these layers.

3.3 Modern geomorphic structure and morphology

Stockton Bight is a coastal sand barrier system. 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. The coastal profile can be divided into several zones displayed in Figure 25.

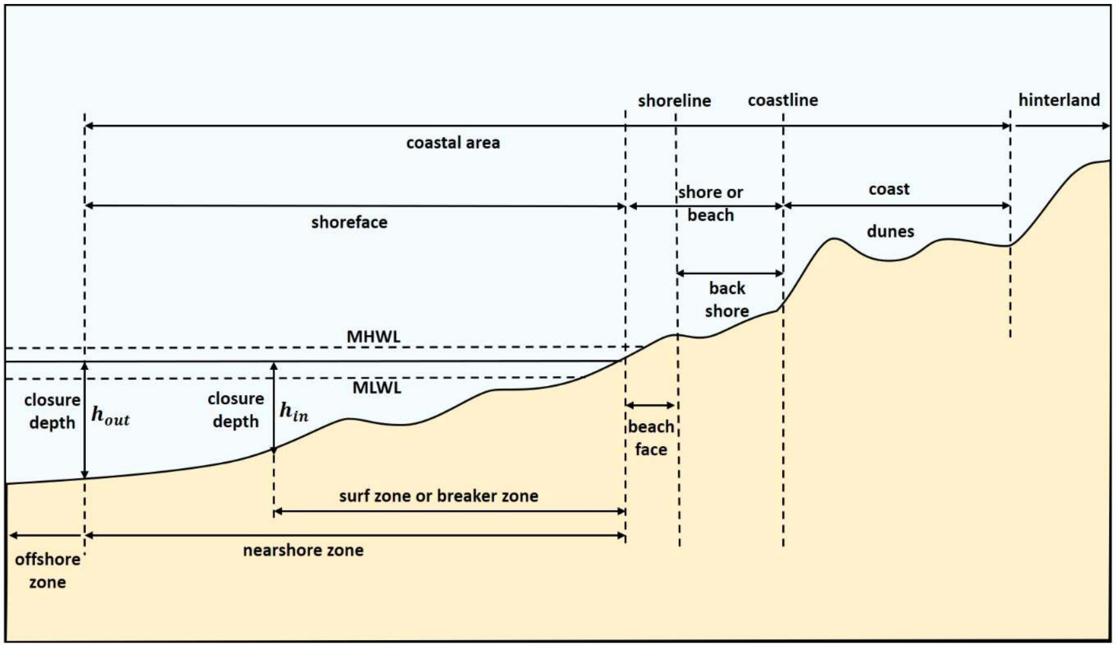

Figure 25: Definition of terms across the coastal profile after Mangor (2020).
Note: shoreline is typically defined at the intersection of the sea level and beach (seaward of annotation in figure).

The sandy beaches and barriers are wave dominated and the centre alignment of the Stockton Bight coastal sand barrier is approximately normal to the dominant wave climate and is open to the ocean to the south and south-east. Breakwaters were constructed on either side of the Hunter River entrance and there has been extensive dredging to the entrance channel down to depths of 17m AHD. The southern area of Stockton Bight is therefore somewhat sheltered from the dominant wave directions. Three seawalls were constructed at the Stockton Beach end of the embayment, these structures have been described in Section 2.2.

The river is not a significant contemporary source of sand sized sediment into the system, as alluvial sediments that reach the ocean during flood events are too fine to be retained on the beach (DHI, 2006). The sediment that forms the barrier is quartz marine sand transported onshore from the continental shelf during postglacial marine transgressions or reworked from older barrier deposits on the coast (Gordon and Roy, 1977). There is a notable trend in sand grain size along the Bight, described as:

- Based on eleven representative samples the grain size found on the beach adjacent to the suburb of Stockton (i.e. southern embayment) is medium to medium–coarse sand with an average median grain size (D_{50}) of 0.37mm (WorleyParsons, 2012). An earlier PWD (1977) report found finer grain sizes adjacent to the northern breakwater with D_{50} of less 0.30mm in the southernmost 1km of the beach.
- Approximately 10km north of the southern breakwater there is a maximum in D_{50} of approximately 0.7mm (Pucino, 2015), this location corresponds to a band of coarse sediments (see Figure 26 – left panel) identified by Roy and Crawford (1980) that may correlate with an ancient arm of the Hunter River.
- North of this there is a progressive fining of sand from the coarse sands in the middle of the Bight to fine sand with D_{50} of 0.24mm in north towards Birubi Point as shown in Figure 26 (right panel)..

The trend is evident in samples from all sections of the profile including the swash zone, foredunes and back dunes (PWD, 1977). Various explanations for this fining have been suggested. Thom et al (1992) reasoned a possible explanation for the contrasting distributions reflect the different sediment histories during periods of lower sea-level (i.e. coarser river sand deposits in the south and finer reworked dune sand in the north). Pucino (2015) reasoned that the distribution in the swash zone was due to the large variability in the distribution of wave energy along the embayment, which comes about from differences in shoreline orientation.

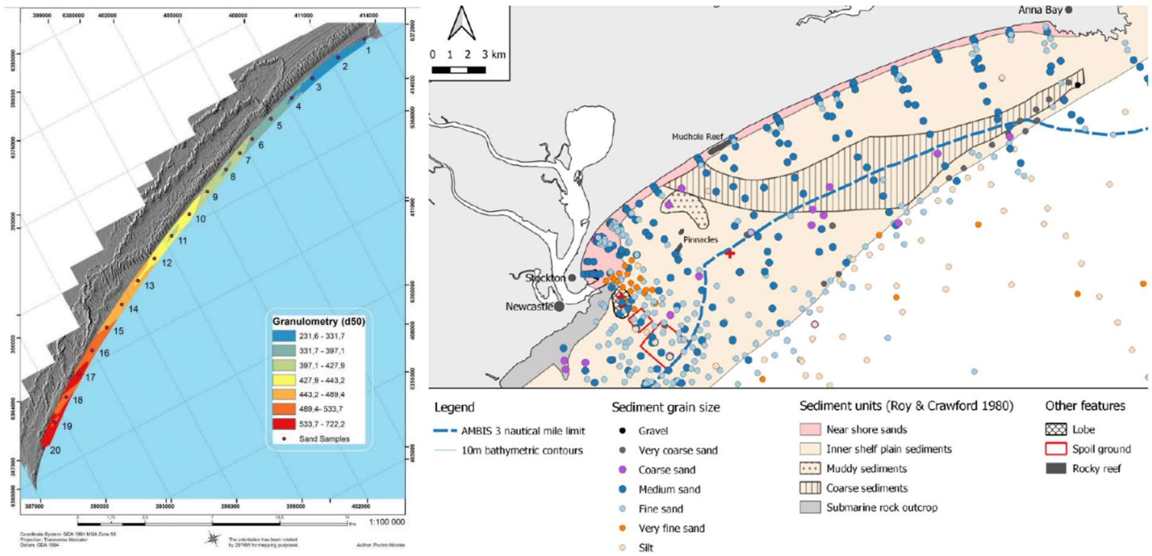

Figure 26: (left) Gradient in grainsize along northern Stockton Bight from interpolated D_{50} values and a classification value from 20 sand sample taken within the swash zone in March 2016 (source: Pucino, 2015) and (right) grain size superimposed on sediment units (MEG, 2020).

3.4 Dune formation and morphology

The dune system within the Stockton Bight is the largest mobile coastal sand mass in Australia (Pucino, 2015). An aerial photograph and elevation map are provided in Figure 27. The entire beach, foredune and transgressive dune system covers an area of 27km^2 and has dune heights of 40m above MSL (Pucino and Condurso, 2016). The active dunes form an important sand sink for the Stockton Bight sediment compartment (Gordon and Roy, 1977). As seen in the elevation map (Figure 27) the morphology of the dune sheet varies considerably along the Bight as the active dune sheet widens from Stockton to Birubi Point. The central section shows three long-walled ridges, the two oldest ones are stable and vegetated which are assumed to have formed as Phase 2 and 3 transgressive dunes 5000 and 2000 years ago which buried the Phase 1 foredune ridges (Gordon and Roy, 1977). The youngest long-walled ridge forms the inner edge of the active dune sheet which was initiated around 500 years ago (Thom et al., 1992). The key features of the Bight's dune system are shown in Figure 28.

At Stockton Bight the system is a transgressive sand barrier system, with the Phase 4 dunes moving inland. As the transgressive dunes migrate inland, they leave a deflation basin where windblown sand has been eroded down to just above the water table, the basin paralleling the rear of the beach. On the seaward side of the deflation basin is the foredune which has frequent blowouts which are aeolian generated landforms that channel the onshore winds and deposit beach sand behind the foredune, lowering the foredune and supplying sand to the deflation plain and transgressive dunes (Pucino and Condurso, 2016). The foredune is significantly affected by wave processes including overwash and storm erosion and as such has a dynamic interrelationship with the beach (Masselink et al., 2011). The Phase 4 transgressive dune field contains transverse dune ridges aligned perpendicular (i.e. transverse) to the dominant winter northwest winds. They occur between Fullerton Cove and Birubi Point with the southwest winds generating a south-west to northeast migration direction.

Pucino and Condurso (2016) found that over monthly to bi-annual periods, landward cross-shore sediment transport was dominant across the Anna Bay entrance. However, a major limitation of aeolian geomorphology is the relatively short temporal baseline of dune activity observations (Hugenholtz et al., 2012). A study on the sand drift dynamics at Stockton Bight was undertaken by Pucino (2015) and included measured rates of the dune field for 2009-2015. The main findings of the measured dune field (including both the transverse dune and the active long-walled ridge) for the period were:

- Measured rates of dune migration at the dune field scale over a four-year period was 26.3m, giving an annual dune migration of 6.5m/yr towards the north north-west.
- The eastern end of the Bight's dune system (Area A in Figure 29) is the most active as the transverse dunes ridges are migrating northeast at an average migration rate of 10.4m/yr.
- Area t in Figure 29 ('The Tongue') has evidence of unimodal wind directions with dunes migrating either west-northwest under winter south westerlies or east-southeast under summer northeast sea breezes.

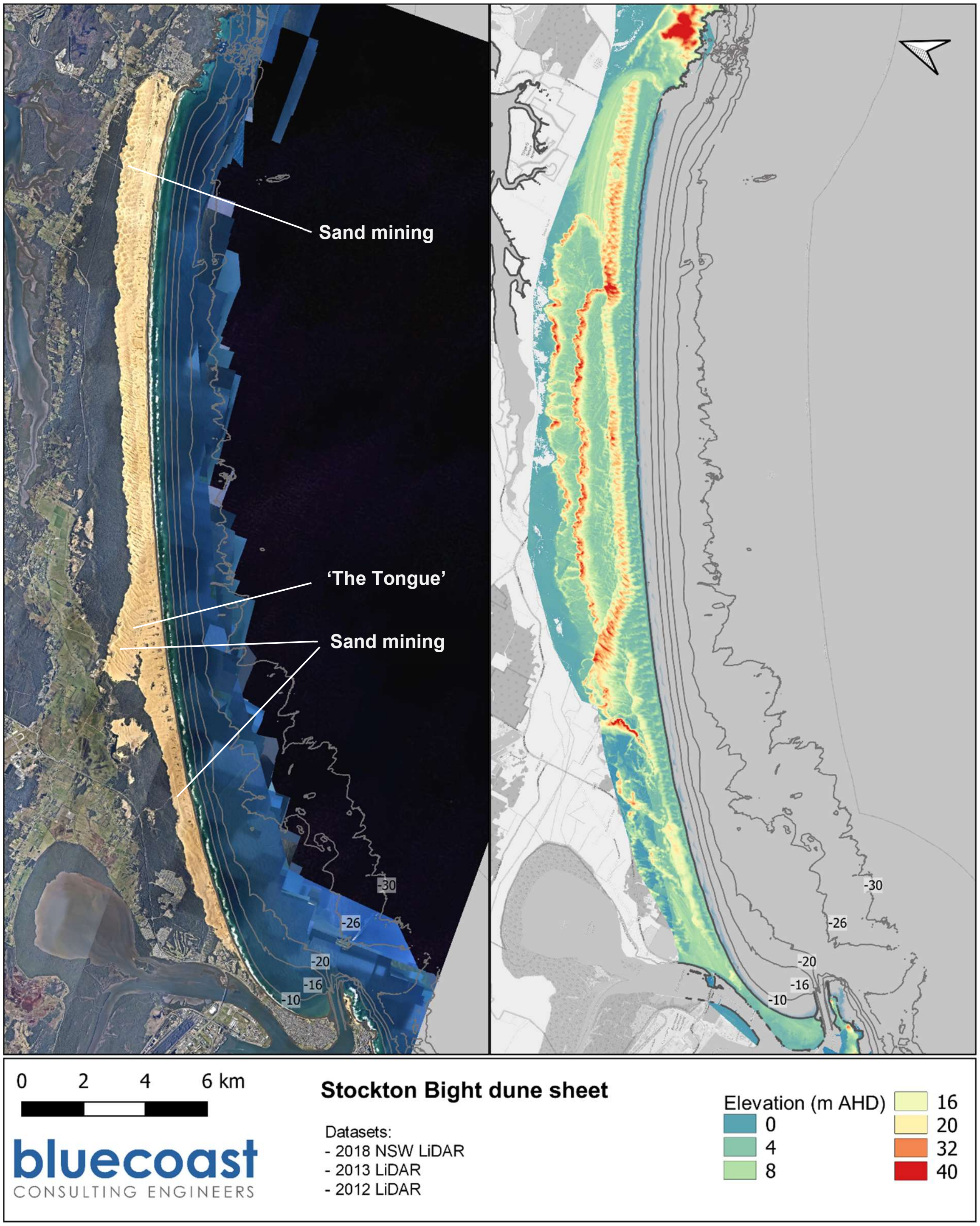

Figure 27: Aerial photograph (left) and LiDAR elevation data (right) showing Stockton Bight dune sheet.

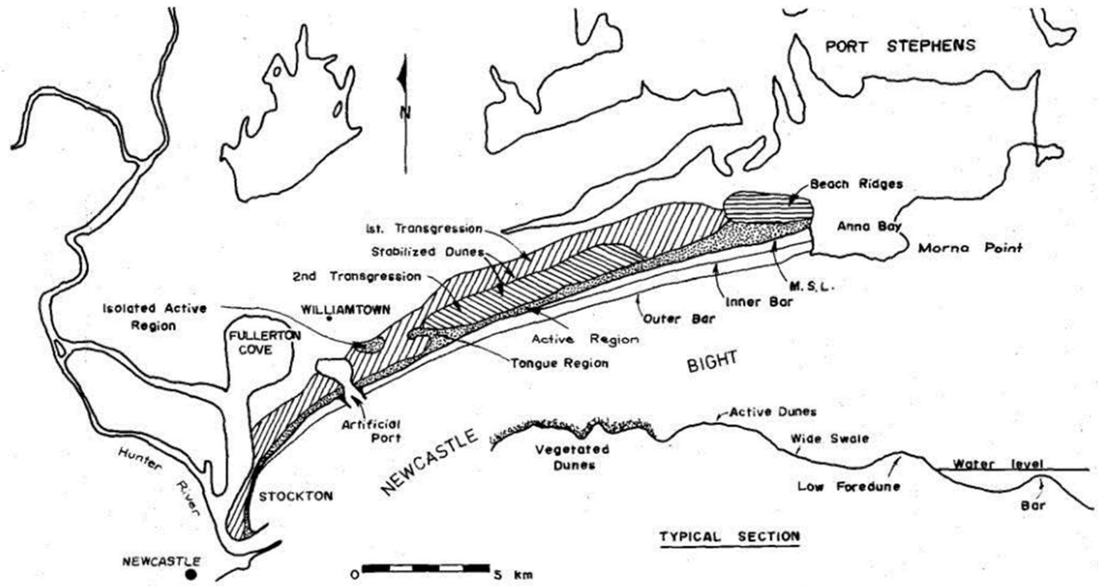

Figure 28: Features of Stockton Bight dune system (Gordon and Roy, 1977). Note that the 'artificial port' was a feasibility concept and is not a feature of today's Stockton Bight.

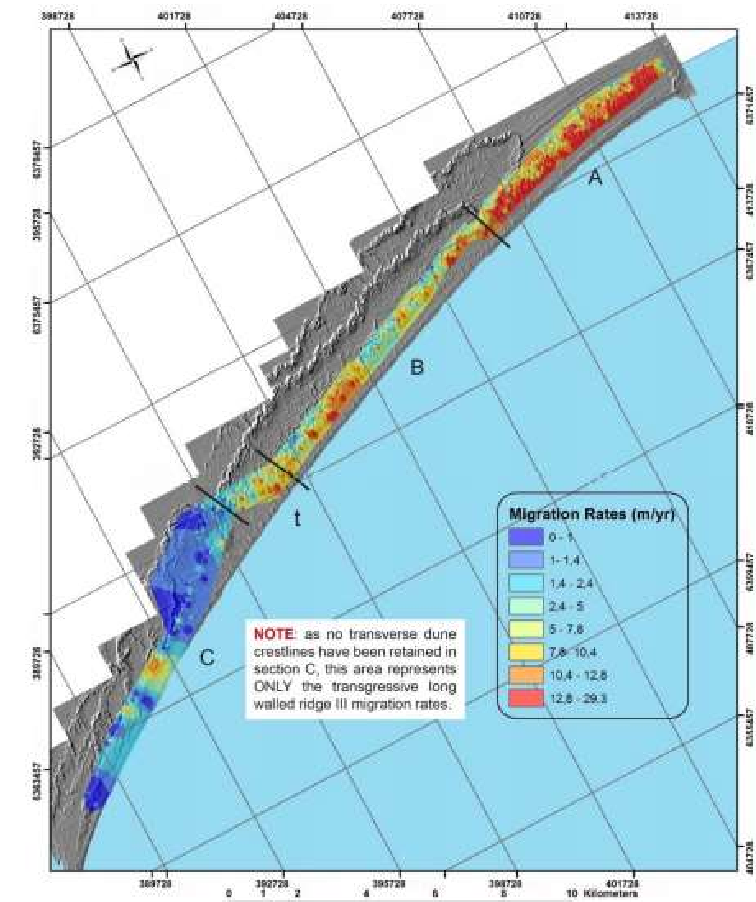

Figure 29: Dune migration rates of dunes along the transverse dune sheet at the north-eastern end of Stockton Bight between 2009-2015 (source: Pucino, 2015).

4 Metocean conditions

4.1 Introduction

This section provides a summary of the analyses of metocean datasets nearby the Stockton Bight study area. Figure 30 displays the location of the monitoring instruments used within the analysis. Further detail and results of the metocean analysis is provided in Appendix A.

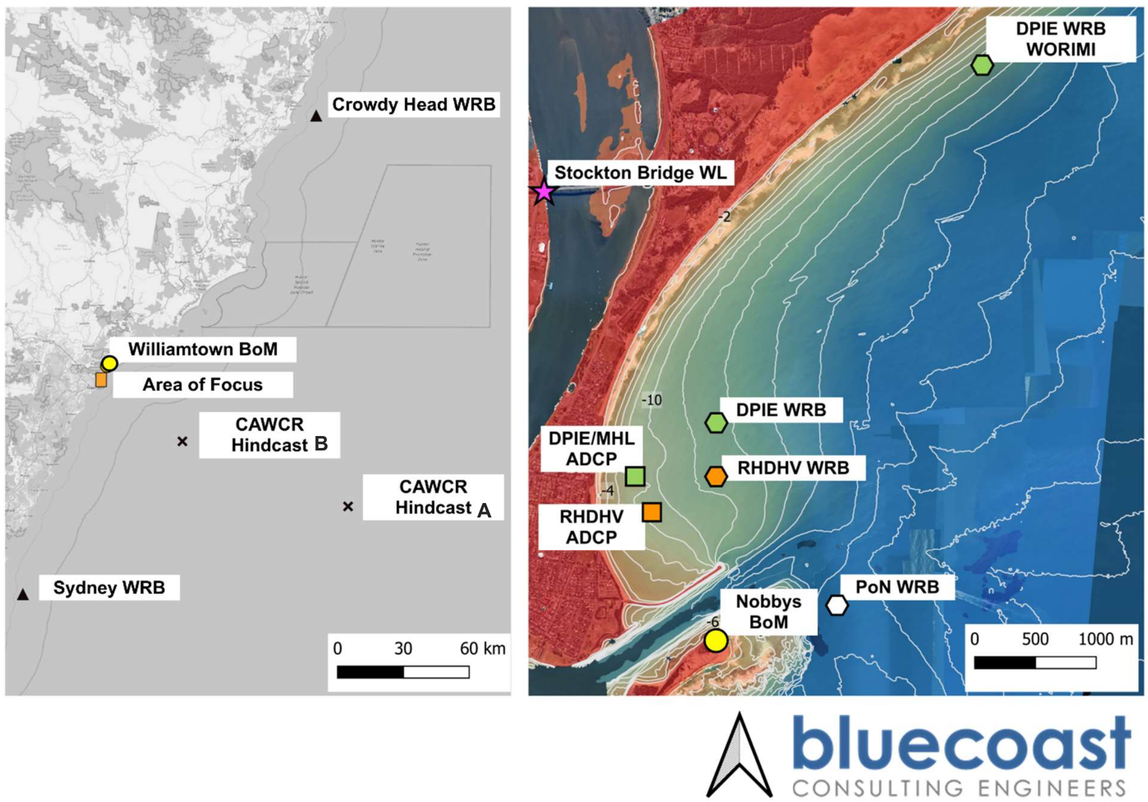

Figure 30: Location of metocean data locations within the study area along with the 2018 Marine LiDAR bathymetry.

4.2 Wave climate

Offshore (regional) wave climate

The Stockton Bight section of the NSW coastline experiences waves generated from three primary sources: Tasman Sea swells, locally generated wind-waves, waves from East Coast Lows (ECL) and tropical cyclone systems. Regional measured deep-water wave data was available from the following sources and displayed in Figure 30:

- Crowdy Head Wave Rider Buoy (WRB) record available from August 2011 to January 2020 (9 years) located in 79m water depth
- Sydney WRB record available from March 1992 to January 2020 (28 years) located in 90 m water depth
- CAWCR 42-year wave hindcast, from the period 1979-2010 with two extraction locations, one further offshore (A) and one closer to shore (B).

Wave roses for swell (swell waves, Tp >8s) and sea (local sea, Tp <8s) for the three offshore wave data sources are provided in Figure 31. The deep-water wave sites are seen to be dominated by moderate energy, swell waves, with mean significant wave heights of 1.56 m, 1.62 m and 2.10 m respectively. Wave roses showing the direction and occurrence of large wave events are presented in Figure 32 which predominantly show associated southerly wave directions.

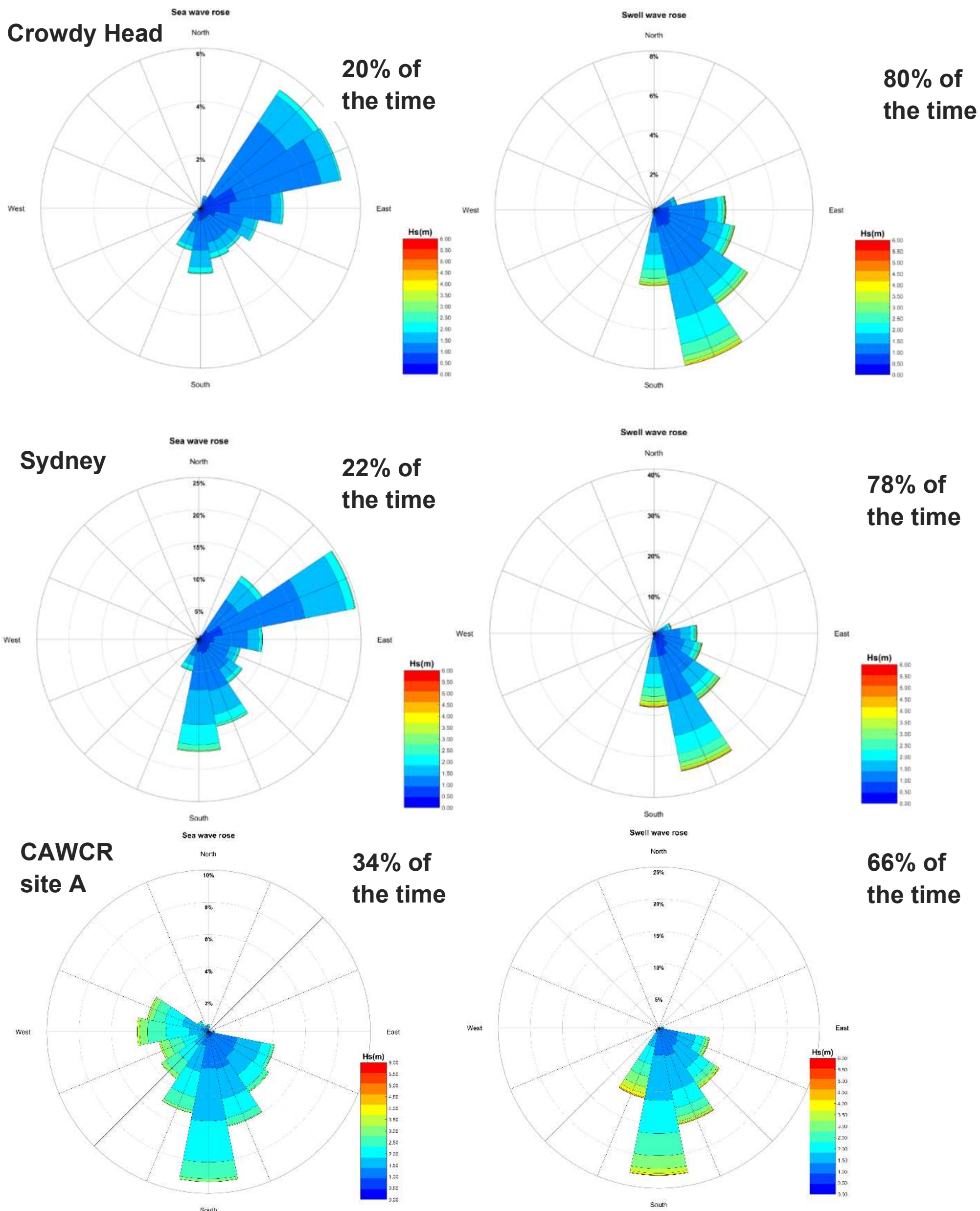

Figure 31: Long-term wave roses for (left) sea conditions (Tp < 8sec) and (right) swell conditions (Tp > 8sec). The percentage occurrence of each sea state is annotated.

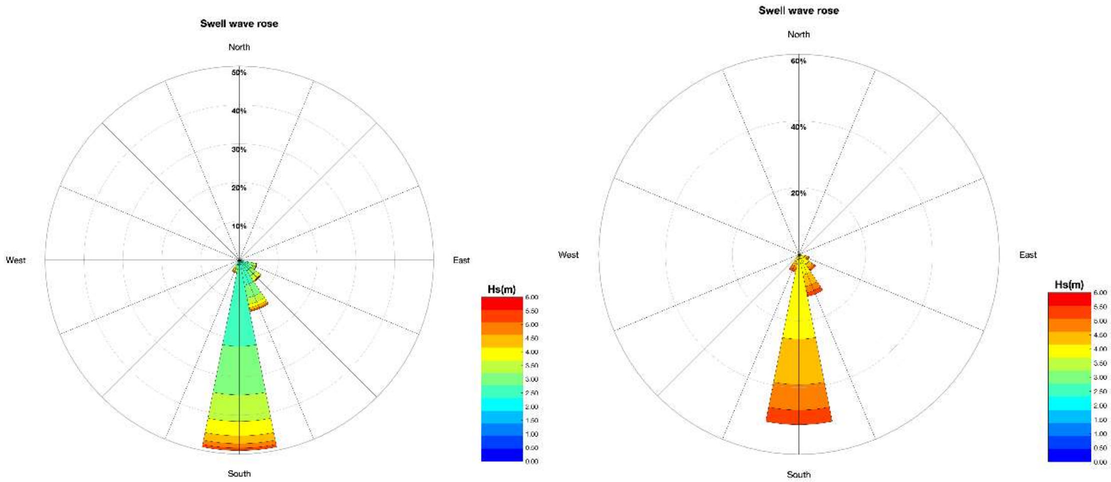

Figure 32: Long-term wave roses derived from the CAWCR hindcast extracted at site A for waves with (left) wave heights over 2.5 m and (right) over 4 m from 1979 to 2010.

<u>Nearshore wave climate</u>

The nearshore wave climate was assessed using data from wave buoys located in depths less than 25m, including:

- The Newcastle WRB operated by Port Authority of NSW has measured waves for the period between November 2009 to March 2020 (11-years) located in approximately 22 m water depth.
- Two WRBs deployed by DPIE (see Figure 30) provide short-term measured waves at Stockton and at Worimi approximately 4 km to the north. The WRB offshore of Stockton (DPIE WRB) in approximately 13 m water depth was deployed between 30th December 2019 and the 13th July 2020. The WRB to the north (DPIE WRB WORIMI) was deployed in 14 m water depth between 9th December 2019 to 25th February 2020.

In addition, a numerical modelling assessment was undertaken to determine the pattern of wave transformation and resulting nearshore currents. For this, a high-resolution SWASH model was setup for the southern embayment of the Stockton Bight. The simulated distribution of nearshore wave heights for a moderate south-east (135°N) offshore wave condition and nearshore currents during ambient swell conditions are presented in Figure 33. The sheltering effects of the training walls and refraction patterns are clearly visible in the modelling results. During the south-east swell conditions, a net northward current was observed in the swash zone.

The observed average as well as seasonal wave climate statistics for the Newcastle WRB can be seen in Table 2 and the wave roses for swell (swell waves, Tp >8s) and sea (local sea, Tp <8s) are provided in Figure 34. At the nearshore Newcastle WRB site, the mean significant wave height is 1.41m, with a 75th percentile wave height of 1.71 m annually, predominately from the southeast. Some seasonal variation is seen over summer which on average measured shorter, lower wave heights more from the east. Due to the narrow continental shelf and the orientation of the coastline with the direction of the prevailing storms and East Coast Lows (ECL) the site is exposed to periodic large wave events. Over the period of measured significant wave heights at Newcastle, the 99.5th percentile was 4.41 m whereas the maximum was 8.52 m.

Wave roses for swell and sea conditions for the short-term WRB deployments carried out by DPIE at Stockton and Worimi are displayed in Figure 35, and show Stockton experiences a more uni-directional wave climate due to its relatively more sheltered position at the southern corner of the Stockton Bight (see Figure 30). The DPIE Worimi WRB is situated further north and is thus exposed to a broader range of swell directions. This is also reflected in the mean significant wave heights, being 1.05m at the Stockton WRB and 1.17m at the Worimi WRB. The 75th percentile wave heights at these locations was 1.21m and 1.32m, respectively.

The two recently deployed DPIE WRBs were also used to produce a plot of concurrent waves and currents, shown in Figure 35. Measured currents for this figure are taken from the recent ADCP deployment by Royal HaskoningDHV (RHDHV ADCP in Figure 30).

Lawson and Abernethy (1977) and DHI (2006) identified a wave focussing mechanism for south to south east waves over the sand lobe located south of the harbour entrance. DHI (2006) predicted this to increase wave heights around the Mitchell Street seawall. The wave focussing that already been identified by vessels sailing in or out of the Port (Lawson and Abernethy (1977). The results indicate that the focussing area is located from the Hunter Water treatment ponds area to the southern end of Fern Bay. DHI suggested that this process tends to exacerbate erosion in this area.

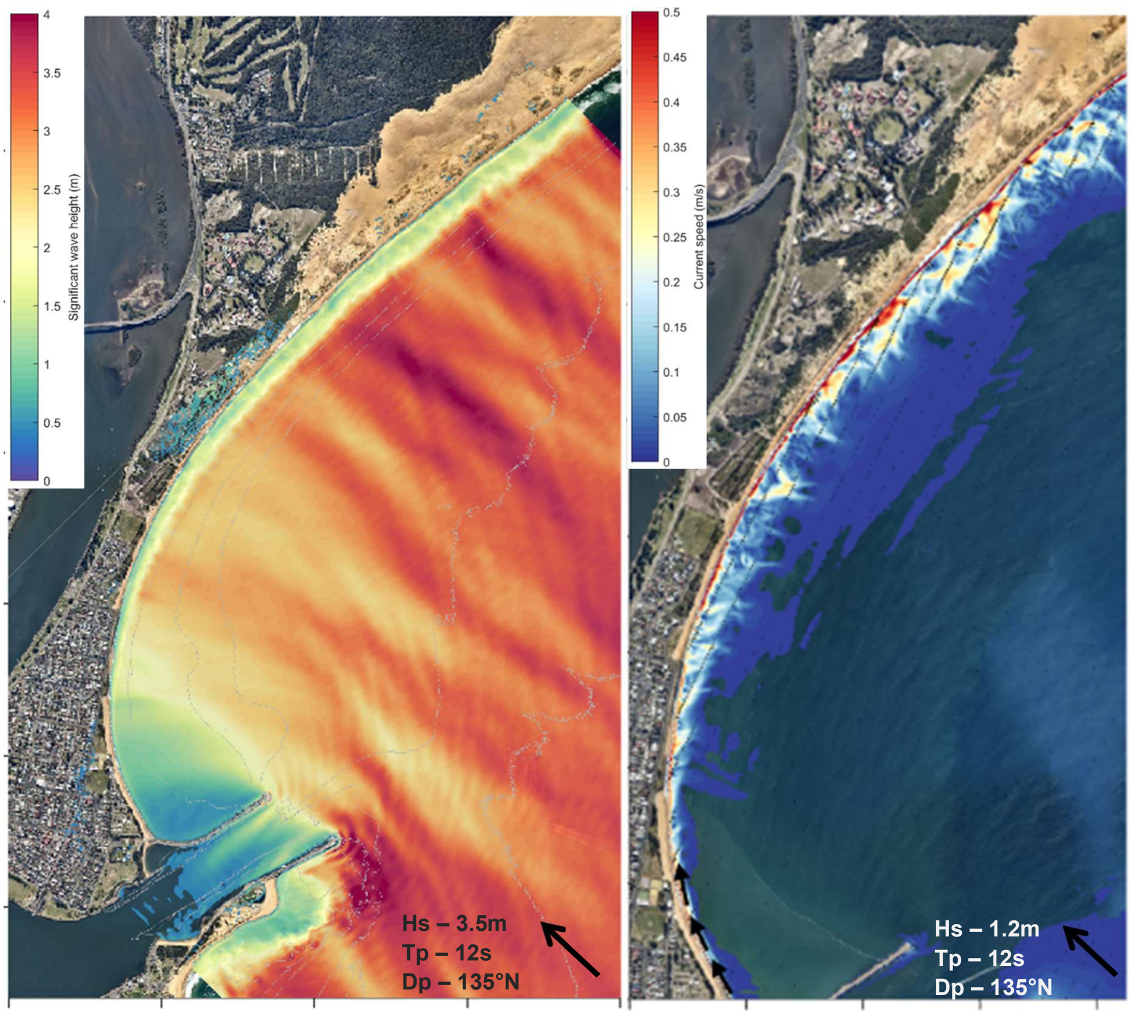

Figure 33: SWASH simulation of (left) nearshore wave transformation into southern Stockton Bight during moderate offshore swell waves and (right) wave driven nearshore currents during ambient swell waves.

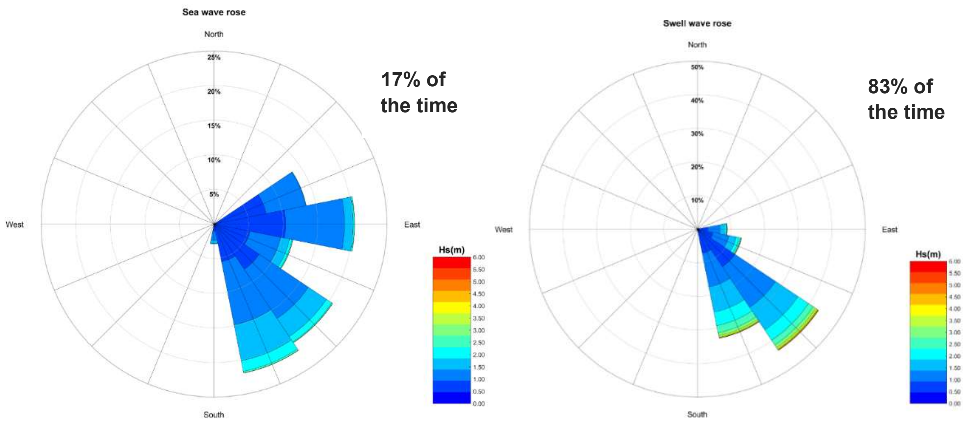

Figure 34: Long-term wave roses at Newcastle WRB for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from November 2009 to March 2020. The percentage occurrence of each sea state is annotated.

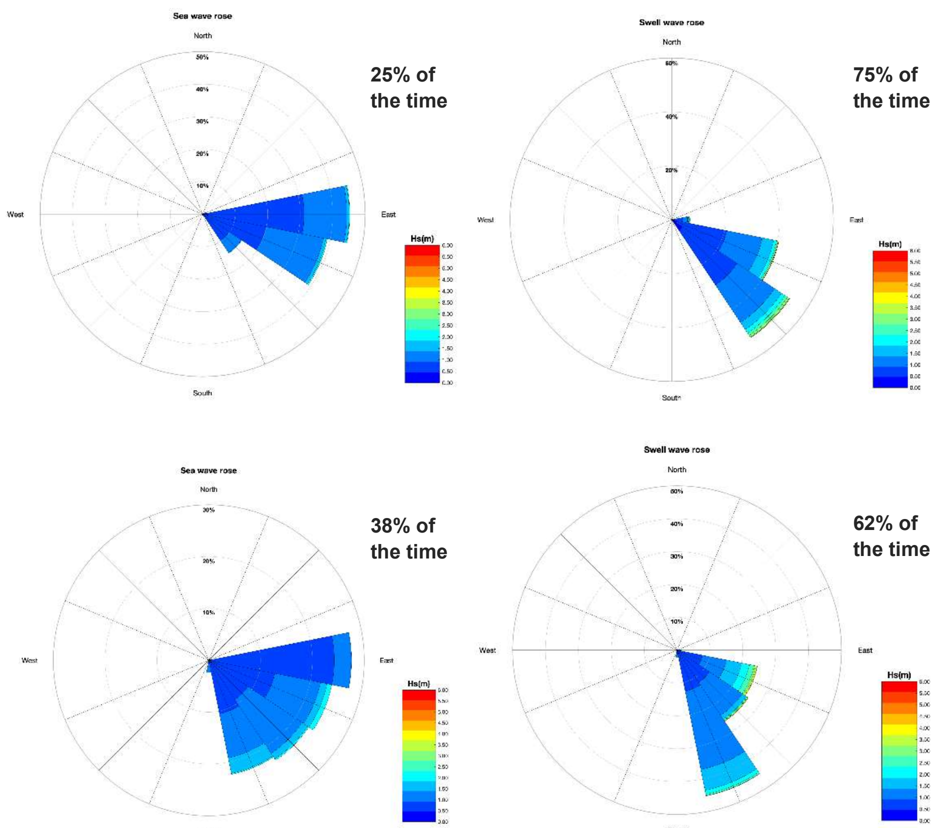

Figure 35: Short-term wave roses for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) at (top) the DPIE WRB Stockton and (bottom) DPIE WRB Worimi. The percentage occurrence of each sea state is annotated.

Table 2: Wave measurement statistics for the Newcastle WRB from November 2009 to March 2020.

Parameter	Statistic	Medium term averages (12-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.41	1.49	1.40	1.32	1.43
	20%ile	0.88	0.83	0.88	0.90	0.87
	50%ile	1.24	1.31	1.25	1.18	1.25
	75%ile	1.71	1.86	1.70	1.53	1.78
	90%ile	2.30	2.59	2.24	2.02	2.35
	99%ile	3.90	4.37	3.58	3.49	3.86
	99.5%ile	4.41	4.88	4.13	3.97	4.26
	Max	8.52	8.17	7.14	6.33	8.52
Peak wave period (Tp) [s]	Mean	10.7	11.6	10.6	9.7	11.1
	20%ile	8.5	9.7	8.2	7.5	8.9
	50%ile	10.8	11.5	10.7	9.7	11.0
	75%ile	12.6	13.0	12.6	11.5	12.9
	90%ile	13.9	14.6	13.9	12.9	14.3
	99%ile	17.1	17.5	17.0	15.9	17.4
	% of time sea (T_p < 8s)	16%	6%	18%	26%	11%
	% of time swell (T_p > 8s)	84%	94%	82%	74%	89%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	125.7	135.8	144.6	93.5	-
	Mean	133.4	136.7	137.5	125.8	133.9
	Standard Deviation	23.1	19.2	22.6	27.2	20.9

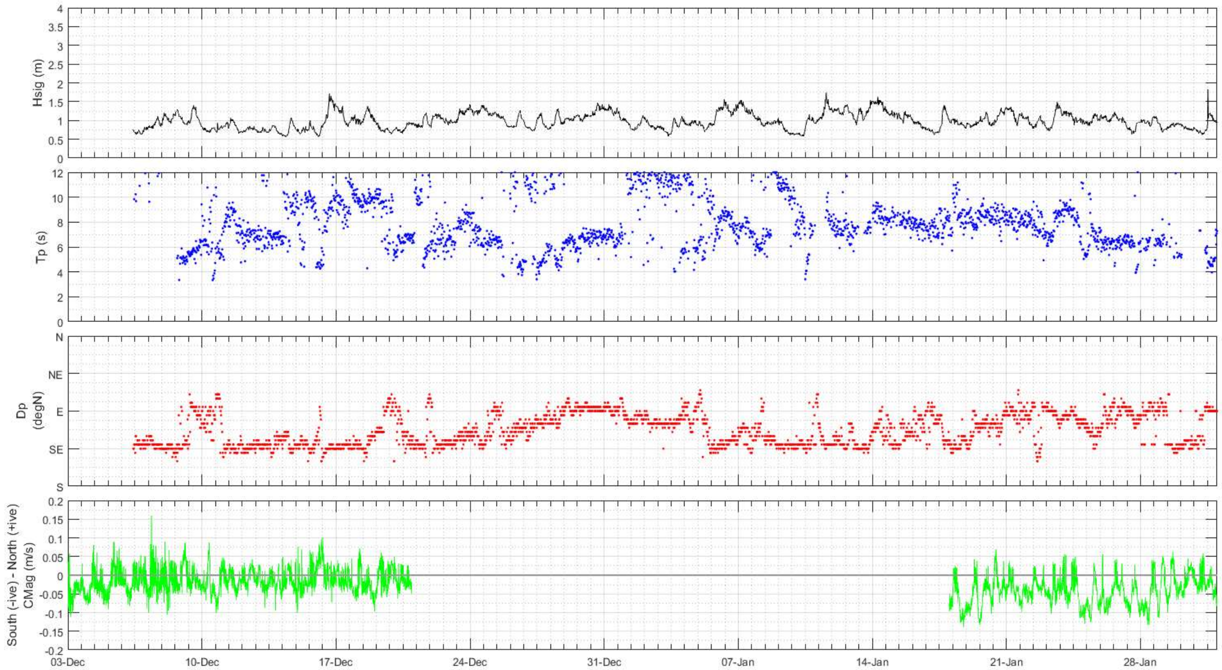

Figure 36: Concurrent wave and current characteristics. Current data from Royal HaskoningDHV ADCP and wave data from DPIE WRB deployments.

<u>Wave direction</u>

Changes to the mean wave direction can occur due to seasonal variations as well as with the larger scale oscillations in climate. The average annual wave direction at the Newcastle (133˚) and Sydney measurement locations shown in Figure 37 suggest only a small annual oscillation in the change in wave directions.

Nearshore waves at the Stockton site were modelled in the DHI (2006) analysis where 12 years of offshore measured data was transformed to give the shallow water wave heights and directions along the Stockton Bight at the 17 m contour (Figure 38). The analysis showed that for north of Fern Bay, at the 17 m contour there is little transformation in wave direction from the measured deep-water waves. In the south while offshore prevailing waves are from the south-east and are diffracted by the training wall at the Hunter River entrance. As the waves move towards the beach variations in depth contours refract and rotate the waves making the wave approach almost perpendicular to the beach. DHI (2006) reported typical wave directions at Stockton Beach between 60 to 120 degrees true north.

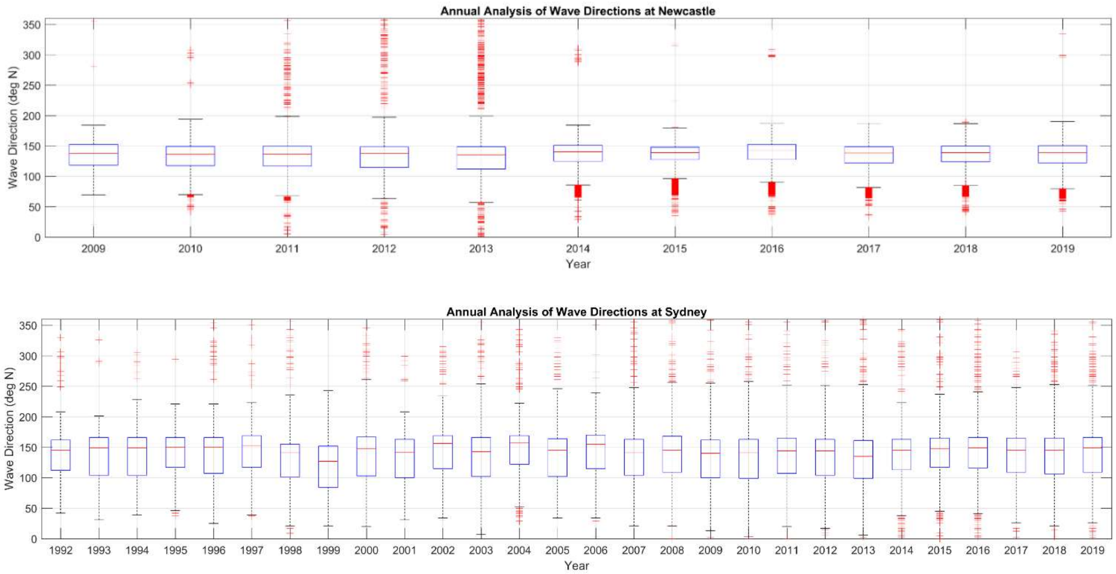

Figure 37: Annual box plots of wave directions at (top) Newcastle WRB and (bottom) Sydney WRB.

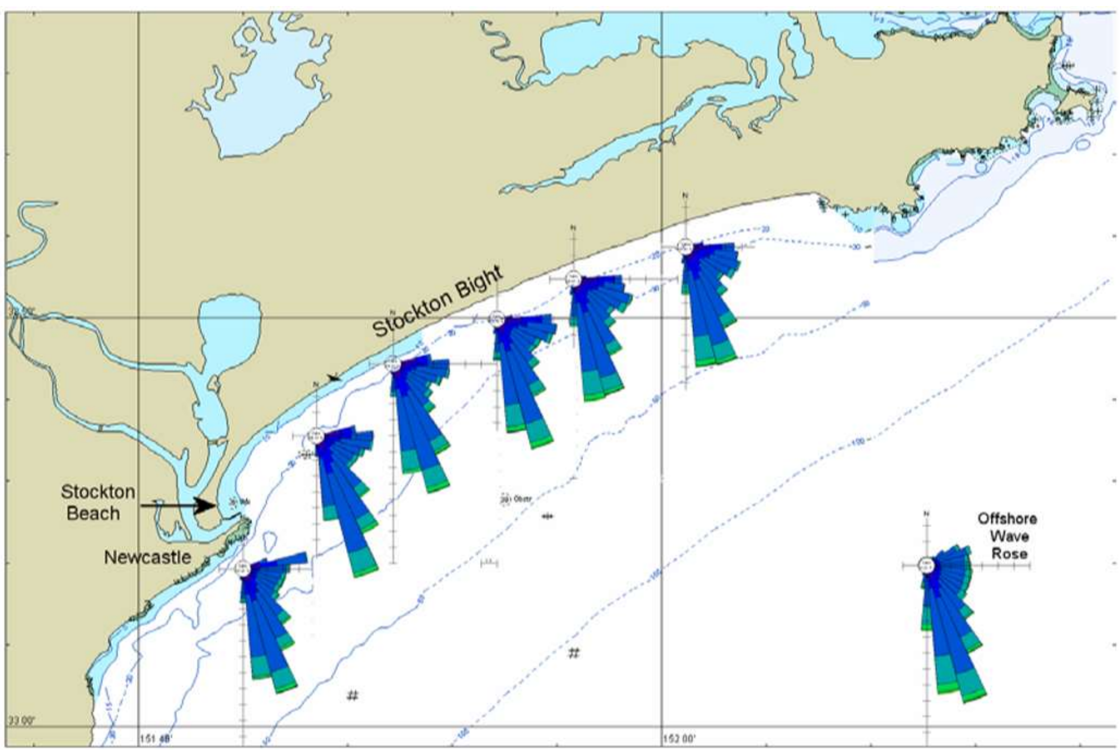

Figure 38: Wave roses from 12 years of transformed offshore measured wave data (Source: DHI, 2006).

4.3 Water level climate

Newcastle Port within the Stockton Bight experiences semi-diurnal tides (two highs and two lows a day) with significant diurnal inequality with tidal planes shown in Table 3 from the Australian Tidal Planes produced by the Australian National Tide Centre. Measured water levels at the site are available at Stockton Bridge MHL tide gauge within Newcastle Port from October 2017 to March 2020 displayed in Figure *30*. A time-series of water levels observed in 2019 are displayed in Figure 39.

Table 3: Tidal planes at Newcastle from the National Tide Centre 2013.

Tidal Planes	Elevation (m Chart Datum)	Elevation (m AHD)
HAT	2.1	1.1
MHWS	1.7	0.7
MHWN	1.4	0.4
MSL	1.0	0.0
MLWN	0.6	-0.4
MLWS	0.4	-0.6
ISLW	0.1	-0.9

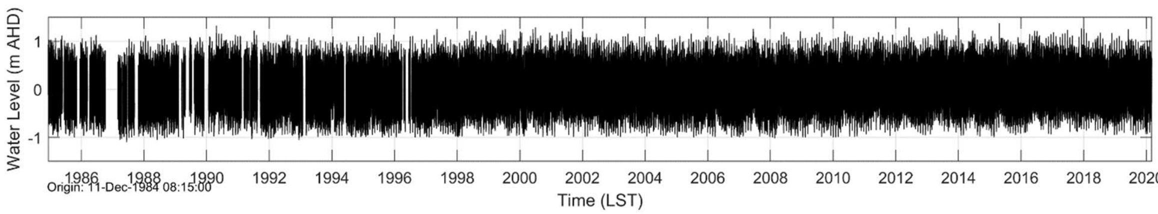

Figure 39: Measured water levels at Stockton Bridge.

4.4 Tidal, fluvial and other currents and circulation patterns

Complex currents at the study site have been documented in previous studies on the impacts of the anthropogenic developments at the location. The impacts of port structures and seawalls on the sediment transport pathways and resulting shoreline position were presented in the 2006 study undertaken by DHI.

Measured currents from both bottom mounted ADCP and ADCP transects were collected within the entrance channel over a spring and neap tide, recording stronger currents on the eastern side of the channel on both the ebb and flood tides. Measured ebb currents were swifter than flood currents (i.e. ebb velocity asymmetry). Modelled tidal and fluvial current speeds at the Hunter River entrance for a spring tide are presented in Figure 40. Current magnitudes through the entrance reach approximately 0.6m/s on a flood and 0.8m/s on an ebb tide which is expected with the addition of seaward fluvial currents on the ebb tide; however, these current vectors are directed offshore (northeast) of the study site and diminish in magnitude after 1km from the entrance channel. Overall, DHI (2006) found that the role of fluvial included currents at Stockton Beach is minimal.

Further analysis on the hydrodynamics at the site during different wave propagation directions in Figure 41 showed that waves propagating from the east and east south-east produce uniform longshore currents north of the study site and minimal currents at the southern end of Stockton Beach due to wave refraction and a resulting perpendicular approach to the shoreline (DHI, 2006). Also evident in some of the east south-east cases was the nodal point at the north of the Mitchell Street seawall where the currents split north and south due to the different angles in wave approach. Whereas waves propagating from the south to south-east in Figure 41 show the largest impact on flow, it is the breakwaters which induce secondary circulation currents. On the leeward side of the breakwaters, the differences in wave setup from the sheltered areas as well as diffracted waves generate a counterclockwise circulation. By the northern end of the Mitchell Street seawall the longshore currents are uniform and to the north. The few spatial variations evident are produced by wave focusing. The study also identified the complex flow patterns at Nobbys Head which was identified as being due to the uneven bathymetry and sand lobe present offshore (DHI, 2006).

Larger regional-scale circulation patterns offshore of the study area are dominated by the East Australian Current. The southerly ocean current (Figure 42) is located along the eastern seaboard of NSW offshore of Newcastle usually seaward of the shelf edge (CSIRO, 2014).

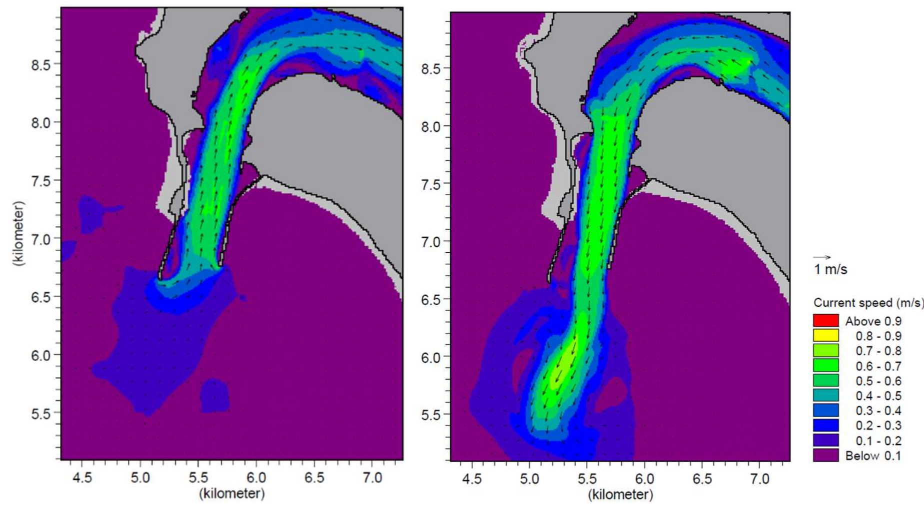

Figure 40: Peak flood (left) and ebb (right) tidal current speed map for a spring tide at the Hunter River entrance (source: DHI, 2009).

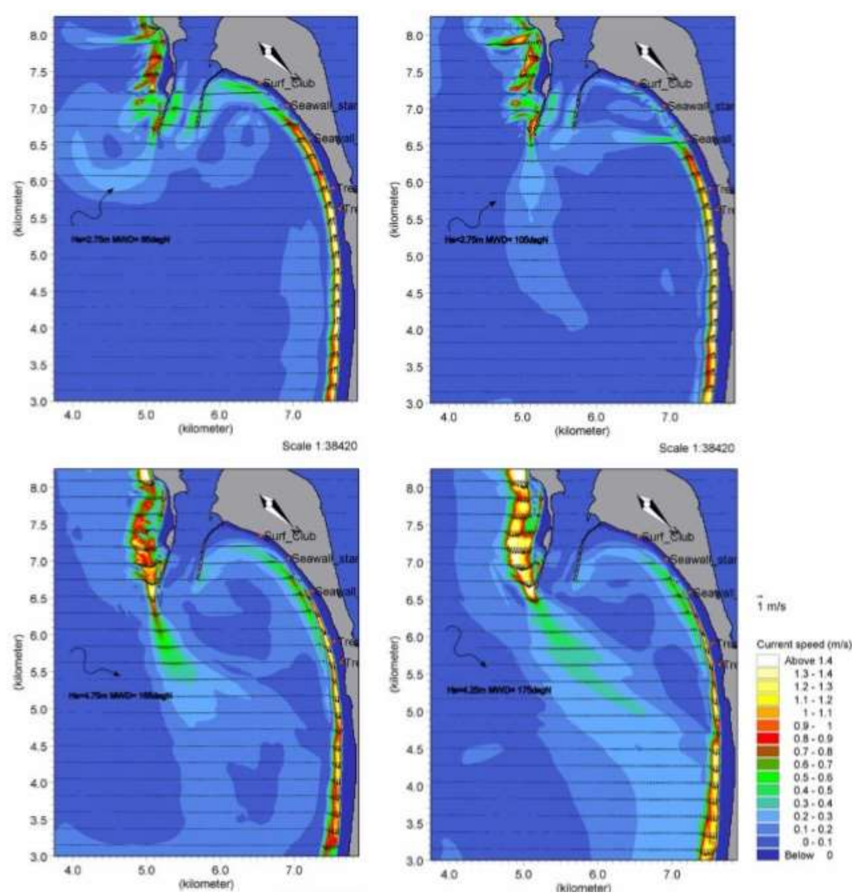

Figure 41: Average currents over a full tidal cycle at Newcastle for four wave cases propagating from (top) east to east southeast and (bottom) south to southeast (source: DHI, 2006).

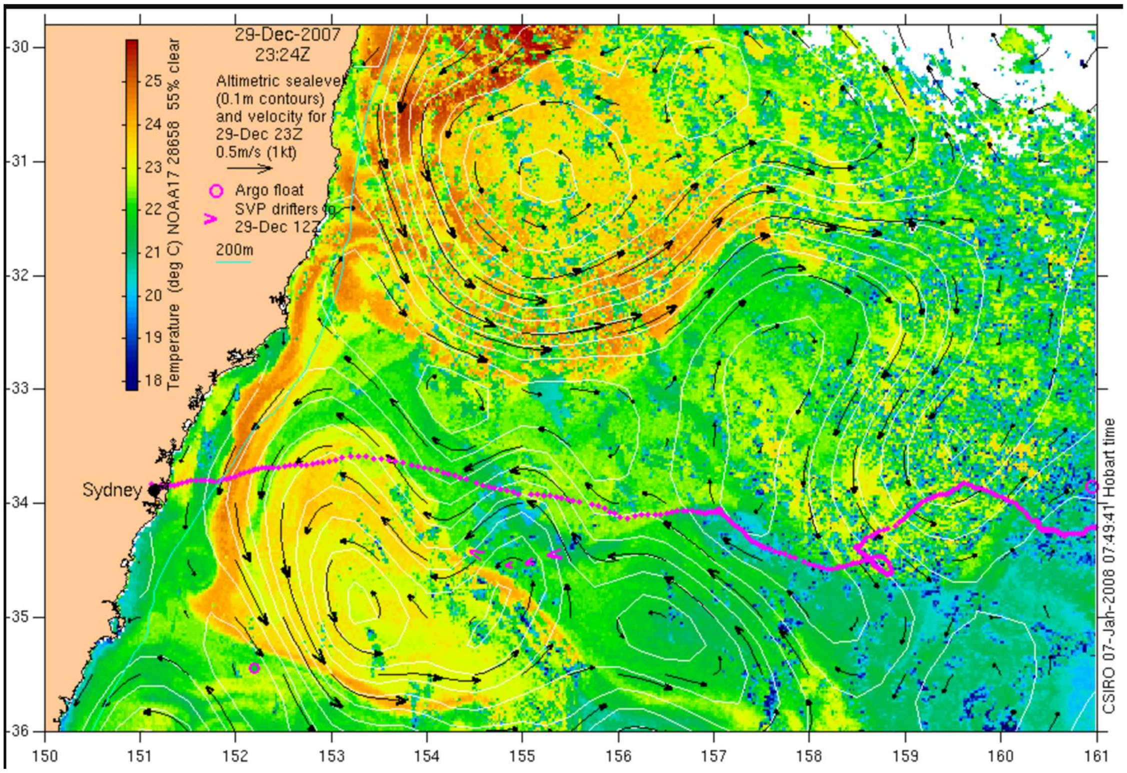

Figure 42: Snapshot of the East Australian Current along eastern seaboard of NSW showing southerly ocean currents offshore of Newcastle together with anti-clockwise eddies (source: CSIRO 2014).

Local measured currents are available offshore of Stockton Beach from four deployments of an Aquadopp ADCP in 2020 undertaken by Royal Haskoning DHV and from an ADCP instrument deployed by DPIE in 2001 (RHDHV ADCP and DPIE ADCP respectively in Figure 30). The measured data available covers a two-month period between June to August 2001 and between the 3rd to 21st December 2019 and 18th January to 1st February 2020. Time series of the measured data for the two-month period in 2001 and first deployment in 2020 are displayed in Figure 46 and Figure 44. From the measured U and V currents the depth averaged, bottom currents (average of the 2 0.5m bins from bed level) and surface currents (average of the 2 topmost 0.5m bins) were processed.

Current speeds in U (east-west) and V (north-south) directional space for the depth averaged currents during both periods are displayed in Figure 45 and Figure 46. The observed depth averaged currents during all deployment periods were predominately offshore towards south-east. During the 2020 deployments, maximum current speeds were measured at the surface (Figure 44) and reached over 0.8m/s and 0.45m/s in the first and second deployment periods respectively, with the highest current speeds occurred at the bottom of the ebb tide. The average bottom current at the sites was below 0.1m/s which is too low to mobilise and/or transport sand sized sediments. The June/August period in 2001 was characterised by high current magnitudes, up to 1m/s to south-south-east. These measurements provide a useful insight into current patterns and magnitudes in more severe conditions where current magnitudes are high enough (typically above 0.3m/s for sand) to mobilise and transport sand during these events.

The measurements suggest that the ACDPs were located in the counterclockwise eddy that occurs during large wave conditions but in depth beyond wave breaking.

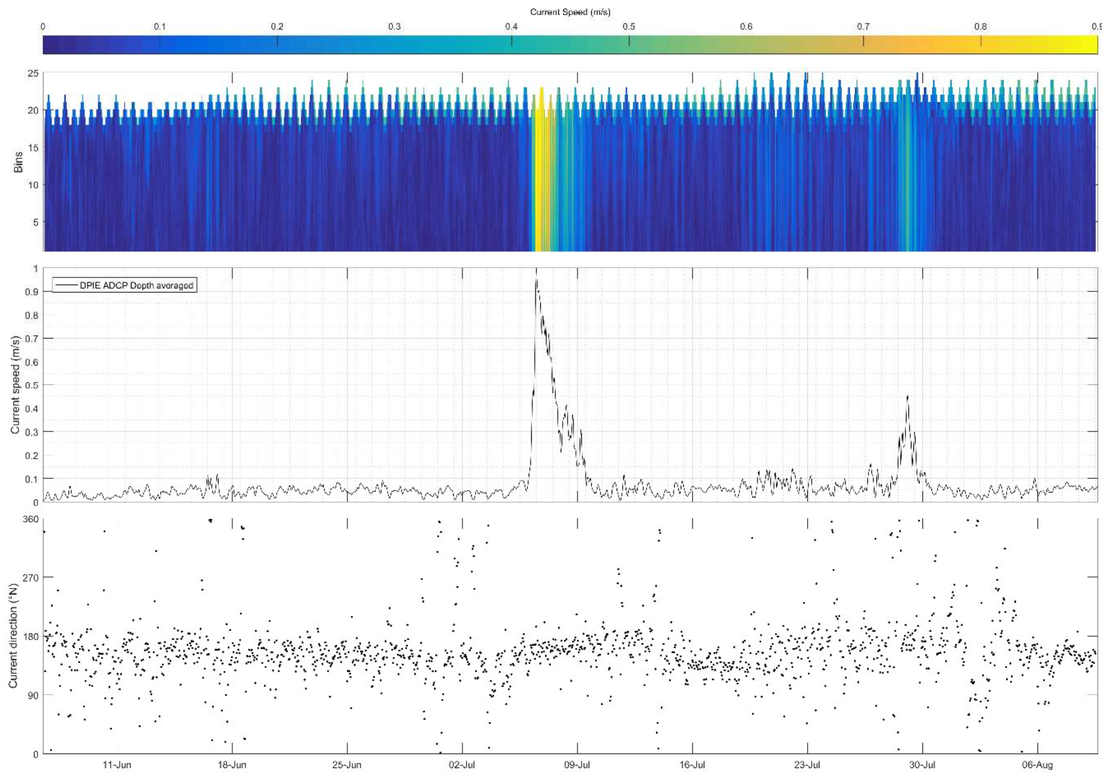

Figure 43: Current speed and direction from the DPIE ADCP data collected between 6th June and 9th August 2001 (Deployment 2).

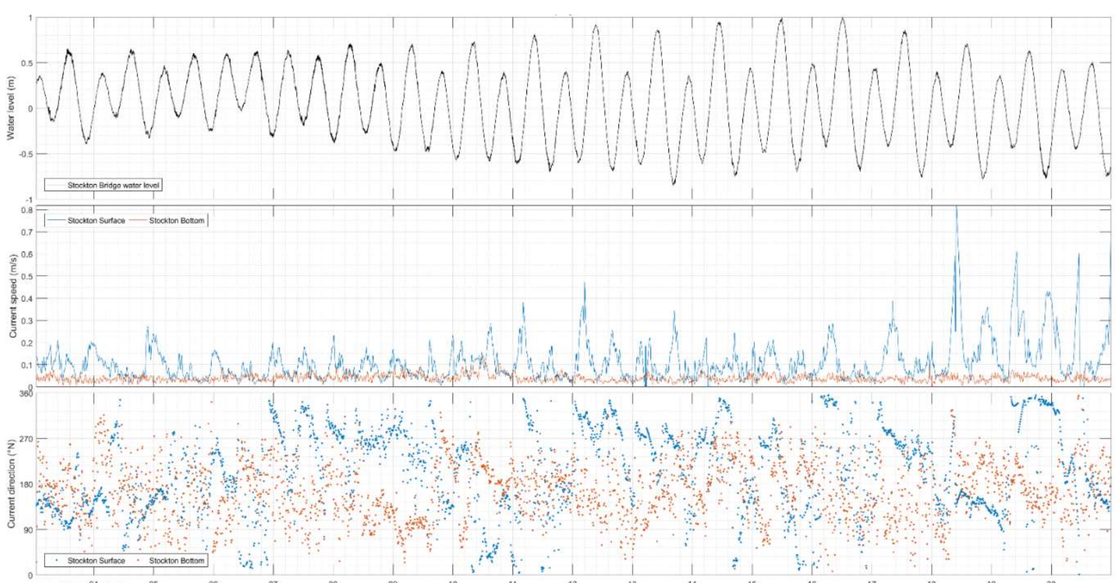

Figure 44: Measured currents at RHDHV ADCP during deployment 1 and 2 and water levels at Stockton Bridge between 3rd to 20th December 2019.

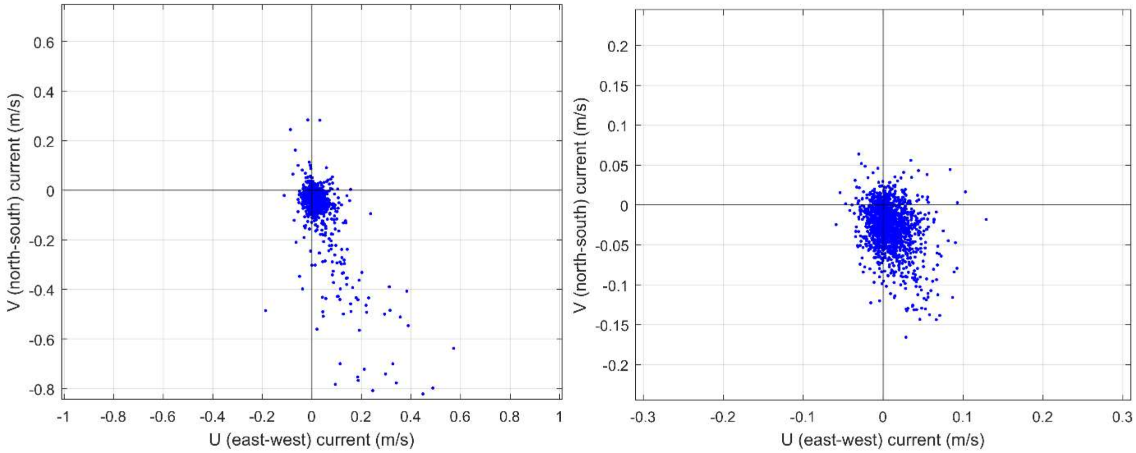

Figure 45: Depth averaged current vectors for the DPIE ADCP during (left) deployment 2 and (right) deployment 3 (2001) .

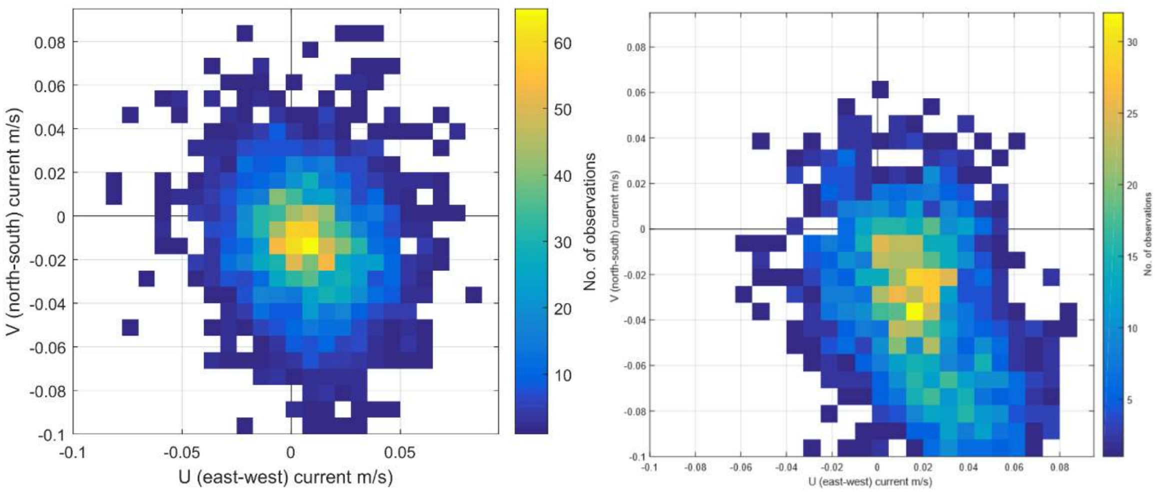

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Figure 46: Depth averaged current magnitudes at RHDHV ADCP during (left) deployment 1 and 2 (18 days duration) and (right) deployment 4 (14 days duration).

4.5 Wind climate

Measured wind data at Newcastle is available at Nobbys and Williamstown BoM weather station (Figure 30) with three hourly, half hourly and one-minute temporal frequencies recorded from 1979. One-minute wind data has been collected from July 2004 at Nobbys and August 1999 at Williamstown.

Overall and seasonal wind roses for Nobbys BoM station are presented in Figure 47 for the one-minute data. Over the summer period, winds predominantly arrive from the north-east to the south with the highest wind speeds coming from the northeast associated with tropical cyclones and ECL systems. Whereas over the winter and autumn synoptic periods, winds are predominantly from a north-westerly direction and associated with anticyclones across southern Australia. Similar descriptive wind roses are presented for the one-minute wind speeds and directions at Williamstown in Appendix A. For assessing the regional wind climate and transport potentials at Stockton Bight, the Nobbys station shows a better representation of the maritime winds influencing the coastal dune system.

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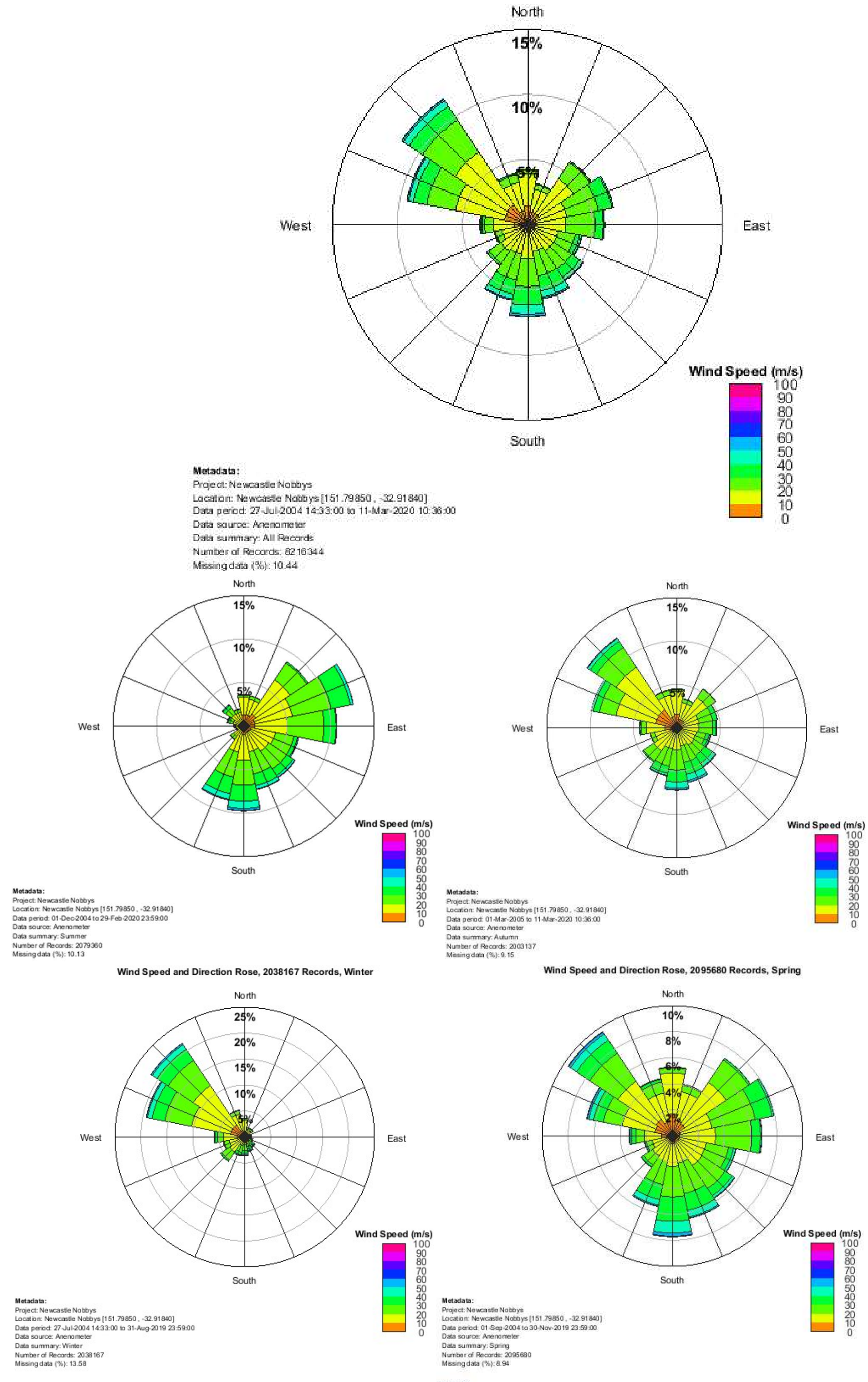


Figure 47: Annual (top) and seasonal wind roses at Nobbys Newcastle BoM station from one-minute data between July 2004 and March 2020.

4.6 Climate setting and climate change [ENSO/IPO/CC]

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

Storm events show seasonality with not only the rate and clustering of events but also variations in storm wave height, direction, duration, period, storm surge and mean sea level (Davies, et al. 2017). Variations in the number or rate of storms are of particular importance to coastal hazard and erosion as closely spaced events, often termed ‘storm clusters’, have been found to induce more erosion than a single longer duration or larger ARI event. The clustering of storms may collectively induce large erosion volumes as erosion is dependent on the pre-storm morphology as well as the wave properties and duration of the storm. These storm parameters show seasonal as well as longer term pattern (Davies et al. 2017)

The ENSO is the oscillation in sea surface temperature in the central and eastern Pacific that leads to seasonal and interannual shifts (typically 18 months) in weather patterns and circulation in across the Pacific. The state and intensity of the ENSO impacts the intensity of trade winds, mean sea level, frequency and intensity of storms. The Southern Oscillation Index (SOI) is often used to determine if the climate is in a state of El Niño or La Niña and is calculated from monthly and seasonal fluctuations in air pressure. El Niño in Australia, indicated by a sustained negative SOI, is associated with drier conditions, a reduction in rainfall, and a decrease in the strength of the easterly trade winds. La Niña, indicated by a sustained positive SOI, is linked to stronger easterly trade winds, increased cloudiness and increased risk of tropical cyclones across northern Australia and ECLs in southeast Australia. Along the east Australian coast, storm events have been found to show strong correlation with the state of ENSO, with storm wave direction, long term mean sea level and the rate of storms being impacted (Davies et al, 2017). Typically, during El Niño events waves are bi-directional with southeast and easterly waves conditions. La Niña events are associated with a uni-directional south easterly wave climate (Mortlock and Goodwin, 2016). Another index used to assess the states of the ENSO is the Oceanic Niño Index (ONI). The variability in ENSO in Australia over time is displayed in Figure 48. The occurrence of extreme storm events at Newcastle is presented in Figure 49, many coincide with strong La Niña events.

The IPO is also related to changes in sea surface temperatures but are periods of a 20-30-year. Changes in sea surface temperature associated with the IPO are mainly in the northern and southern Pacific, whereas ENSO is linked to temperature changes in the equatorial Pacific.

Due to climate change, as the climate warms under increased global temperatures the seawater also warms and increase in mass. Not only does this lead to sea level rise (SLR) but it also impacts the climate variability as the circulation patterns are driven by differences in sea surface temperature. It can be expected that as the sea surface temperatures rise, the duration and intensity of extreme storm events will also rise. A combination of increases in extreme storm events combined with a higher sea level will lead to larger or more frequent storm surges at the coast. Various other complex climatic drivers exist and interact such as the Southern Annular Mode (SAM) and the Indian Ocean Dipole (IOD) and the relationships and interaction with respect to coastal conditions and shoreline response is not well understood.

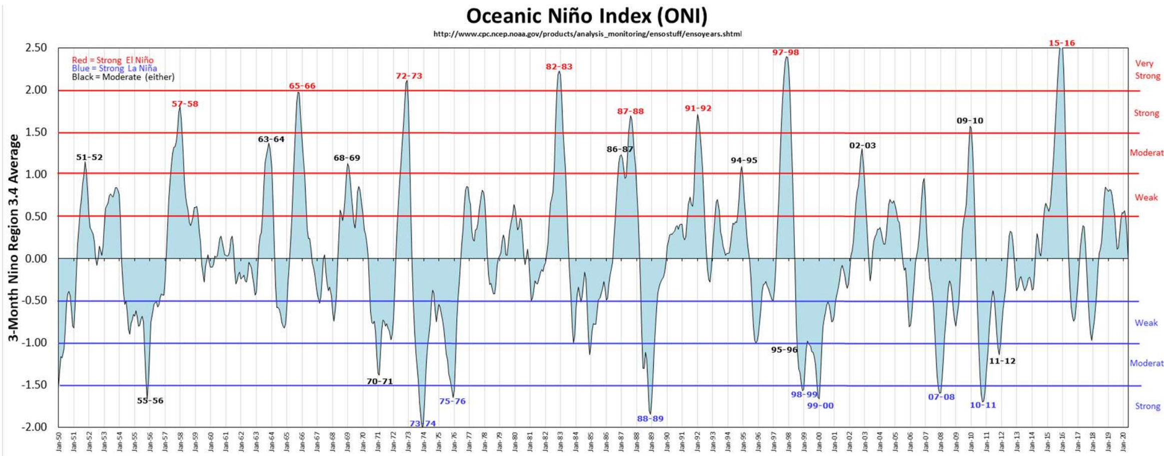


Figure 48: ENSO oscillations and relative intensities based on ONI index between 1950 and 2020 (source: NOAA).

Note: The red/blue annotations indicate strong El Niño and La Niña years, respectively.

Storm Date	Peak Ocean Level (AHD)	Hs (m)	MWD (deg true N)	Duration (hours)
May 1974	1.47	9.2	155*	75
June 1974	1.09	6.7	170*	217.5
Sept 1995	0.86	6.3	165	48
May 1997	1.21	9.9	151	78
July 1999	1.18	6.1	117	66
June-July 2000	1.26	6.1	177	54
July 2001	0.93	6.7	167	36
Jun-Jul 2002	0.81	6.0	174	48

*Directions were estimated based on personal discussions with Mark Kulmar, Dept. of Commerce, Manly Hydraulics Laboratory.

Figure 49: Overview of extreme storm events from May 1974 until June 2004 with associated water levels at Newcastle Pilot Station except for the 1974 events which were from Fort Denison (Source: DHI, 2006)

5 Bight sand budget

5.1 Preamble

Using datasets available, the following section provides an assessment of surveys, volumetric analysis of changes to the coastal profile as well as derivation and explanation of a sand budget derived for the Stockton Bight. Descriptions of sand movement processes such as cross-shore and longshore sediment transport are provided in Section 2.3 with a summary of the relevant process within Stockton Bight provided in Section 4.

5.2 Volumetric analysis

A key knowledge gap identified in the Scoping Study (CN, 2019a) was to determine the changes in the subaqueous part of the coastal profile. The coastal profile is the part of the cross-shore profile that is highly dynamic largely due to the action of waves, as well as tide, wave-driven currents and wind. The coastal profile can be divided into several zones, herein we will discuss the subaerial part (i.e. the land-based part above 0m AHD) and of the subaqueous part (i.e. the part below the water approximated by 0m AHD) as displayed in Figure 25.

An assessment of the change in the sand volume within Stockton Bight was undertaken adopting the analysis compartments in Figure 50. This assessment considered the datasets listed in Table 8 for the:

- Subaqueous part of the profile using historical bathymetric surveys from the period from 1866 to 2018.
- Subaerial part of the profile using:
    - NSW beach profile dataset between the northern breakwater and Fern Bay for the period from 1953 to 2020.
    - Available LiDAR data with various coverage between Stockton and Birubi Point for the period from 2011 to 2018.

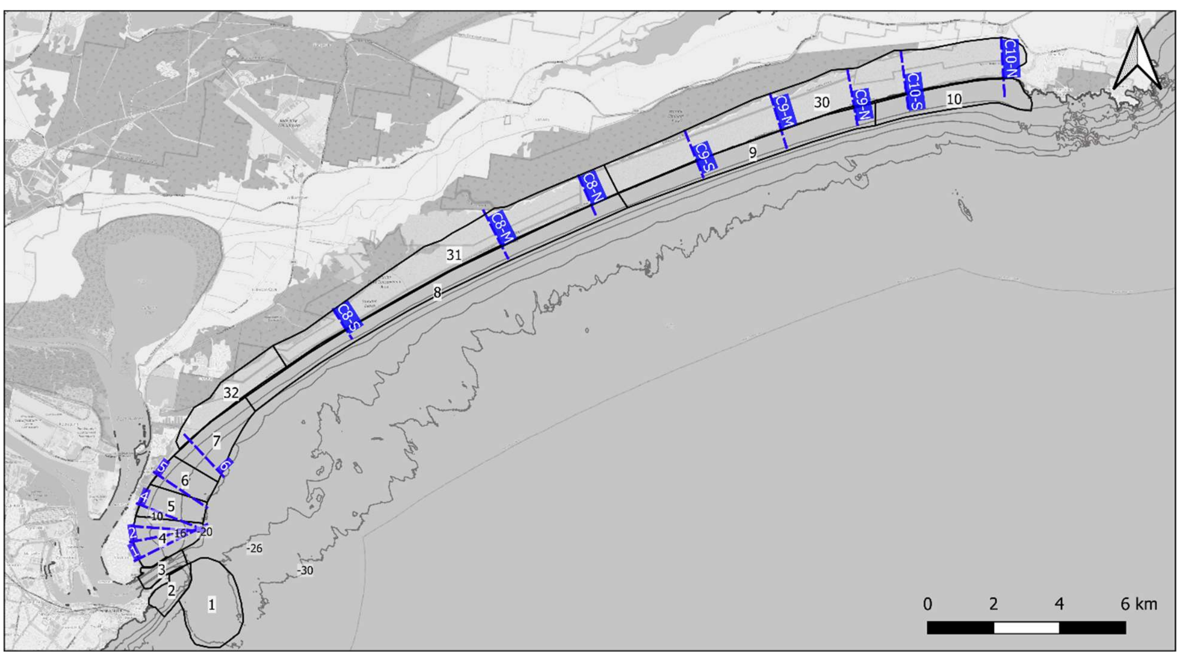


Figure 50: Adopted compartments (black boxes) and profile locations (blue lines) for the volumetric analysis.

5.2.1 Subaqueous change

To determine the changes in the subaqueous zone, the sand volume relative to the 2018 survey was calculated for each survey. Where survey coverage allowed, volumes were determined for the adopted nearshore compartments (Figure 50). The subaqueous sand volume change for all compartments are provided in Table 4. A timeseries showing the subaqueous sand volume change in compartment 4 and compartment 5 offshore of Stockton Beach, the compartments with the largest number of datasets available, is shown in Figure 51.

The observations show a long-term trend of sand loss from the subaqueous part of the coastal profile in the southern areas of the Bight. While survey data is sparse for the northern areas, a long-term trend of accretion was identified there. The comparisons of surveys across the compartments show:

- Over the 152-year record over 8 million cubic metres of sand has been lost from compartments 4 and 5. Using linear regression this is equivalent to a long-term rate of approximately 76,000m^3/yr. Until 1988 the rate of sand loss, as determined by linear regression, was 70,000m^3/yr. Since 1988 the rate of loss has increased to just over 107,000m^3/yr with the value of 100,000m^3/yr adopted as the representative rate for these two compartments.
- Sand loss has also been observed further downdrift in compartments 6 and 7, however, there is less temporal coverage available. Within compartments 6 and 7 there has been around 5 million cubic metres of sand lost since 1988, a rate of loss of 170,000m^3/yr.
- For compartments 8, 9 and 10 the satellite derived bathymetry data (2010 and 2012) obtained for this study is the only dataset available for comparison against the 2018 bathymetry. Given the limited cross-shore extent and intermittent data gaps, the volumetric analysis was undertaken for a series of profiles extracted from areas with appropriate coverage. Three profiles were extracted for each compartment to calculate the subaqueous profile volume changes (Figure 51) and an average rate was applied to the compartment length. While compartment 8 showed a net loss of sand of around 130,000m^3/yr, the northern compartments 9 and 10 show net accretion of around 140,000m^3/yr for the six to eight-year period.
- Compartment 3 covers the extent of the navigation channel and as expected, the volumetric analysis shows a long-term trend of sand loss from the subaqueous profile. Surveyed sand quantities in this compartment have been substantially affected by dredging (more information is provided in Section 6.1.4).
- Compartment 1 covers the extent of the sand lobe located offshore of Nobbys Head to the east of the entrance channel and compartment 2 covers the subaqueous section of Nobbys Beach. Compartment 2 has gained over 2 million cubic metres of sand since 1957. Compartment 1 has spare temporal coverage but appear to be relative stable with only minor changes observed on the sand lobe.

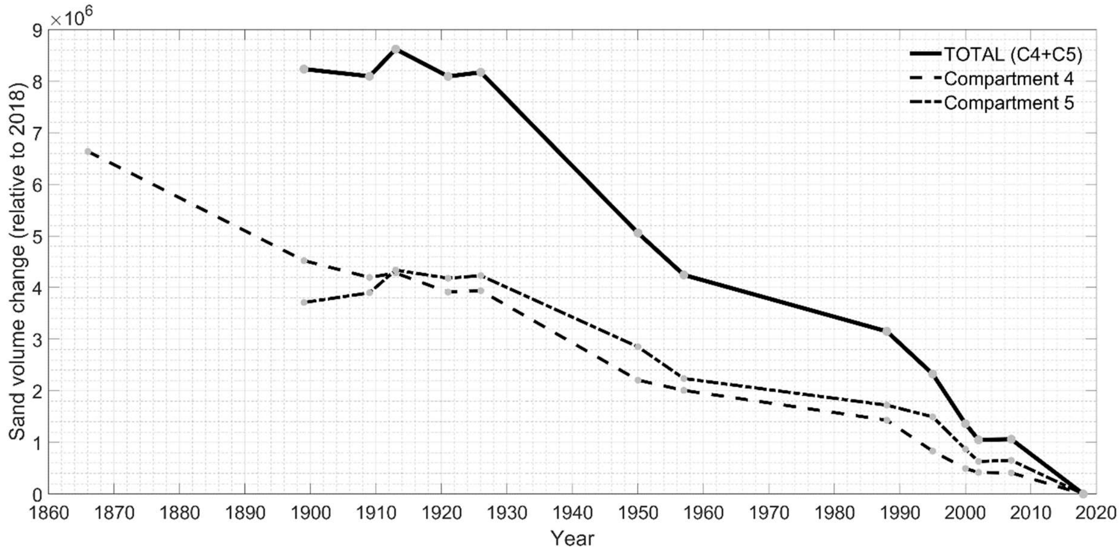
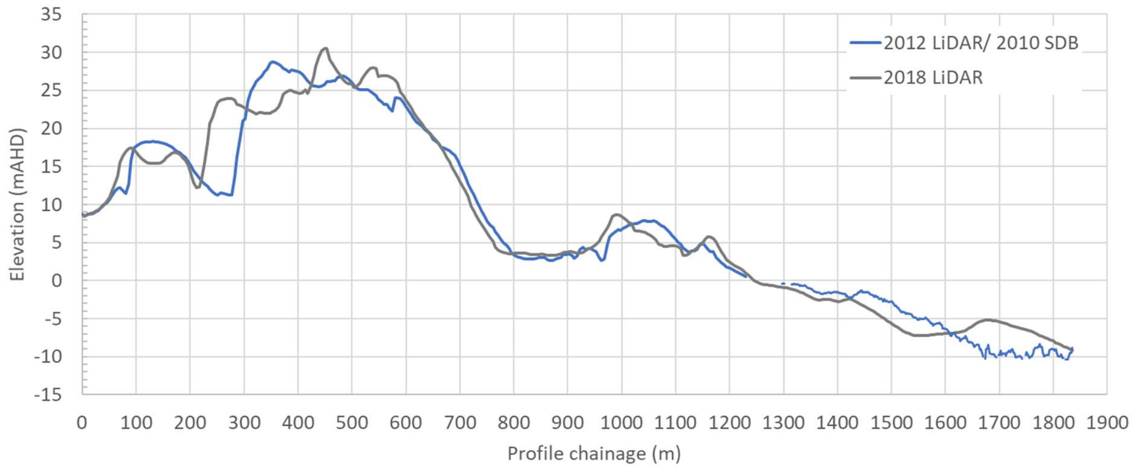
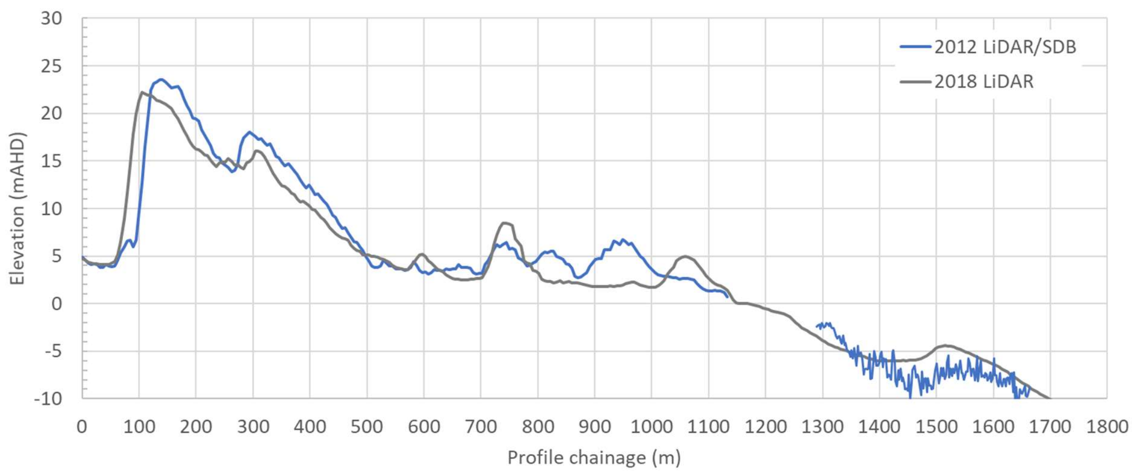


Figure 51: Long-term sand volume change at Stockton Beach (Compartments 4 and 5).





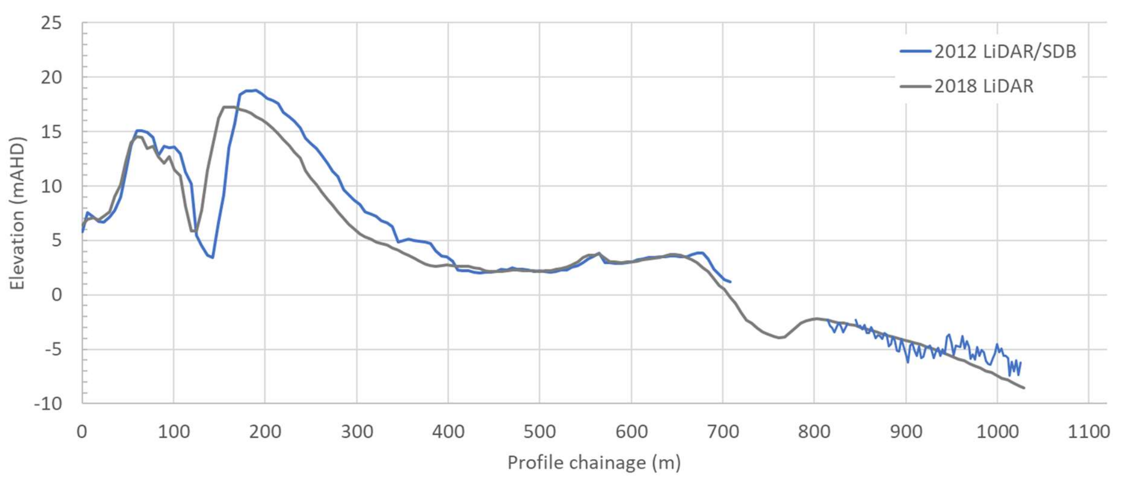


Figure 52: Comparison of full coastal profiles based on LiDAR and Satellite Derived Bathymetry (SDB) data at location (top) C10-N, (mid) C9-M and (bottom) C8-S.

Table 4: Cubic metres of sand relative to 2018 seabed levels in compartments at Stockton Bight.

Compartment	1	2	3	4	5	6	7	8	9	10
Compartment Area (m^2)	3,842,271	998,478	722,599	2,211,858	1,642,237	1,502,772	2,589,952	6,124,734	4,940,111	3,385,692
Year of survey	Volume loss (m^3) relative to 2018									
1866	-	-	3,557,757	6,635,863	-	--	-	-	-	-
1899	-	-	3,733,369	4,5217,95	3,710,343	3,314,104	-	-	-	-
1909	- -	-	4,196,072	3,897,621	-	-	-	-	-	
1913	- -	-	4,280,922	4,338,313	-	-	-	-	-	
1921	-	-	3,507,018	3,910,804	4,180,107	-	-	-	-	-
1926	-	-	5,597,229	3,938,704	4,230,474	-	-	-	-	-
1950	-	-	3,132,118	2,206,424	2,850,520	-	-	-	-	-
1957	-	-2,082,451	3,129,213	2,006,998	2,237,630	1,459,643	-	-	-	-
1988	162,285		137,695	1,429,336	1,721,124	1,836,225	-	-	-	-
1995	-	-	-	829,893	1,494,680	-	-	-	-	-
2000	-	-	-	493,237	867,584	-	-	-	-	-
2002	-167,575	-115,039	244,260	417,654	630,852	454,507	629,244	-	-	-
2007	-	-	400,192	409,488	651,785	449,090	484,744	-	-	-
2010	-	-	-	-	-	-	-	-	-	-653,776
2012	-	-	-	-	-	-	-	-791,454	-337,122	-
2018	0	0	0	0	0	0	0	0	0	0

Sensitivity analysis for sand loss rates

To quantify the level of uncertainty to the pivotally important sand loss rate in the southern embayment a sensitivity analysis was undertaken. This analysis focused on sediment compartments 4 and 5 where the adopted rates were based on the 1988 to 2018 period as:

- **112,000m^3/yr** – consisting of the adopted subaqueous sand loss rate of 100,000m^3/yr combined with the subaerial loss rate of 12,000m^3/yr.

Selection of this 30-year period was justified by the channel deepening project that occurred in the late 1980's and corresponding acceleration of observed sand losses within the southern Stockton Beach compartments. Prior to the channel deepening project, the navigation channel was around 11m deep and still unsafe for the passage of larger vessels due to the presence of a shallowing sand shoal. Sediment tracer measurement in the 1966 indicate that around 23,000m^3/yr of sand moved northward from this shoal towards Stockton (Boleyn and Campbell, 1966). The channel deepening project created a 150m wide channel to a depth of 18m, and it was no longer possible for any significant quantities of sand to move from the channel to Stockton (i.e. the deepened channel was an effective sand trap). Sand bypassing of the entrance is discussed further in Section 6.1.2.

This value can be compared to the longer-term rate of 83,000m^3/yr. The longer-term rate is around 30,000m^3/yr (or 27%) less than the adopted rate. The long-term rate is based on the addition of the subaqueous loss rate of 76,000m^3/yr (152-year record from 1866 to 2018) and the subaerial loss rate of 7,000m^3/yr from the longest available photogrammetry record.

DPIE's 2018 coastal LiDAR (LADS) survey has been adopted as the baseline survey for the subaqueous volumetric analysis. To test the influence on this selection, the DPIE jet ski single beam survey from the 13th July 2020 was adopted as an alternative baseline survey and selected volumetric analysis undertaken. The results are shown in Figure 53, with the subaqueous sand loss rates in compartments 4 and 5 for the 13th July 2020 baseline calculated as approximately 73,000m^3/yr (excluding the 2018 coastal LiDAR survey) and 83,000m^3/yr (including the 2018 coastal LiDAR survey) as compared 107,000m^3/yr for the 2018 baseline. Or between 23 and 32 per cent lower, respectively. These differences can largely be explained by small observable difference in the seabed level between the surveys. The 2018 Coastal LiDAR survey is slightly lower and returned a mean, median and standard deviation of vertical difference of 0.20m, 0.18m and 0.5m when compared to the 13th July 2020 survey.

The two surveys used as baselines in this sensitivity analysis were collected used different methods at different spatial resolutions. It is not clear which is more accurate. The DPIE's 2018 coastal LiDAR (LADS) survey was adopted for this study, as this is the only survey with both subaerial and subaqueous zones over the entire Stockton Bight. It is also captured at a much higher resolution than the available single beam bathymetric (i.e. subaqueous only) surveys.

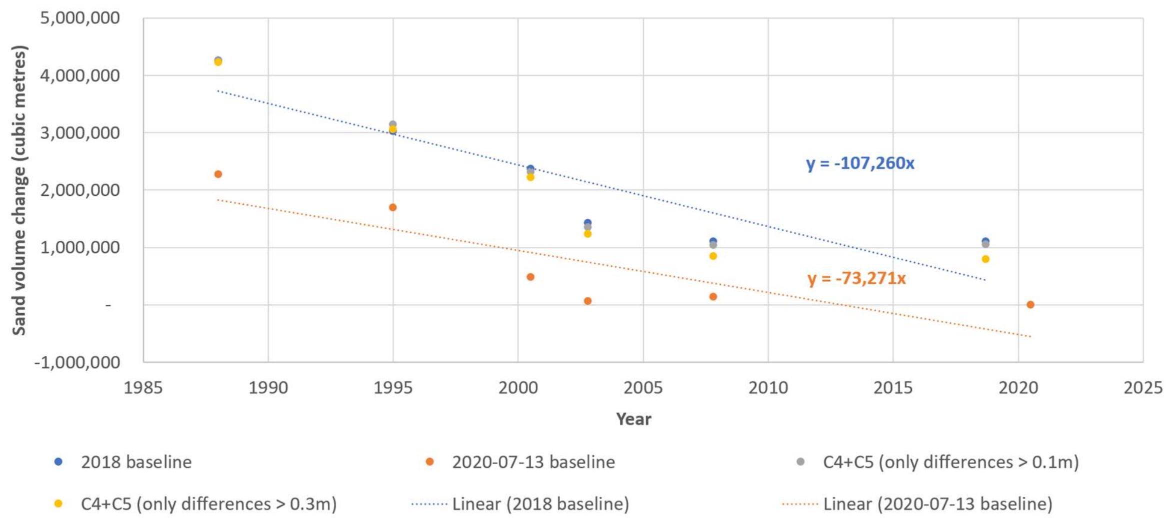


Figure 53: Results of sensitivity analysis to baseline survey selection.

Note: the plot shows linear regression lines fitted to the sand volume change in compartments 4 and 5, for the 13th July 2020 baseline, the case with the 2018 survey excluded is shown.

A sensitivity analysis to survey error was also undertaken whereby all survey differences less than ±10cm and ±30cm were excluded from the volumetric analysis using the 2018 baseline. The results were a subaqueous sand loss rate of approximately:

- 111,000 m^3/yr or 3 per cent higher without excluding the ±10 cm tolerances
- 119,000 m^3/yr or 11 per cent higher without excluding the ±30 cm tolerances

These relatively small changes in the computed rates are consist with the observed survey differences displaying a consistent pattern of large differences in discrete areas rather than small differences over large areas.

While, as noted in Section 1.5, a degree of uncertainty remains in these estimates, overall, the sensitivity analysis has confirmed that the adopted subaqueous sand loss rate in compartment 4 and 5 of 100,000m^3/yr are defendable. Moreover, the results of the sensitivity analysis have been used to quantify the uncertainty in the sediment budget and sand movement rates presented herein.

The question of accuracy is often raised when using bathymetric surveys for volumetric analysis. And particularly when historical surveys undertaken using previously available techniques (e.g. lead lines) are used. Other issues include accounting for land subsidence and/or sea level rise. While there maybe inaccuracies in the older historical surveys these have not been used to derive the sand loss rates carried forward to the Bight's sand budget (see Section 5.3).

Volumetric analysis has also been completed for the older (pre-1980's) surveys and while this quantitative information is referenced herein, these older surveys were mainly used to provide evidence of the presence of large morphological features like the ebb tide delta (or entrance bar) that once existed off Stockton Beach. This feature had dimensions of approximately 900m (cross shore) by 1,500m (alongshore) with depths less than two metres (relative to AHD). Waves breaking across this relict bar is depicted in Figure 54, providing a form of validation for the presence of the feature. Wave breaking is also annotated on the shoal as 'Nearly always breaking' in the navigation chart from 1866. Another validation of the presence of this bar is the numerous shipwreck that were mapped onto this shoal in historical charts. Moreover, the location of the ebb tide delta is in keeping with the morphological settings of the time.

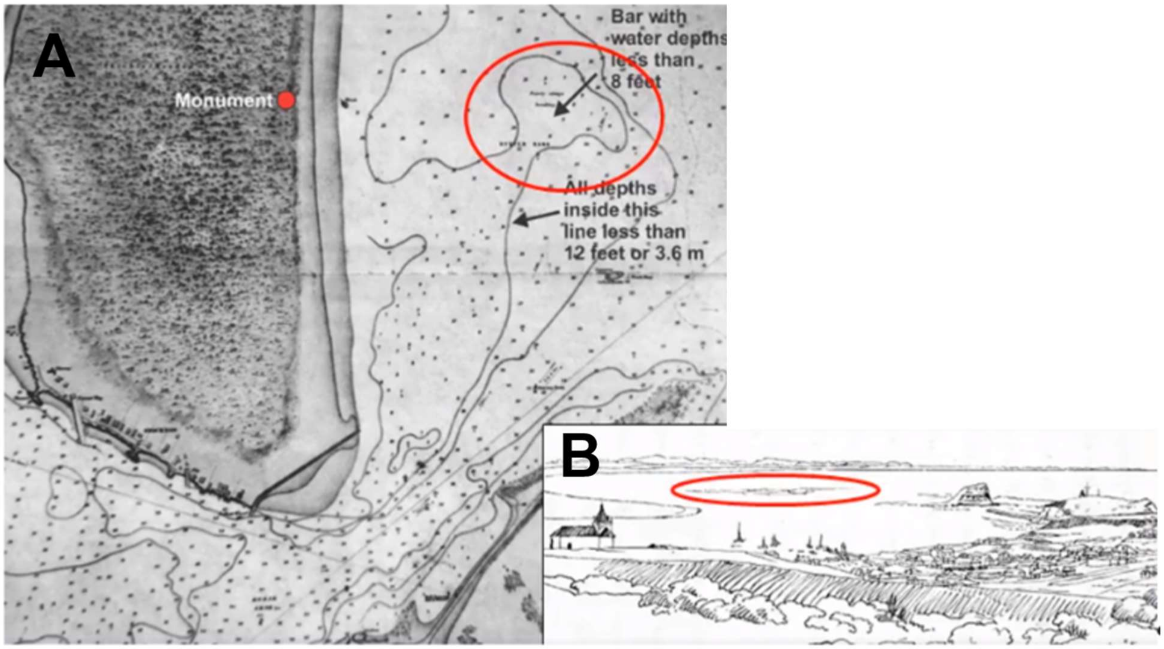


Figure 54: Cross-checking of historical survey data based on other sources of information (source: University of Newcastle, Professor Ron Boyd)

Note: the red circle in both images show the location of the 'Oyster Bank' the relict ebb tide delta. The insert (B) shows a depiction of early Newcastle with wave breaking clearly depicted in the drawing.

Accounting for sand placement activities

The sand volume changes presented in Figure 51 and Table 4 are based on the bathymetric surveys only, they do not consider any sand placed in the compartments as part of beach nourishment efforts.

The Port of Newcastle (PoN)[3] is responsible for maintaining safe depths in the port's navigation channel. This requires maintenance dredging of significant annual quantities of silt and sand (~300,000 to 500,000m^3/yr) from the port's channels. A small proportion of this material is sand dredged from Area E (the port entrance), which PoN place in the nearshore area of Stockton Beach as a beneficial reuse of the dredged material. This sand is placed within an area prescribed by then NSW Office of Environment and Heritage (now DPIE). The placement area is within compartments 4. The remainder of the maintenance material dredged from the port channels is dumped offshore.

Table 5 presents the known sand nourishment volumes placed in compartment 4 from Area E. Based on the quantities in the table, approximately 34,000m^3/yr of sand was placed in at Stockton between 2009 and 2019. Had this sand not been placed as beach nourishment the rate of sand lost from compartment 4 and the adjacent compartment 5 would have been higher (e.g. approximately 100,000m^3/yr (sub-aqueous from survey) + 12,000m^3/yr (sub-aerial from photogrammetry) + 34,000m^3/yr (sand placements from dredging records) = 146,000m^3/yr). It is unclear if beach nourishment placements were carried out prior to 2009 although there is reference to some sand placements in the 1960s.

Capital and maintenance dredging are further discussed in Section 6.1.4.

[3] Prior to 2014, the Newcastle Port Corporation (NPC) were responsible for the operations of the port, including channel maintenance dredging.

Table 5: Cubic metres of beach nourishment sand placed in compartments 4 and 5 because of port operations[4].

Year	Sand volume placed at Stockton (m^3)
2009/2010	130,000*
2010-2011	unknown (likely nil)
2012	9,233
2013	29,845
2014	6,309
2015	58,280
2016	27,945
2017	25,839
2018	25,542
2019	30,958**
TOTAL	**343,951**

*Volume sourced from WorleyParsons (2012).
**In December 2019 approximately 3,500m^3 of nourishment material that had been sourced from local quarries and was placed on the upper beach at the southern end of Stockton Beach. This was undertaken as part of a pilot study. The sand trial volume has been added to the volume placed by PoN.

Comparisons to previous studies

WBM (1998) presented a volume for one million cubic metres as the net loss of sand from the 3km of beach north of the breakwaters for the period between 1957 to 1995. This is equivalent to a sand loss rate of approximately 26,500m^3/yr. The 3km alongshore extent is similar to that of compartments 4 and 5 but the WBM (1998) sand loss rate is only half of that value that can be obtained from the volumes in Table 4 for the equivalent period. The reason for the difference in the estimated sand loss rates is unknown but may be due to the cross-shore extent of the surveyed area used by WBM.

Umwelt (2002) undertook a comprehensive analysis of historical bathymetric surveys to estimate sand loss rates for two areas (Area 1 and Area 2). Area 2 extends alongshore from the northern breakwater to south of Fort Wallace (see Figure 55) and is similar in extent to the combined area of compartment 4 and 5. Umwelt estimated Area 2 to experience an average sand loss rate of:

- 1921 to 2000: 67,000m^3/yr
- 1988 to 2000: 370,000m^3/yr

The long-term loss rate calculated by Umwelt for Area 2 is consistent with the sand loss rate from 1866 to 1988 calculated herein (70,000m^3/yr). However, the rate of 370,000m^3/yr given for the period from 1988 to 2000 is much higher than the rate of 100,000m^3/yr estimated herein for the period between 1988 and 2018. It is noted that the lower rate presented herein does not discount the beach nourishment quantities. However, when these are included (i.e. equivalent loss rates of 134,000m^3/yr) the rates are still lower than Umwelt's 1998 to 2000 rate and the difference is likely due to the shorter period of the analysis using the data available at the time of Umwelt's 2002 report.

[4] The volumes presented in this table have been sourced from various sources including records from PoN. The table may not present a complete and accurate picture and sand volumes placed at Stockton Beach (e.g. there may have been placements prior to 2009). Full and accurate records of maintenance and capital dredging and placements are important to inform coastal management.

DHI (2006) analysed bathymetry surveys from 1995, 2000 and 2002 and presented survey difference plots that showed erosion occurring in the surf zone, similar to the patterns presented in the Section below. While no volumetric analysis was presented in DHI (2006), that report did refer to the sand loss volumes and rates provided in the Umwelt (2002) report. Sand loss rates from Umwelt's Area 1 were used by DHI to justify the calculated net northward alongshore sediment transport rates of 20,000 to 30,000m^3/yr for the period between 1866 and 2004. However, it is recommended that littoral drift rates and the sediment pathways and fluxes calculated by DHI (2006), see Figure 20, be revisited based on the volumetric analysis completed herein.

Figure 55: Sand loss analysis areas used in the Umwelt (2002) report – (left) Area 1 and (right) Area 2.

Pattern of subaqueous losses

To examine the pattern of subaqueous sand loss at Stockton Beach, the following analysis results are provided:

- Maps of the changes in seabed levels relative to 2018 were produced for selected surveys and are shown in Figure 56 to Figure 59. In these maps, red indicates areas where the seabed has lowered, either by erosion (e.g. Stockton Beach) or by port dredging (e.g. entrance channel). Blue areas indicate areas of accretion. Areas of accretion are either formed by deposition of sediment (e.g. accumulation of littoral drift in the 'sediment trap' created by the port dredging – see compartment 20) or by sand placement activities (e.g. the effect of the beach nourishment placements that can be observed in compartment 4).
- Plots of the coastal profiles observed in the surveys at profile 3 and profile 4 (see Figure 50) along with the survey differences relative to 2018 are provided in Figure 60 and Figure 61, respectively.

There are several important features noted in these patterns:

- Erosion of the seabed in the southern embayment (compartments 4 and 5) has predominately occurred on the shallow slope inshore of the ~8m AHD depth contour indicating littoral processes by wave driven currents (i.e. longshore transport). More work is required to interpret the survey differences, but it appears that most of the sand lost from the southern embayment has moved north along the surf zone and shoreline. This is discussed further in Section 6.1.6.

- The effect of sand placement from Area E are evident. It is noted, however, that sand placements were undertaken shortly before the 2018 Marine LiDAR being captured. The majority of the approximately 340,000m^3 of sand placed in this area since 2009 is no longer evident in the survey difference maps. The bulk of the material is assumed to have moved onshore and then been transport/dispersed by alongshore and cross shore transport process. This is discussed further in Section 6.1.7.
- Erosion of the inner surf zone is still observed in compartment 4 inshore of the dispersed sand nourishment, this may be due to the response of the shoreline to erosion occurring to the north (i.e. realignment of the zeta shaped embayment in response to lack of sediment supply), see Figure 62.
- There has been minor accretion of the north-eastern aspects of the sand lobe (compartment 1), indicating a possible sand movement pathway from the entrance area offshore to the sand lobe located offshore of Nobbys Head.

Previous studies have suggested that the erosion problem at Stockton Beach was progressively worsening, with significant volumes of sand being permanently lost from the beach system (Umwelt, 2002). Moreover, studies have suggested that the on-going erosion is, at least in part, a result of the cessation of littoral drift past the entrance to the Hunter River and into the southern Stockton Bight compartment. These findings are supported by the analysis of long-term sand losses from Stockton Beach completed herein.

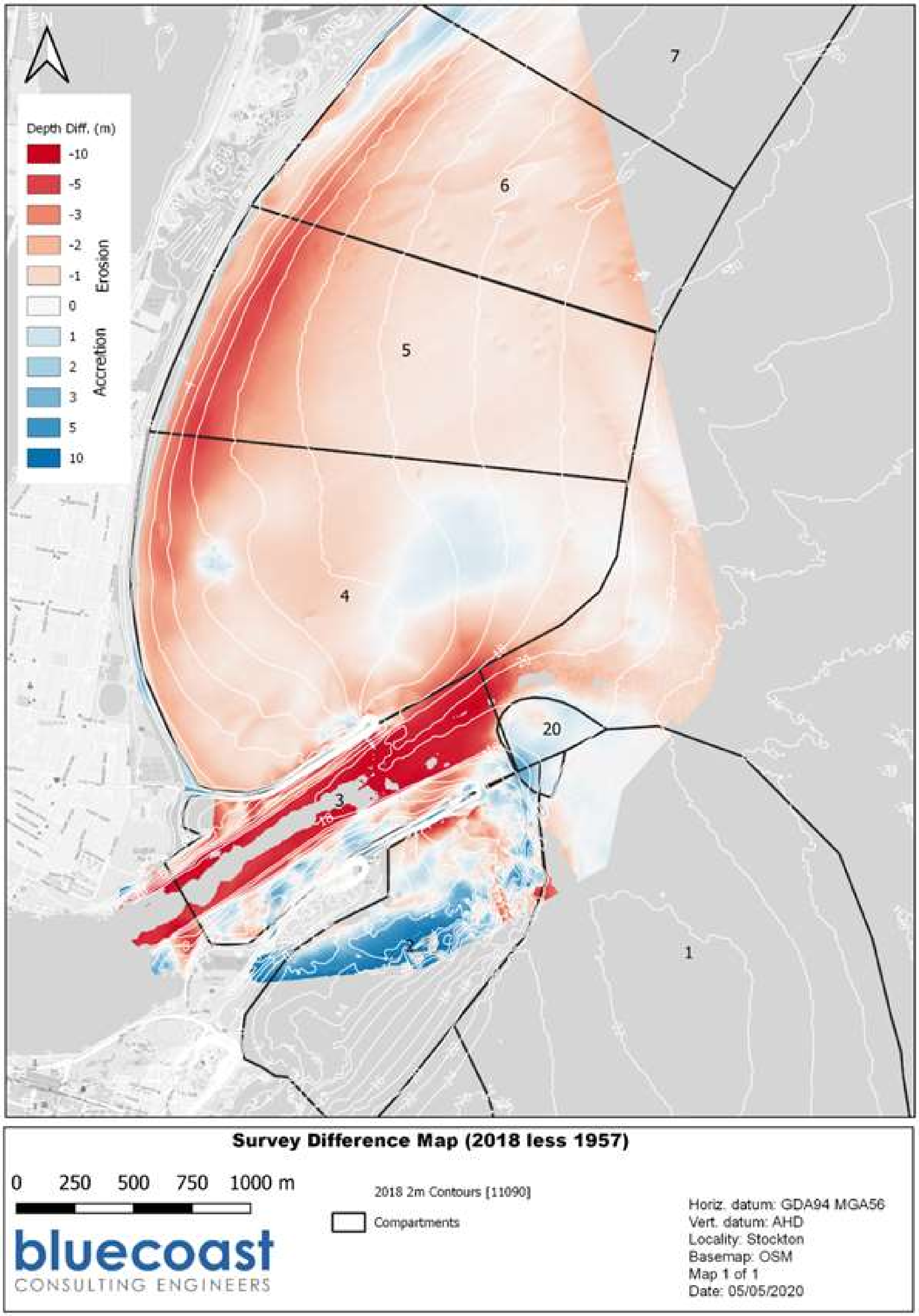


Figure 56: Survey difference map for 1957 relative to 2018.

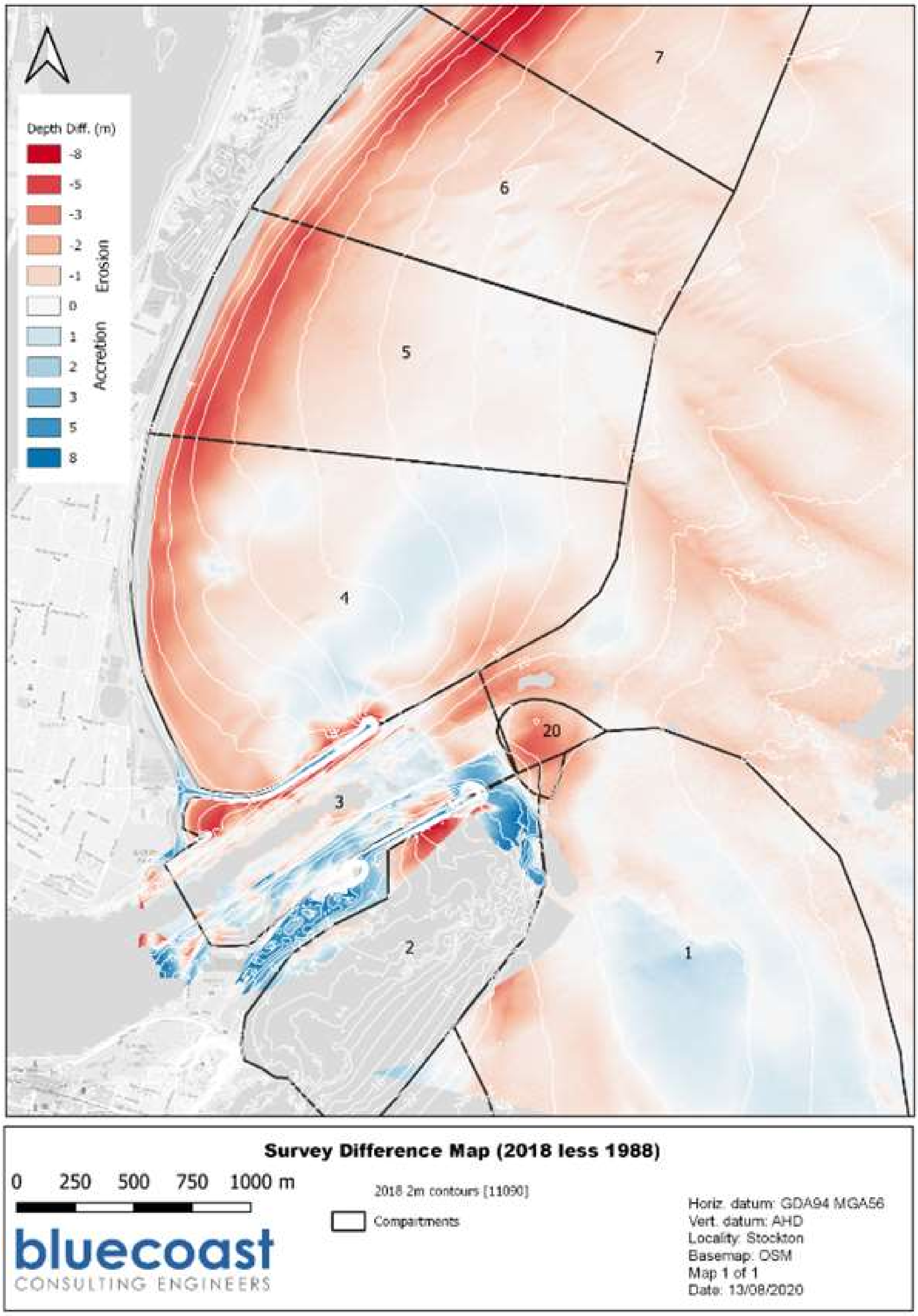


Figure 57: Survey difference map for 1988 relative to 2018.

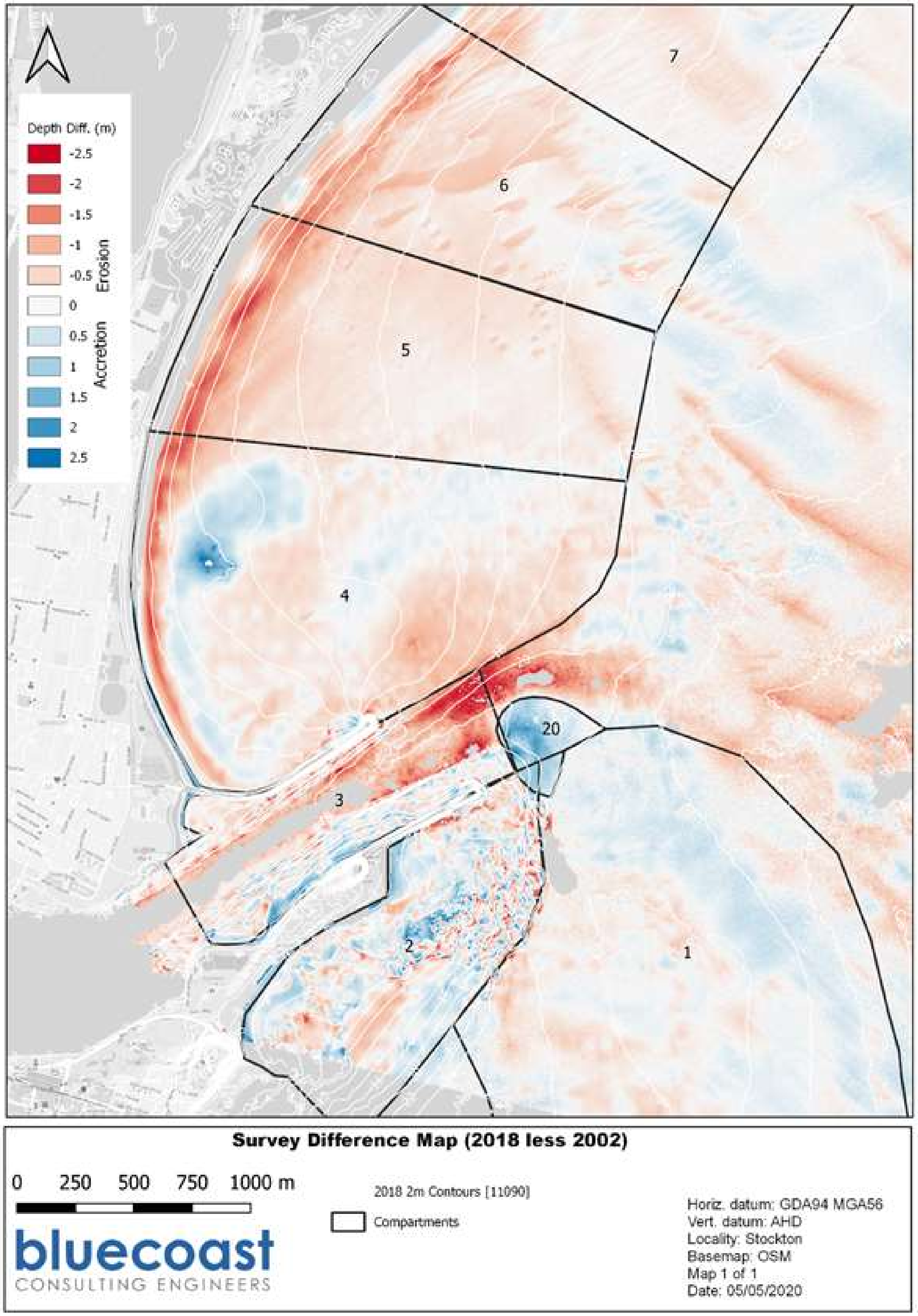


Figure 58: Survey difference map for 2002 relative to 2018.

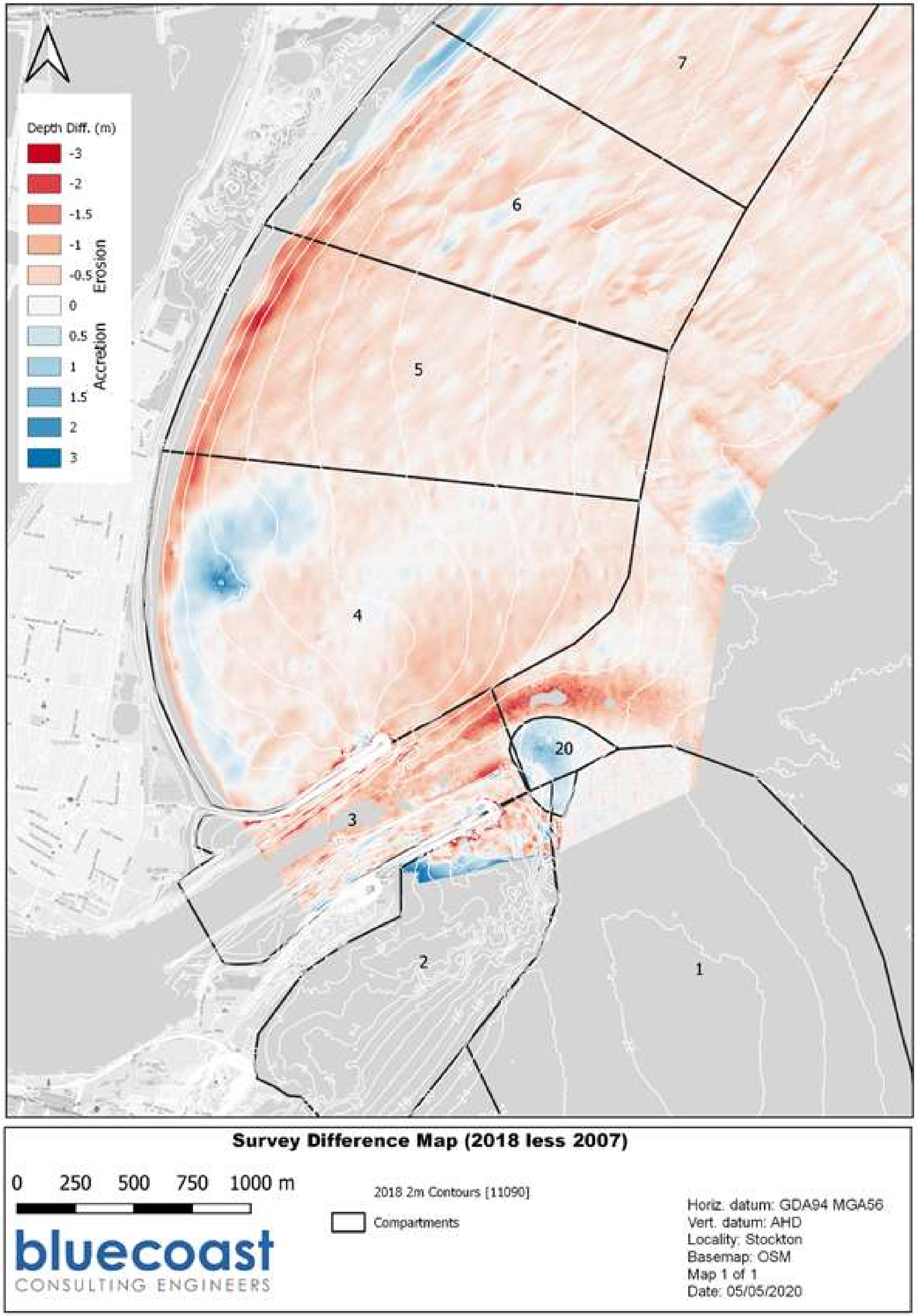


Figure 59: Survey difference map for 2007 relative to 2018.

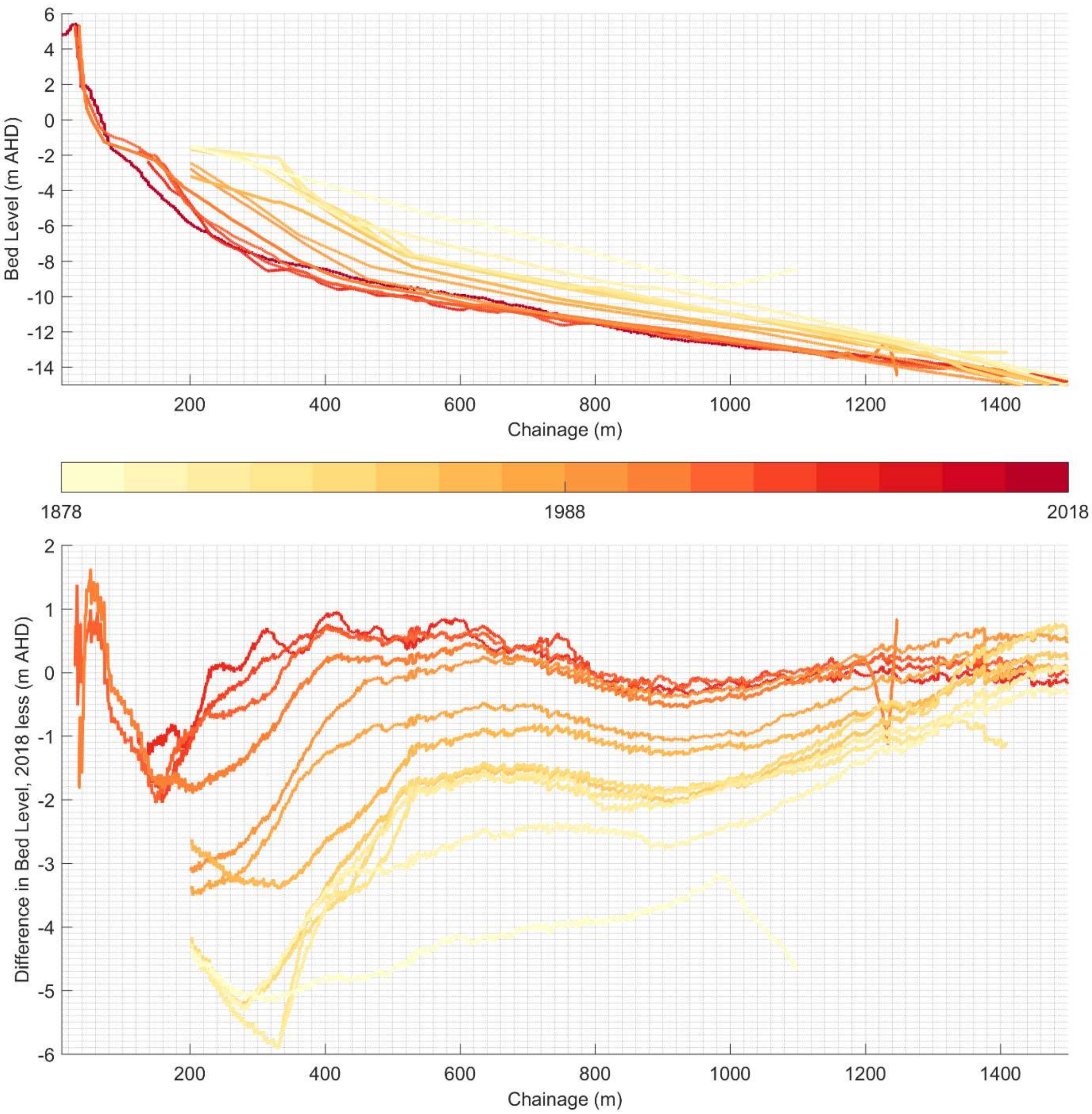


Figure 60: Historical coastal profiles (top) and profile change (bottom) based on historical bathymetric surveys for profile 3.

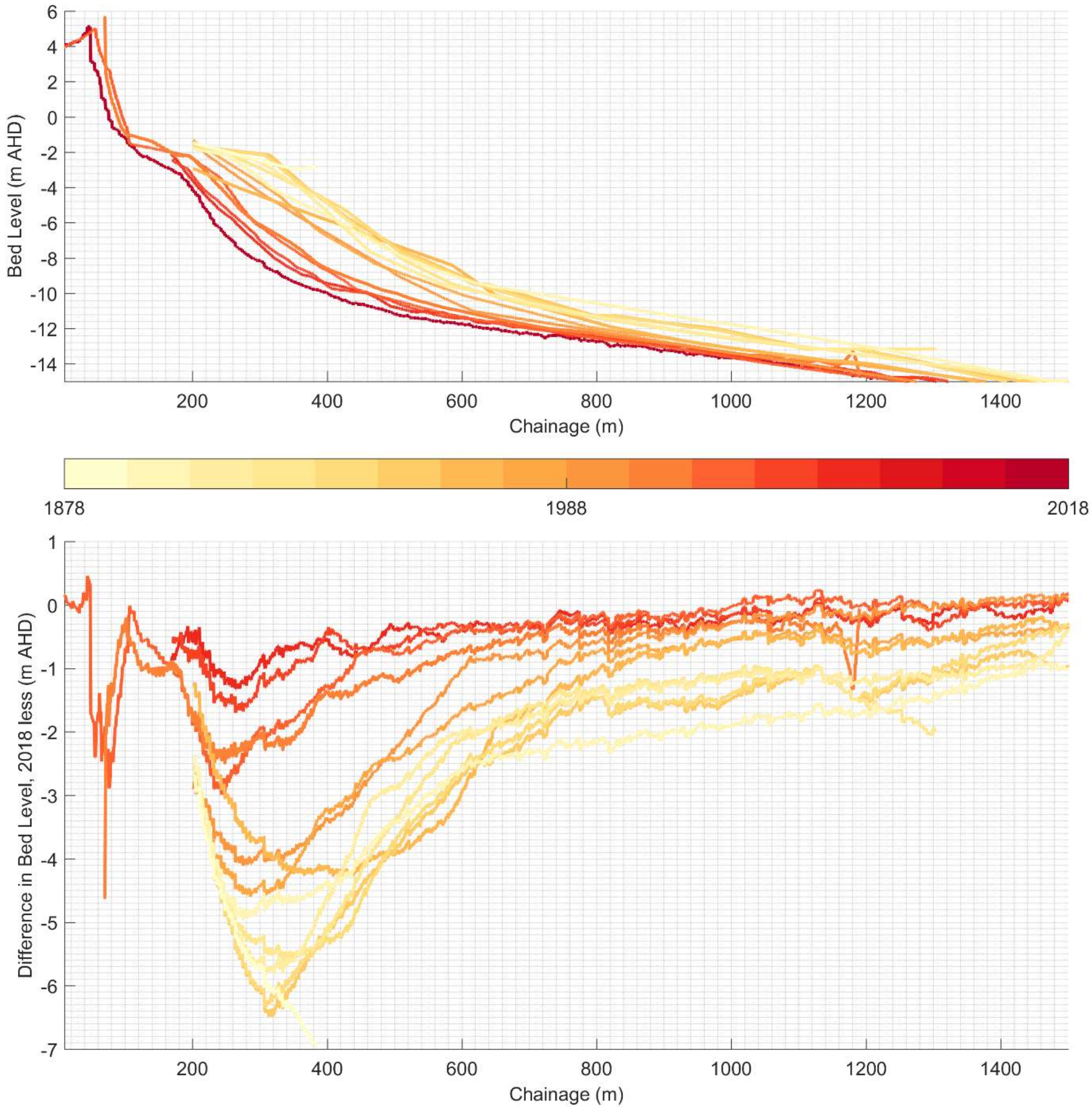


Figure 61: Historical coastal profiles (top) and profile change (bottom) based on historical bathymetric surveys for profile 4.

Figure 62: Mean sea level (0m AHD) shorelines from 2018 (inner) and 1994 (outer) showing realignment of the southern embayment.

5.2.2 Subaerial change

Beach profiles

The NSW beach profile data from the NSW photogrammetry database (DPIE, 2020) was analysed to determine the subaerial sand losses between the northern training wall and Fern Bay. No photogrammetry beach profile data was available for the remainder of the Bight. Instead topographic LiDAR data between 2011 and 2018 was found suitable for determining changes to the beach profile in this area. For comparison, trends observed in satellite derived shoreline positions from CoastSat between 1987 and 2019 (Vos et al., 2019) have also been assessed.

A summary of the estimated rates of volumetric change of the beach profiles are shown in Figure 63 and Table 6. Further detail on the analysis approach and profile changes are provided in the following paragraphs.

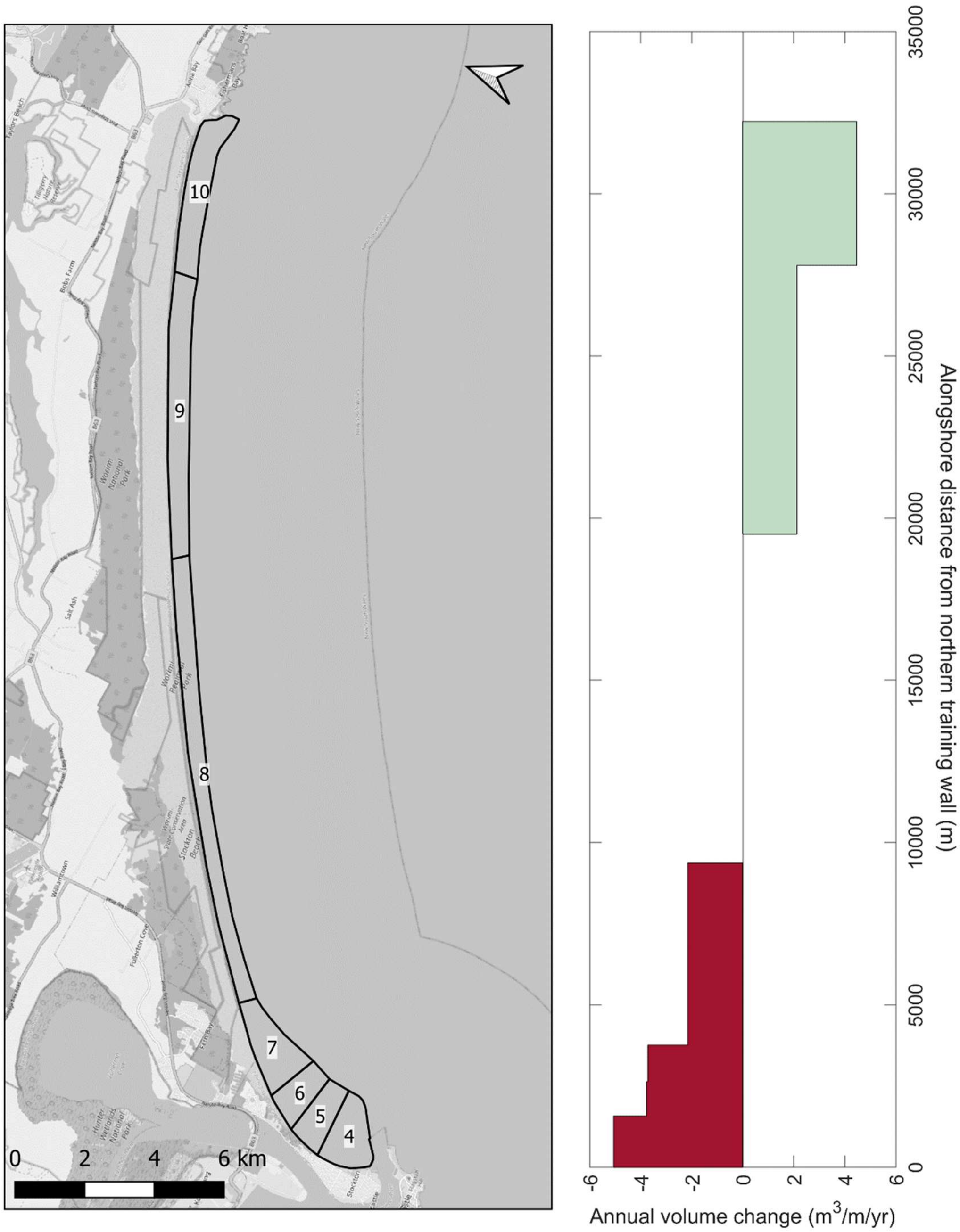


Figure 63: Estimated subaerial (net) rate of volume change along Stockton Bight.

Table 6: Summary of estimated long-term volume change of the subaerial beach along Stockton Bight.

	C4	C5	C6	C7	C8	C9	C10
Volume change rate (m^3/yr)	-8,000	-4,000	-4,200	-12,100	0	17,600	19,900
Linear change rate (m^3/m/yr)	-5.1	-3.8	-3.7	-2.2	0	2.1	4.5

Southern Bight

The analysis period adopted included photogrammetry data collected between 1952 and 2018 over the Stockton Blocks A, B and C and Fern Bay Blocks 3 and 4 (see Figure 64) which was the full temporal period available at the time of analysis. Where survey extents allowed, the photogrammetry record was extended to February 2020 using recent drone survey data collected by CN. The drone survey only covered analysis blocks Stockton Block A, B and C. From a linear regression analysis of the shoreline positions for various periods it was determined that the earlier photogrammetry data was not representative of the observed processes since completion of PoN's channel deepening project, therefore (long-term) trends in the subaerial beach profile were determined utilising data from 1985 to 2018 (2020 at Stockton).

A series of historic beach profiles for selected profile locations within each of the analysis blocks are shown in Figure 65. Figure 66 presents a timeseries of subaerial beach volumes for the Stockton and Fern Bay blocks. Similar to subaqueous extents, the Stockton CMP area (i.e. northern breakwater to Meredith Street) is conservatively considered to cover Block A, Block B and Block C. Between 1985 and 2020 the combined beach volume in these blocks has reduced by approximately 420,000m^3, an average loss rate of 12,000m^3/yr. Within Block 3 of Fern Bay beach volumes have reduced by approximately 136,000m^3 between 1983 and 2018. Beach volumes in Block 4 of Fern Bay, the northern most block along the stretch of coast, has seen an increase in beach volume by approximately 102,000m^3 between 1983 and 2018. The average rate of change in sand volume within these neighbouring blocks is a loss of 4,000m^3/yr in Blocks 3 and a gain of 3,000m^3/yr in Block 4.

The historic recession rates were estimated by extracting the cross-shore position of a defined elevation contour (i.e. 3 and 4m AHD) for each year in the data set. A linear regression analysis was then undertaken to estimate the long-term trends in recession or accretion.

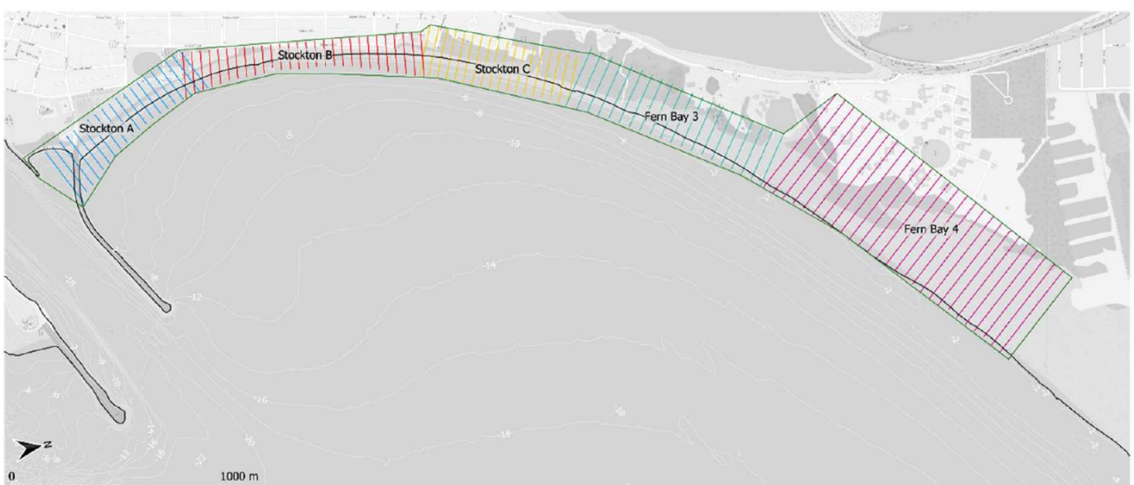


Figure 64: NSW photogrammetry blocks and profiles (coloured lines) at Stockton Beach.

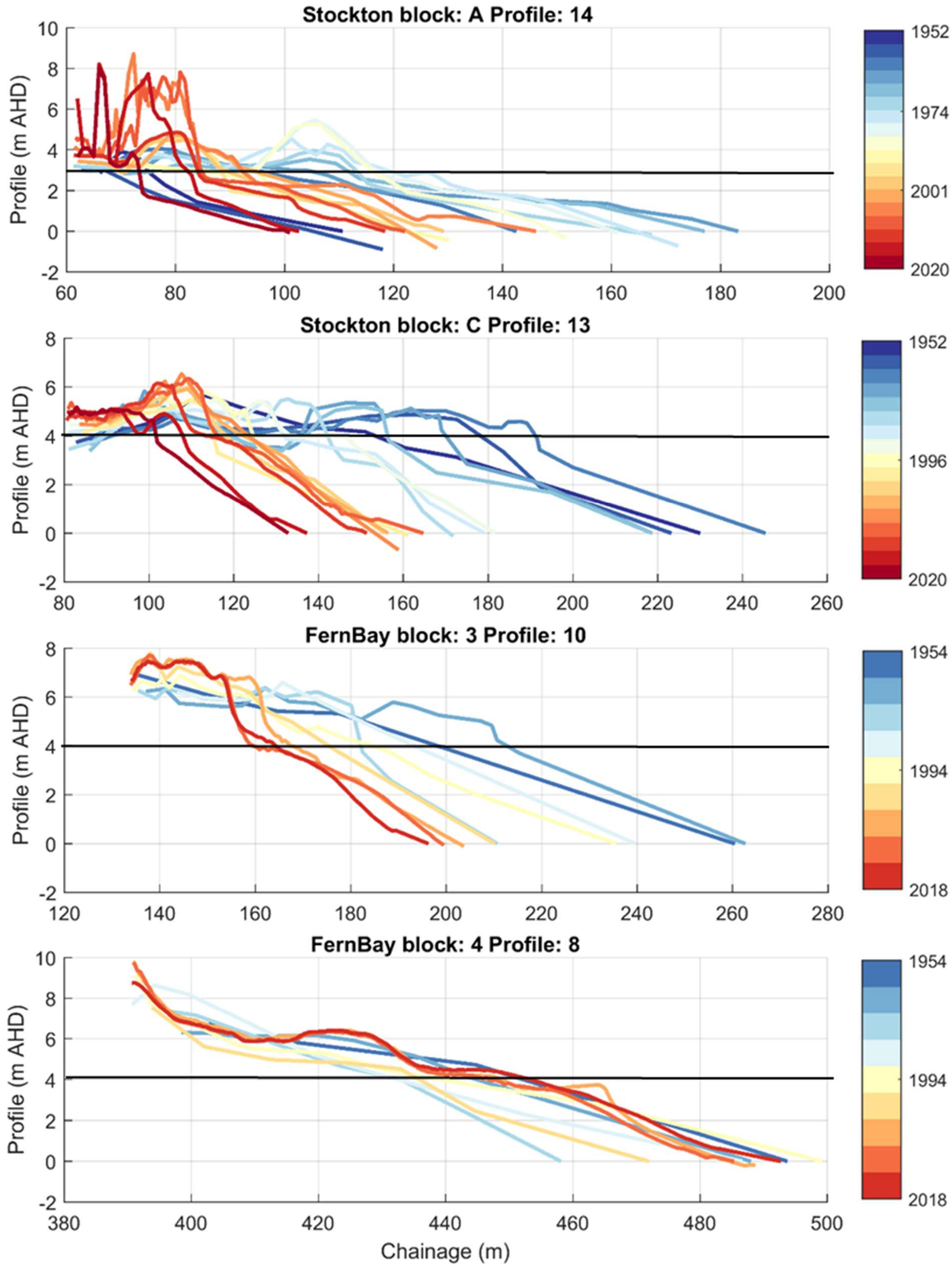


Figure 65: Photogrammetry profiles at blocks Stockton A to Fern Bay 4.

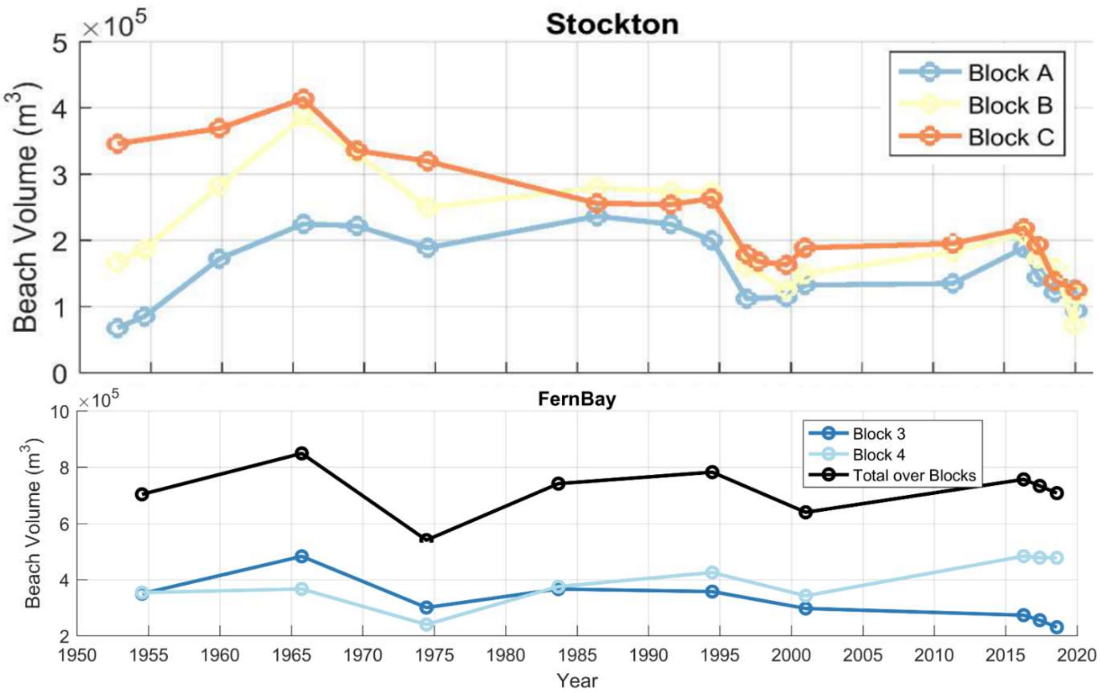


Figure 66: Timeseries of subaerial beach volumes for Stockton (top) and Fern Bay (bottom).

Beach profiles have been extracted from the available LiDAR data and the volumetric change between the 2012 and 2018 calculated to estimate the change to the subaerial beach of the corresponding analysis compartment. The extracted profiles are shown in Figure 52 (previous section). The volume calculations were undertaken for the beach area between the 0m AHD contour and the top of the foredune.

As the period between the available data set is relatively short (i.e. 6 years) a comparison of the estimated rates to trends observed in the satellite derived shoreline data was undertaken for verification. Two example timeseries of observed changes in shoreline position are shown in Figure 67. Potential cyclic (e.g. seasonal, decadal) changes to shoreline positions along Stockton Bight have been further assessed in Section 6.1.9. The observations in the shoreline positions and the estimated changes in beach profile volumes based on the LiDAR data were found to agree well and are considered to represent the long-term behaviour of the subaerial beach in the Bight.

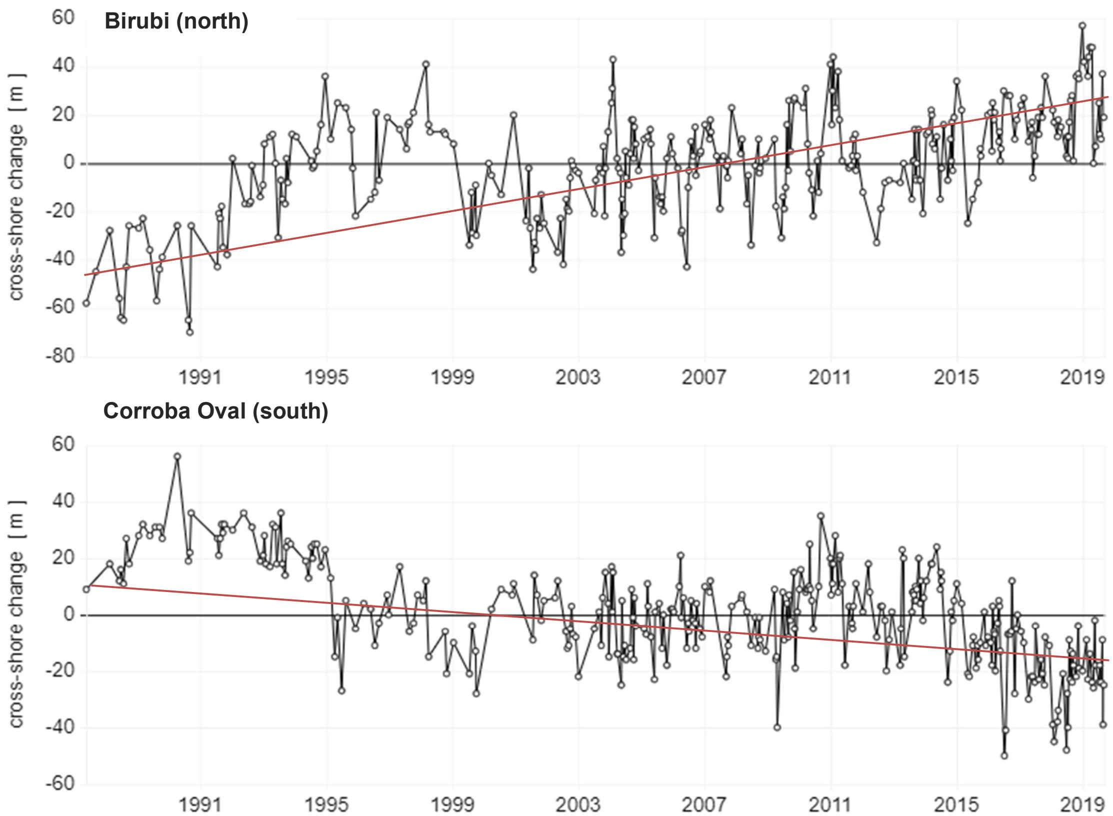


Figure 67: Example timeseries of changes in shoreline positions based on CoastSat (Vos et al., 2019) for the northern end (top) and southern end (bottom) of Stockton Bight. Note, the trendline is approximated.

Dune sheet

The total volume of the dune sheet (vegetated and non-vegetated) above the average elevation of the deflation basin (~3m AHD) was estimated as 489Mm^3. The elevation differences within the active dune compartments C30, C31 and C32 have been calculated over a 5 to 7 year period, largely using the 2012 and 2018 LiDAR data (see Figure 68). Where required, data gaps in the 2012 data were substituted using available data from 2011 and 2013. No repeat LiDAR data was available for the sand sheet extension near Williamtown through the neighbouring stabilised dune known as ‘The Tongue’. However, repeat LiDAR data was available for all other areas of the non-vegetated, active dune sheet.

The annual volumetric changes observed in the three dune compartments are presented in Table 7. It is noted that the calculated volumes include sand mining activities in compartment 30 and 31. Sand mining activity in compartment 31 near Fullerton Cove is stated at 300,000m^3/yr (RHDHV, 2020b) for extractions in the mobile dune (assumed 80% of annual quantity) as well as vegetated dune. Sand mining of the mobile dune in compartment 30 is evident near Anna Bay (off Nelson Bay Road) with estimated annual quantities of 50,000m^3/yr (TRRA, 2019), however no extraction records have been available for this study. Overall, a net erosive trend was identified in the most southern compartment (C32) whereas a net increase in sand volume was identified for compartments 31 and 30 over the analysis period.

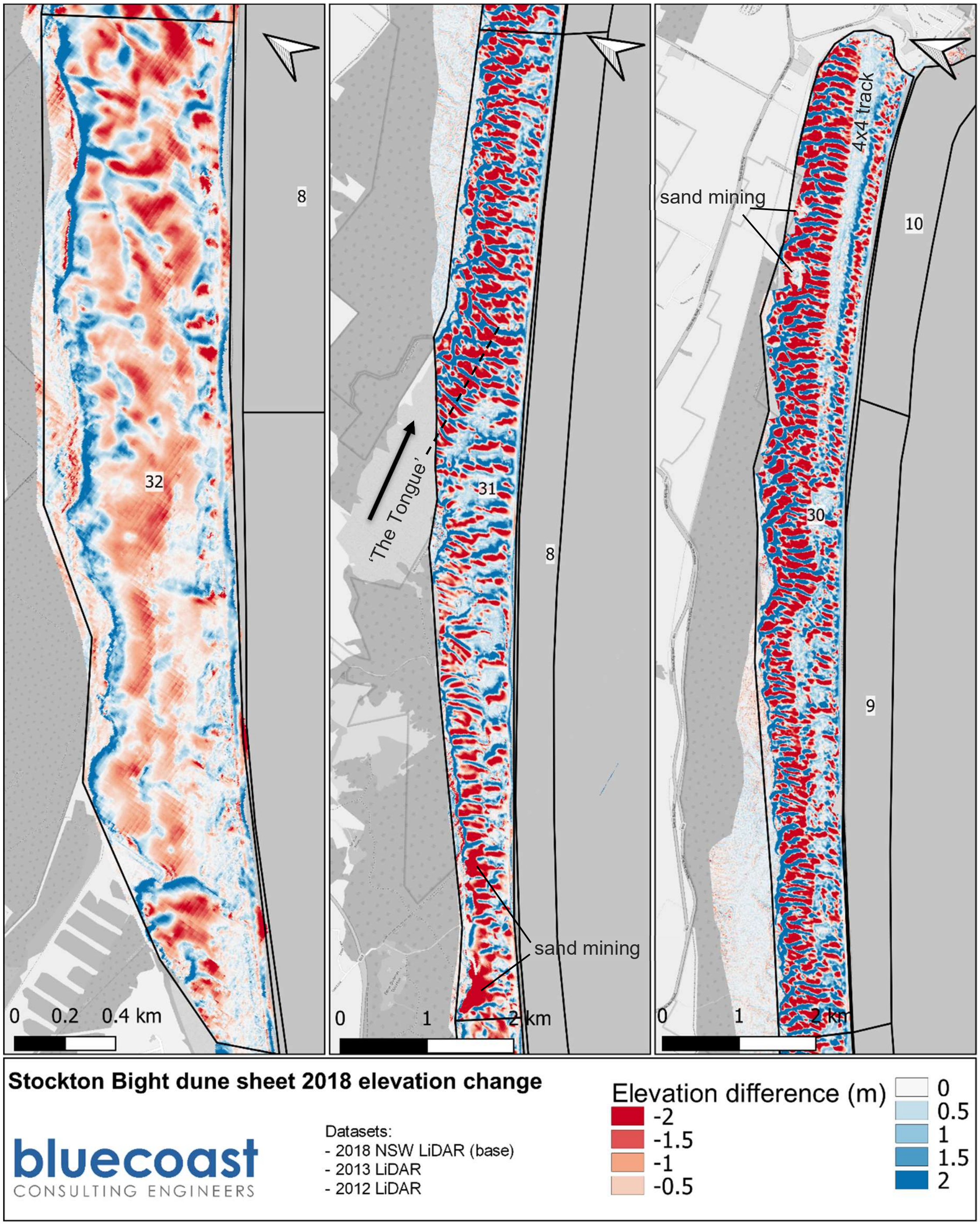


Figure 68: Elevation difference of the Stockton Bight active dune sheet between 2012/13 and 2018.

Table 7: Rates of volumetric changes observed in the adopted compartments on the active dune sheet between 2011-13 to 2018 .

	C30	C31	C32
Volume change (m^3/yr)	142,660	56,281	-13,586

As the 2018 LiDAR data does not cover the full extent of the sand sheet extension ‘The Tongue’, a volumetric profile analysis of the transverse ridges was undertaken where repeat survey was available to estimate the sand transport into the adopted analysis compartments. While variability in the migration direction has previously been observed in this area (Thom et al., 1992) a net northeast migration of the dune ridges was found in this area as seen in the West-East profile presented in Figure 69 (see profile location as dashed line in Figure 68). The northeast migration rate of the dune ridges with average crest elevations of around 15m was estimated at 2.5m/yr over the 6-year analysis period. Over the width of ‘The Tongue’ this was then estimated as a net sand transport rate into the adjacent analysis compartment C31 as 78,750m^3/yr.

Similarly, the alongshore migration of transverse ridges in compartment 30 showed a net north-east direction with an estimated rate of 7.2m/yr resulting in sand transport of around 145,000m^3/yr into compartment 31. This compares well with previous estimates presented in Pucino (2020).

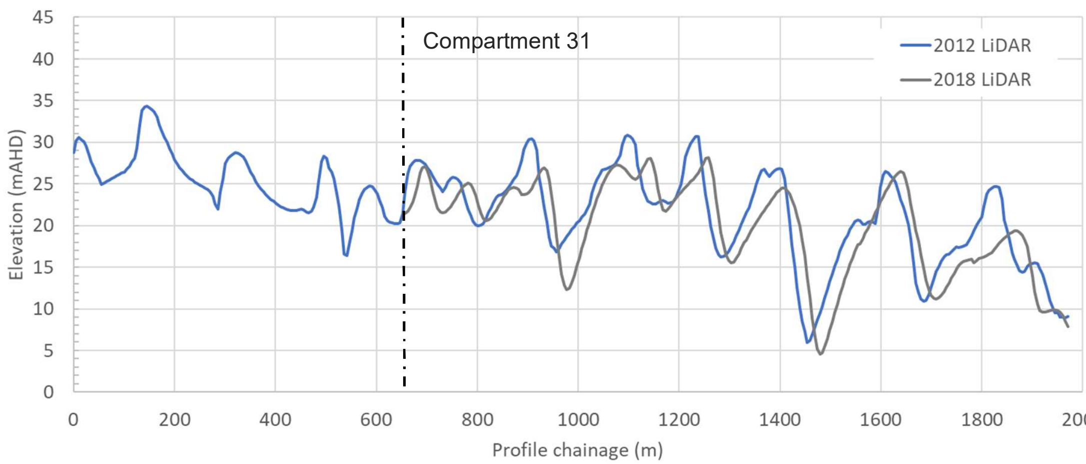


Figure 69: Transgressive W-E dune profile at the sand sheet extension near Williamtown (‘The Tongue’) showing net seaward sand transport into compartment 31.

5.2.3 Overall pattern of change

Based on the available topographic and bathymetric survey information Figure 70 shows the elevation changes observed across the entire Stockton Bight over the 5 to 11 years to 2018 (depending on the survey source). It is acknowledged that the metocean conditions that drive the elevation changes may not be representative of the longer-term conditions, however, this contemporary assessment suggests a series of notable features, including:

- clear net sand loss in the southern embayment predominately in the littoral zone, as described above
- net accretion in the north eastern coastal compartments superimposed on background cross-shore differences (i.e. changes in bar morphology) between survey dates, including seaward of the rocky headland at Birubi Point
- east-north-east migration of transverse dune ridges and northward migration of the transgressive dunes with an overall net accretion in the mobile dune system that backs the active coastal compartments
- sand mining extractions in the southern area (i.e. the older dune system) shows as continuous areas of net sand loss (red colour and as annotated in Figure 68).

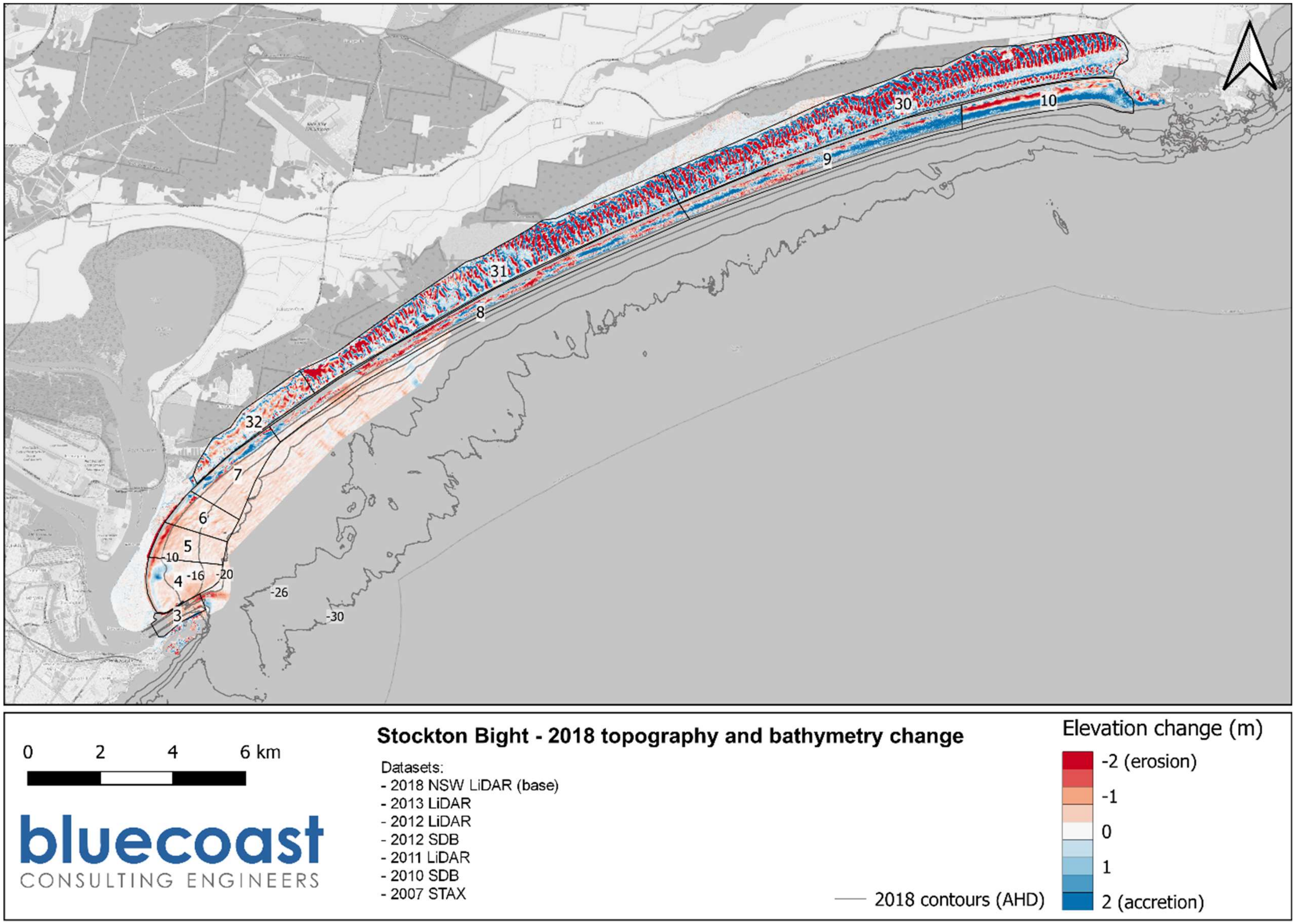


Figure 70: Elevation changes across Stockton Bight based on contemporary topographic and bathmetric survey informaiton.

5.3 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 Stockton Bight have been assessed for a series of coastal compartments (or 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 within the mobile dune sheet and anthropogenic changes such as dredge material placement and sand mining.

Sand transport rates and directions between the defined coastal compartments vary from year to year and with seasonal changes in the metocean climate. Adopting a historic analysis over several decades can provide long-term averages and net sand transport pathways useful to inform sound coastal management. Adopting such long-term analysis also reduces the relative significance of survey errors in the historic data which was confirmed by undertaking a sensitivity analysis of volume changes to small vertical differences in the survey data and adopted baseline survey (see Section 5.2). The error bands based on the sensitivity analysis are presented with the estimates transport rates.

The progressive transport rates between compartments were estimated using the sediment budget approach shown in Figure 71 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
- assessing the progressive surveyed changes in sand quantities for each compartment (where possible) since 1988 (i.e. after the port's channel deepening project)
- assuming sand bypassing of sand at the navigation channel and breakwaters (i.e. sand inflow to Stockton Bight at southern end) is nil as inferred by bathymetric changes
- known dredge material placement quantities, sand mining quantities and onshore sand transport rates based on literature (Roy, 2001)
- windblown sand inflow to the system from the Williamtown ('The Togue') dune compartment based on transgressive dune behaviour evident in available LiDAR data for adjacent compartment (no repeat LiDAR data was available for the Williamtown dune compartment).

Based on the above approach, inputs and outputs are applied to determine the change in volume (ΔV) in which $_{IN}$ and LST_{OUT} is longshore transport into and out of the compartment respectively, ON_{IN} is the onshore transport of sand via natural onshore sand supply or port sand placements, and $DUNE_{OUT}$ is the outflow to dunes (and potential inflow from dunes) via aeolian transport (see Figure 71).

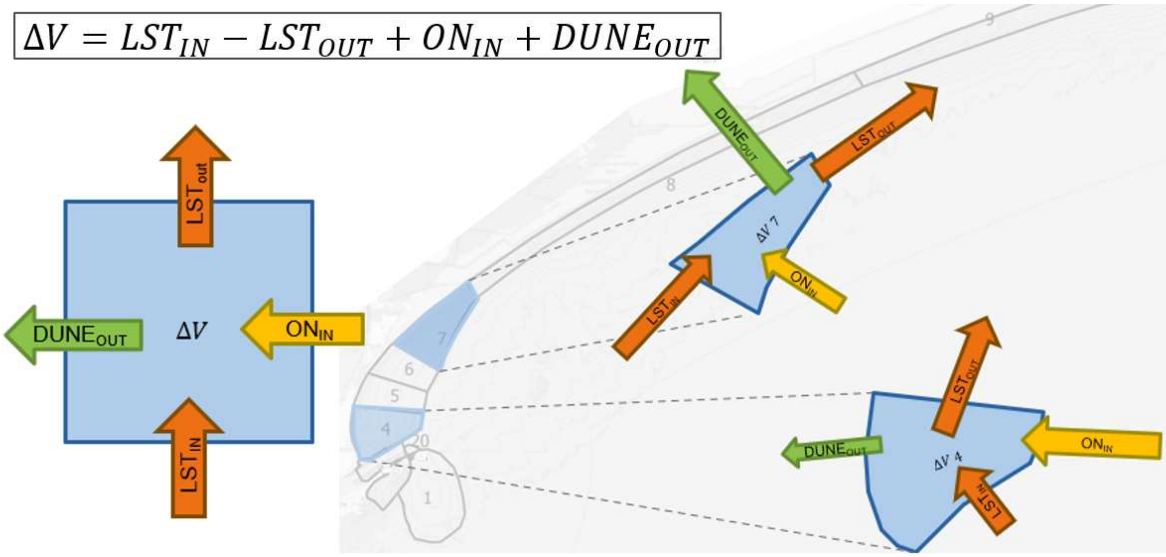


Figure 71: Schematic of the sediment budget analysis approach for Stockton Bight.

The sediment budget and net compartment changes within Stockton Bight are presented in Figure 72 and Table 8. In line with the survey analysis presented herein the sediment budget suggests that the southern compartments in Stockton Bight show a net erosive trend while the northern beach and dune compartments show a net gain in sand volumes. The pivot point of this trend was found within compartment 8, approximately mid-way along the Bight and as the coastline turns more to the east. The highest annual net north-eastward sand transport rates were found between compartment 6 and 7 and are gradually decreasing with alongshore distance in updrift and downdrift direction. Bypassing of sand around Birubi Point at Anna Bay was estimated to be around 44,000m^3/yr.

It is noted that only limited survey data was available for the dune compartments and compartments 8 to 10 which required analysis to be undertaken over a shorter period of 5 to 8 years. In absence of hydrographic surveys and photogrammetry data, the adopted datasets included LiDAR and satellite derived bathymetry data for years 2010, 2011, 2012, 2013 and 2018.

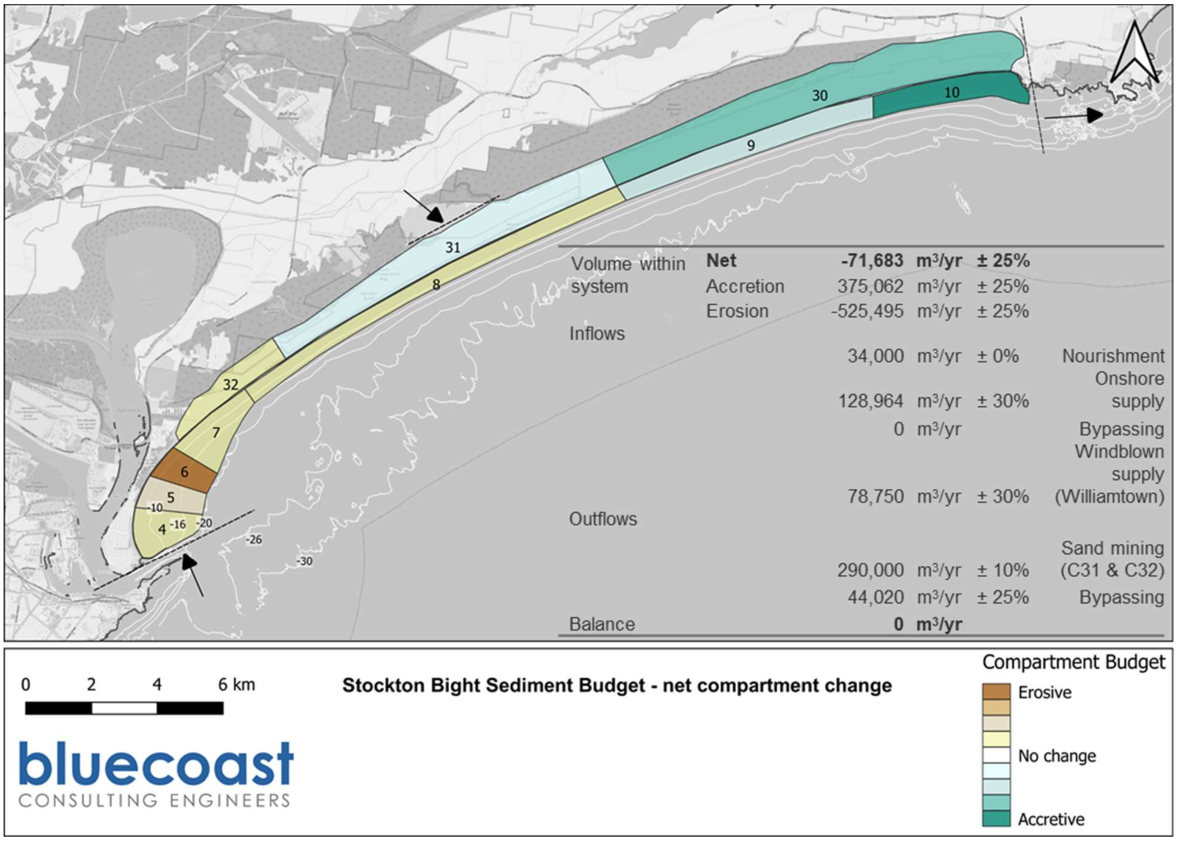


Figure 72: Sand budget for Stockton Bight.

Table 8: Summary of sediment budget calculations.

Area	ID	Sand volume rates (m³/yr)					Error estimate	Comment
		Net change	LST (in)	LST (out)	Onshore transport (in)	Dune transport (out)		
Stockton Bight (coastal)	C4	-53,000	0	87,000	40,320	-	±10%	Port sand placements
	C5	-59,000	87,000	146,000	4,240		±25%	
	C6	-137,189	146,000	283,000	4,504	-	±25%	
	C7	-52,062	283,000	225,250	22,440	110,000	±25%	
	C8	-131,909	225,250	197,159	40,560	160,000	±25%	
	C9	73,776	197,159	134,568	33,120	100,000	±25%	
	C10	81,722	134,568	44,020	17,780	26,606	±25%	Bypassing to north
Stockton Bight (dune)	C30	142,660	-	-	-	0	±30%	Aeolian transport
	C31	56,281	-	-	-	66,055	±30%	Aeolian transport
	C32	-13,586	-	-	-	123,586	±30%	Aeolian transport

6 Quantified conceptual sand movement model

6.1 Sand sources, sinks and pathways

This section provides a detailed explanation of the sand source, sinks and pathways and the coastal processes that drive the sand movements associated with the observed volume changes along Stockton Bight. These drivers of sand movement have then been linked together with the Bight's sand budget to provide the quantified conceptual sand movement model presented in Section 6.2. The inferred coastal process understanding, details and supporting evidence for the quantified model are provided in this section.

6.1.1 Nobbys Beach, Horseshoe Beach and the sand lobe

Nobbys Beach has been created by the accumulation of marine sand following the construction of the Macquarie Pier and breakwaters in the early 1800's (see Figure 73). Further evidence suggests that during this period sand bypassing of the entrance to Newcastle Harbour was occurring. The evidence of sand bypassing in this period, as detailed in Section 6.1.2, includes sand tracing results, the growth of an entrance shoal and sand accumulation at Horseshoe Beach (within the harbour). An analysis of the change in sand volume in the subaqueous and subaerial components of Nobbys Beach and the smaller Horseshoe Beach on the western side of Macquarie Pier has been completed (both seen in Figure 73). To complete the review of areas south of the harbour where sand may be accumulating the sand lobe that exists offshore of Nobby Beach was examined.

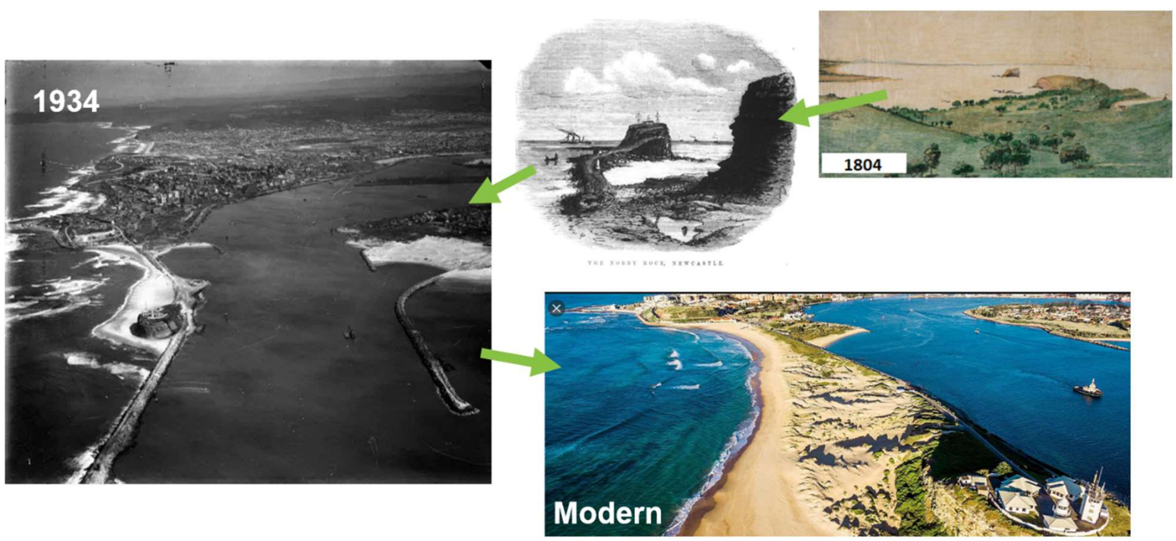


Figure 73: Images showing the creation of Nobbys Beach and Horeshoe Beach from previous open water/reef.

Subaqueous changes

The analysis of the subaqueous beach profile at Nobbys was reported in Sections 5.2.1, see compartment 2. Due to limited survey coverage the 2002 is the only survey available for comparison with the 2018 survey with the differences in volumes provided in Table 4. Between 2002 and 2018 there was a volume gain of around 115,000m^3 within compartment 2 or an annual rate of approximately 7,200m^3/yr. No subaqueous survey was available for Horseshoe Beach and this has been estimated based on the subaerial changes.

Subaerial changes

For the subaerial assessment of Nobbys Beach two methods were compared. The first was an analysis of volume change using the average beach and dune height, the average height of the offshore reef both from the 2018 Coastal LiDAR data. The average height of the offshore reef was used as the bedrock shelf and was assumed to be a fixed depth upon which the beach sand has. For Horseshoe Beach which is on the western side of Macquarie Pier and is not covered by the NSW photogrammetry database only this first method was applied. Figure 74 displays the calculated volumes along with the average heights adopted for the volume estimates with each area. The subaerial volume of Nobbys Beach between Macquarie Pier and 0 m AHD is 618,240m^3. The volume in Horseshoe Beach was estimated as 106,854m^3.

The second method used the NSW beach profile data from the NSW photogrammetry database (DPIE, 2020). The analysis period adopted included photogrammetry data collected between 1955 and 2018 over beach profiles in Newcastle Blocks 7, 8 and 9 as displayed in Figure 75. Historic beach profiles for selected locations within Blocks 7, 8 and 9 are shown in Figure 76. Figure 77 presents a timeseries of subaerial beach volumes for Newcastle Block 7, 8 and 9. Between 1975 and 2018 the combined beach volume in these blocks has increased by approximately 665,000m^3, an average rate of accretion of 15,000m^3/yr.

The alongshore variation beach volumes within Blocks 7 to 9 is demonstrated in Figure 78. Overall, the Blocks at Nobbys Beach have experienced long-term accretion. The rate of change in beach volume increases between Blocks 7 and 8, however the change in beach area remains constant between the blocks. This increase in volume (height) relative to the neighbouring Block 7 but not an increase in beach width could indicate that windblown sand and dune vegetation contributes to the height of the beach profile in Block 8. Between the two methods, calculations of the subaerial volumes for Nobbys Beach showed good agreement (within 10%) of 618,240m^3 and 665,000m^3.

Sand lobe

A large, oblate shaped sand lobe extends off Nobbys Head in a south easterly direction. It is estimated to be about 4.4km wide, averaging 2–3m thick with a maximum thickness of 7.5m (WorleyParsons 2012). Core sampling by WorleyParsons (2012) showed the sands to be medium to medium–coarse grained and suitable for beach renourishment. While the source and the age of the sand deposits that make up the sand lobe are not well understood, previous investigations have suggested that this feature either:

- Has been aggrading with littoral transport over geological time (WorleyParsons, 2012). The East Australian Current, albeit of less influence compared to other areas along the east coast may also have a role at the sand lobe. That is theory is that the sand lobe is likely to have been formed over 100-1,000’s of years.
- The alternative theory is that the virtually continuous dredging and offshore dumping of sediment that commenced in the port in 1859 with approximate total quantities of 140 million cubic metres is at least partly responsible for this feature. In the early days of port dredging much of this material would have been sand (i.e. river entrance shoals and flood tide delta sands rather than the fine sediment predominately being dredged now). As such this feature may be attributable to the offshore dumping rather than a pre-existing sediment body. The shore perpendicular nature of this feature makes it unlike other NSW seabed sand bodies.

It is also worth noting that the sand lobe increases waves off the river entrance (Treloar and Abernethy (1977) and may contributes to wave focussing at Stockton Beach (DHI, 2006)

However, accretion of littoral sand in this location in recent years is significant as it indicates a potential additional source of sand for beach nourishment for Stockton Beach under a ‘working with nature’ approach (i.e. keep sediment moving along the coast). Other potential sources of offshore sand for beach nourishment also exist (MEG, 2020) and further investigations are recommended to determine the suitability of each source for this purpose.

More sampling is required to assess the sand lobe material and its suitability for use as beach nourishment. It is understood that NSW Resources and geoscience, Mining, Exploration and Geology (MEG) is undertaking these investigations and once completed a review is recommended to confirm the geological origins of this feature.

Regardless of the origin, if deemed suitable for beach nourishment there is a potential win-win situation if the sand lobe would be the source of future beach nourishment at Stockton. This is because the wave focusing over the lobe, that affects both Stockton Beach and vessels within the navigation channel, could be reduced with careful planning of the nourishment dredging.

Using the 2002 and 2018 bathymetric surveys, contemporary accumulation over the sand lobe (compartment 1) of approximately 10,500m^3/yr was observed. This is more than the 5,000m^3/yr rate estimated by Patterson Britton and Partners 2004 as reported in WorleyParsons (2012).

Combined rates of sand accumulation at Nobbys Beach, Horseshoe Beach and the sand lobe

Initially following the construction of Macquarie’s Pier only a small amount of sand accumulated at Nobbys Beach. It was not until all the breakwater extensions had been completed that the beach formed in earnest. While sand has been accumulating on the updrift (southern) side of the entrance for some time, in the absence of longer-term data the most reliable rates of sand accumulation are based on the more recent beach and bathymetry data. The combined rate of sand accumulation on the southern side of Newcastle Harbour is calculated as:

- **Nobby Beach:**
  - Subaerial: 15,000m^3/yr based on rate from photogrammetry
  - Subaqueous: 7,200m^3/yr based on rate from 2002 to 2018 survey analysis
  - Combined rate: ~22,200m^3/yr
- **Horseshoe Beach:** ~3,800m^3/yr over 84-year period between 1934 and 2018
- **Sand lobe:** ~10,500m^3/yr based on rate from 2002 to 2018 survey analysis
- **Total accumulation:** **36,500m^3/yr (± 30%)**

The breakwaters were extended due to the shoaling occurring in the harbour entrance. The lack of any significant sand build-up at Nobbys until after the breakwater were extended suggests that the majority of sand was bypassing prior to the breakwater extensions.

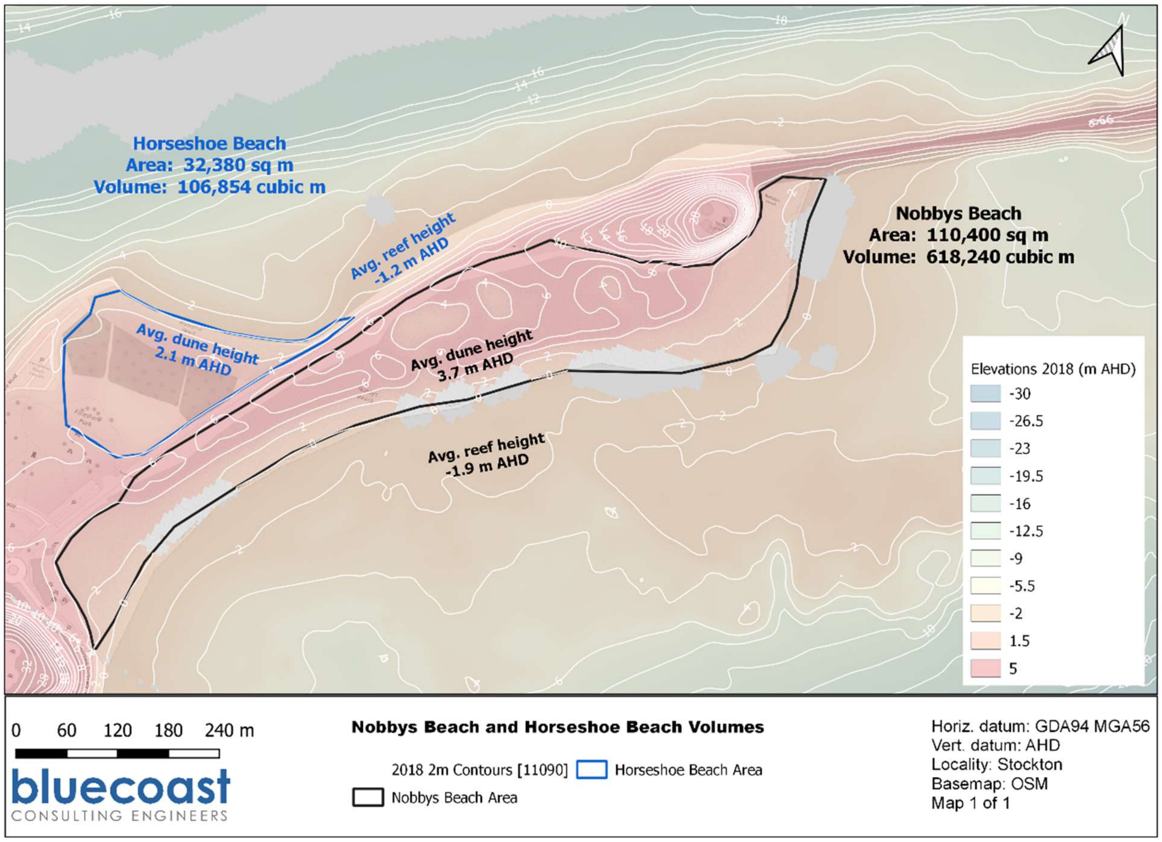


Figure 74: Survey map with volume calculations for Nobbys Beach and Horsehoe Beach, Newcastle (based on 2018 LiDAR elevations).

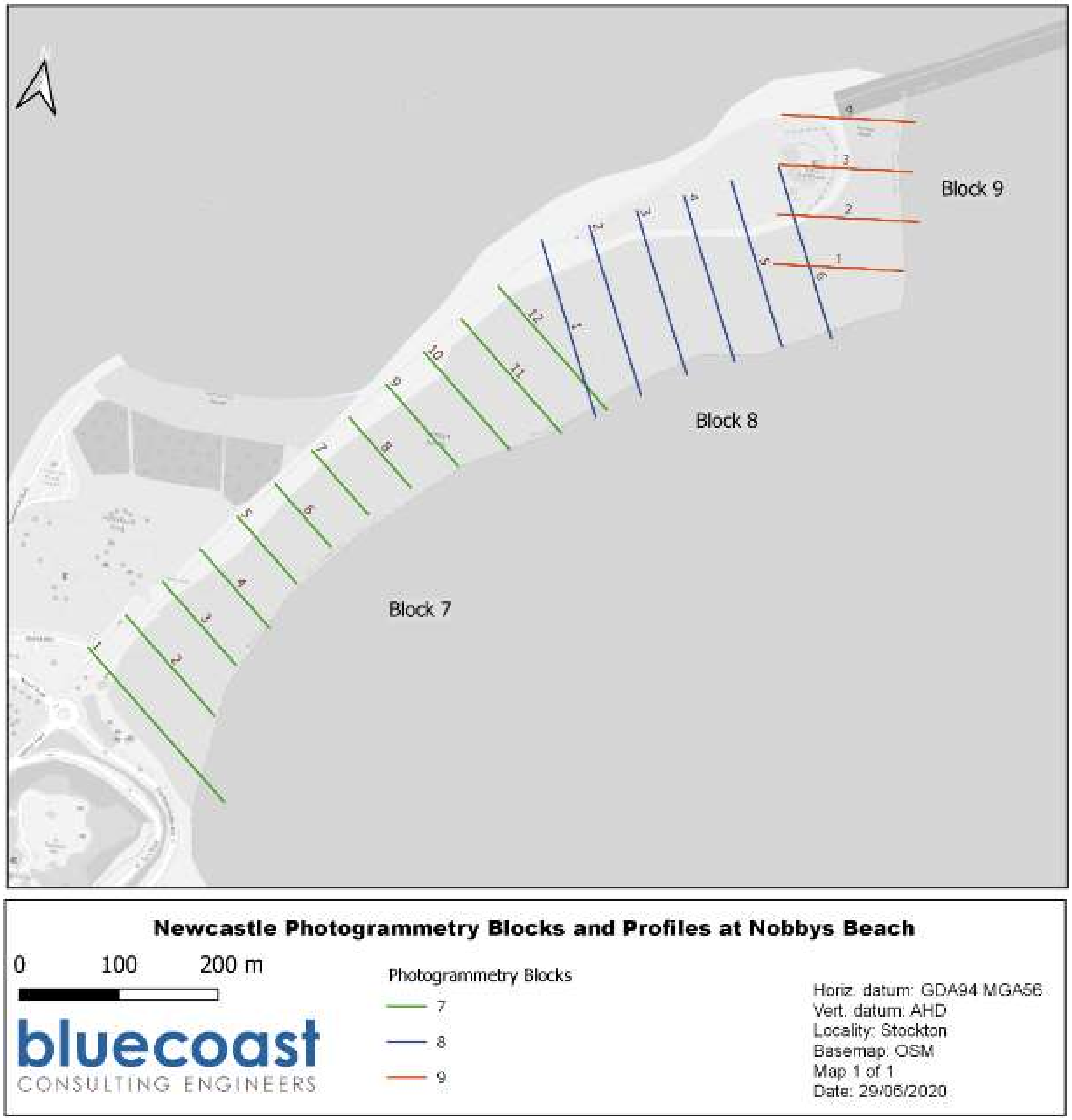


Figure 75: NSW photogrammetry blocks and profiles (coloured lines) at Nobbys Beach, Newcastle.

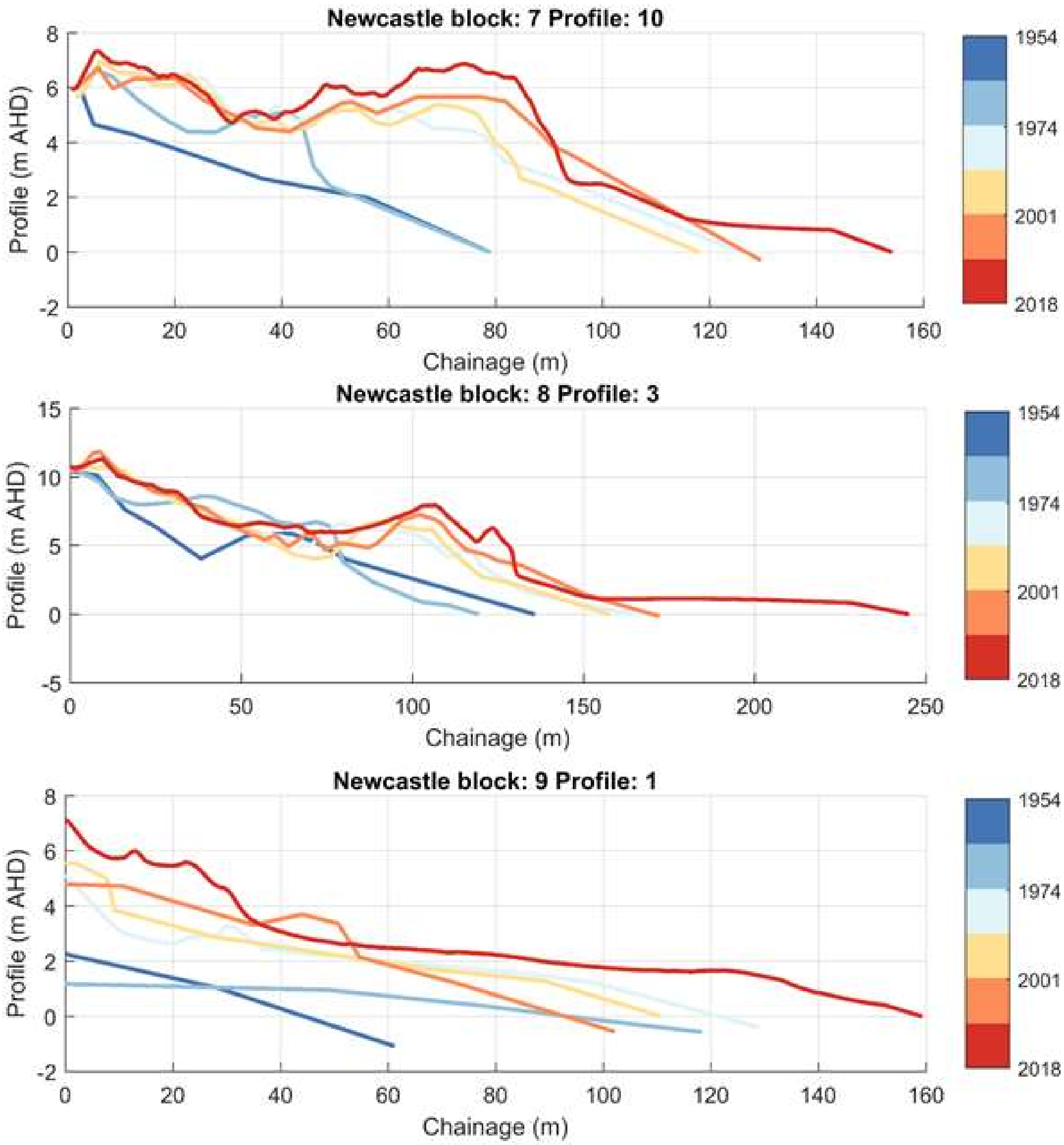


Figure 76: Elevations of sub-aerial beach profiles over time for a selection of profiles in Newcastle Blocks 7, 8 and 9.

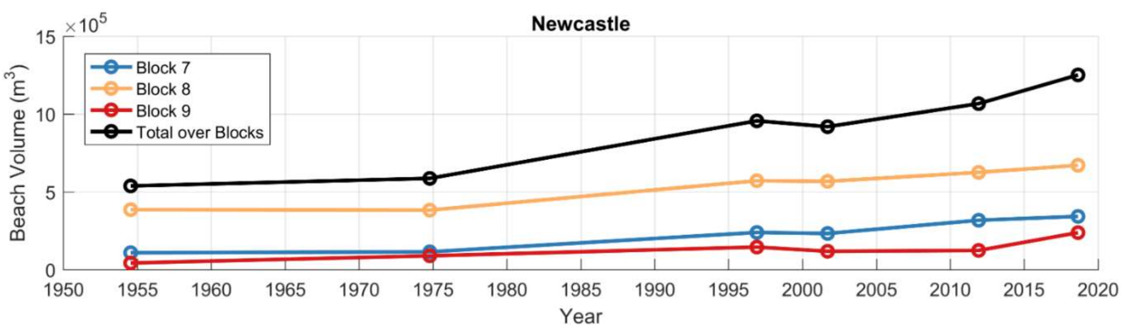


Figure 77: Timeseries of sub-aerial beach volumes for Newcastle Block 7,8 and 9 and the total beach volume over all Blocks.

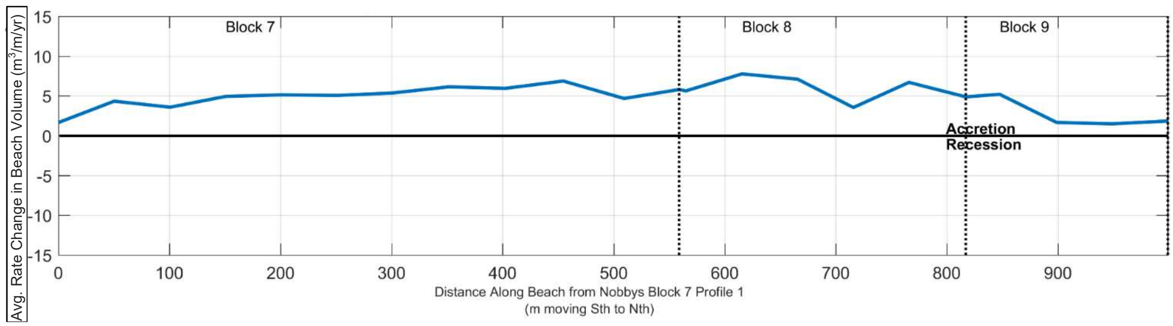


Figure 78: Average rate of beach volume change between 1985 to 2018 along Nobbys Beach.

6.1.2 Sand bypassing

The average annual rate at which sand bypasses the entrance to Newcastle Harbour and enters the southern end of Stockton Beach is of principal importance to understanding the Bight's sand budget and applying sound coastal management at Stockton. Consideration must be given to the impact of the breakwaters and the port's navigation channel on the rate of sand bypassing.

Prior to the development of the port, the entrance of the Hunter River was characterised by shallow depths (less than 6 metres) with large sand shoals both within the harbour and on an ebb tide delta adjacent to the northern side of the river off Stockton Beach (see Figure 79). The sand shoals, particularly those off Stockton claimed several ships and entry to the port was hazardous in unfavourable sea conditions. The southern and northern breakwaters were constructed in stages with final extension completed in 1898 and 1912, respectively (Umwelt, 2002). Port dredging commenced in 1859, operating near continuously for more than 160-years, removing an estimated 140 million cubic metres[5] of sediments (clay, silt and sand), almost all of which has been dumped at an offshore spoil ground (i.e. removed from the active system).

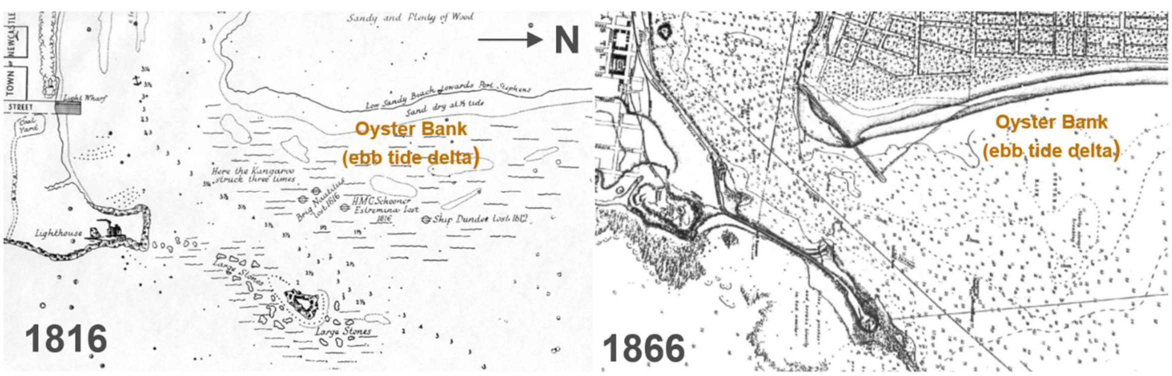


Figure 79: Early surveys of the entrance to the Hunter River.
Note: Location of large sand shoals in the lee of Nobbys Head and the associated reef system.

Sand has accumulated on southern (updrift) side of the breakwaters to form Nobbys Beach and Horseshoe Beach (inside the harbour). Downdrift (north) of the breakwaters ongoing erosion of over 15

[5] This figure is based on the estimate of the total dredging quantities up to 1993 of 130 million cubic metres reported in Patterson Britton (1992) and updated to reflect the current quantity using an average maintenance dredging rate of 355,000m^3/yr. The average rate is based on the annual maintenance volumes between 2000 and 2012 as reported in NPC (2013).

million cubic metres of sand has been experienced (within compartments 4 to 7 from 1899 to 2018, see Section 5.2.1).

Observations of a sand shoal that formed in the harbour entrance, just offshore of the northern breakwater (see left panel of Figure 80), provide further insight. The volume and location of the shoal as surveyed remained much the same from 1921 until the early 1950's (Boleyn and Campbell, 1966). From the 1950's, the shoal rapidly accreted increasing in size and shallowing, which in the absence of fluvial sand supply, is a clear indication of sand bypassing the southern breakwater. This continued until dredging operations were undertaken between 1962 and 1967 to remedy the navigation hazard. Further reports of shoaling and navigation hazards occurred in the 1970's until major channel deepening project was undertaken between 1978 and 1983 which removed the shoal. Since channel deepening regular maintenance dredging of the entrance's navigation channel has been required, further evidence of sand bypassing. Since 2009 sand has been removed from the entrance area (Area E) and placed at Stockton Beach at an average annual rate of 34,000m^3/yr.

The only previous measurement of the sand bypassing rate was reported by Boleyn and Campbell (1966). A sand tracing experiment whereby a radioactive tracer was placed south of the entrance and offshore of the reefs at Nobbys (see Figure 80). Between the end of March 1966 and end of July 1966 the movement of the tracer was tracked and the results combined with wave hindcasts to determine the average annual rate of sand passing the entrance in a net northward direction as 98,000m^3/yr. Two colours of fluorescence tracer were also placed on the shoal in the harbour entrance and while most of the spread was observed in the direction of the harbour alignment, a northward littoral drift of 23,000m^3/yr was determined.

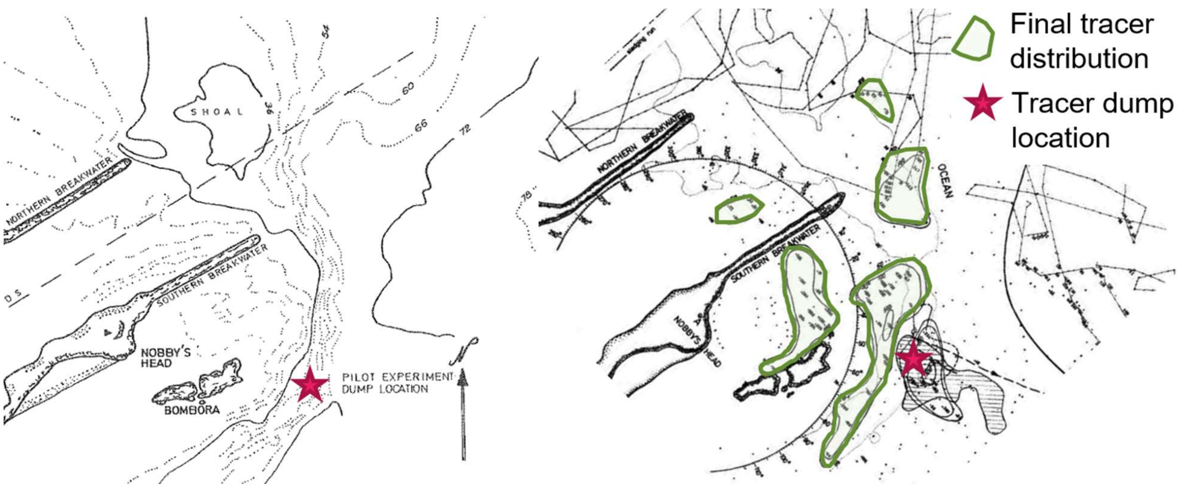


Figure 80: Radioactive sand tracer results completed in 1966 showing net northward transport (source: Boleyn and Campbell, 1966).

WBM (1998) and DHI (2006) calculated potential longshore transport rate at Nobbys Beach in the order of 30,000 to 33,000m^3/yr, respectively.

Conceptual sand movement pathways south of the entrance to the Hunter River are shown in Figure 81. Based on the observed long-term erosion within the southern embayment and the acceleration of that erosion since the major channel deepening project (1978-1983) it has been assumed that in the contemporary setting there is no sand bypassing to Stockton.

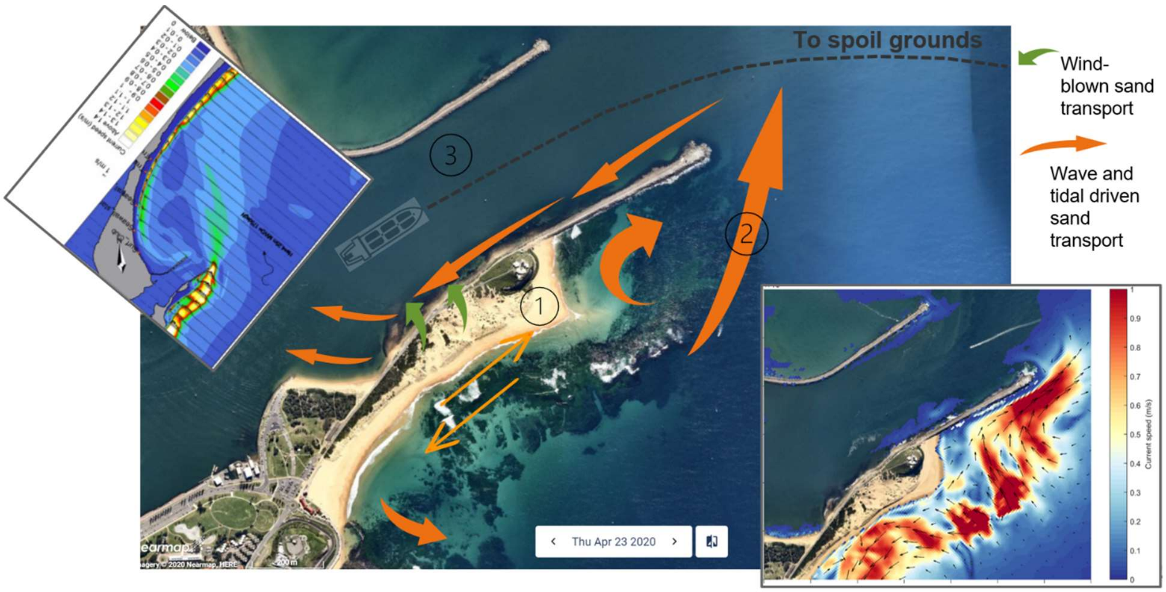


Figure 81: Sand movement pathways south of the entrance to Newcastle Harbour.
Note: Insert top, littoral currents from DHI 2006 showing the major current and pathway outside the reef. The bottom insert shows the wave driven currents from the SWASH model for south-east wave conditions.

In estimating of the rate of sand bypassing adopted for this study, the components, as labelled in Figure 81, have been considered:

1 Sand impounded south of the entrance by Macquarie Pier and the southern breakwater (i.e. sand accretion at Nobbys Beach). As discussed above this has been calculated to have occurred at a long-term rate of approximately 36,500m^3/yr.

2 Sand moves around the northern breakwater and is then trapped in the navigation channel and subsequently dredged from Area E and placed in the nearshore of Stockton Beach. The mechanical bypassing mechanism have been occurring since around 2009 with an average annual rate of sand transfer of 34,000m^3/yr (see Section 5.2.1).

3 Sand that enters Newcastle Harbour mixes with river mud (i.e. fluvial clays and silts) or is otherwise subsequently dredged and disposed at the offshore spoil ground (i.e. outside the active sand transport system). The records necessary to estimate annual quantities of sand associated with this pathway were not available to this study[6].

DHI (2006) correctly identified a mechanism for this to occur during easterly or large diffracted southerly waves which are known to break along the shallow southern parts of the channel. Subject to further confirmation and measurements there is also a flood tide asymmetry believed to occur on this pathway. Windblown sand over Macquarie's Pier is also a minor contributor to this quantity (see Figure 81). Gravitational circulation (due to saline and freshwater density flows) giving rise to upstream residual flow near the bed may also be another mechanism (Norman et al., 1992).

It is understood that the procedure used by the port's *David Allen* trailer dredger to determine if a hopper load is suitable for placement at Stockton (i.e. mostly sand) is undertaken by a visual assessment of the material as it enters the hopper. This is only undertaken when dredging in

[6] See Section 6.6 and 6.9 in NPC's 2013 report titled "Long term monitoring and management plan for the 2011-2021 ten-year dredging and sea disposal permit for Newcastle Port."

Area E (nearby the entrance). If a hopper load is assessed as unsuitable (too much fines content) or it is outside Area E it is taken offshore for disposal outside the active sand movement zone.

The adopted total rate of natural sand bypassing herein is 100,000m^3/yr. The sum of component 1 and component 2 rates (described above), which are known to have been occurring concurrently is 70,500m^3/yr. While component 3 cannot be quantified herein it is assumed to take up the remainder of the total natural sand bypassing rate. The total adopted natural bypassing rate is justified by the measurements of littoral drift by Boleyn and Campbell (1966) and the contemporary erosion in the southern embayment of Stockton Beach (compartments 4 and 5 rate of 112,000m^3/yr). The construction of the breakwater greatly reduced the natural sand bypassing, to around 25-30% or 25,000 to 30,000m^3/yr. Following completion of channel deepening works, it has been reasoned from the available observations that sand bypassing the port's entrance stopped completely. This is supported by the physical barrier to sand movement represented by the combined effects of the breakwater and the deepened navigation channel. In 2009, a proportion of the former sand bypassing was restored by mechanical means (i.e. port's sand placements) at Stockton (34,000m^3/yr).

This rate is subject to uncertainty of ±25-30%. Given its importance, it is recommended that further effort is expended to reduce the uncertainty including obtaining and analysing the detailed maintenance dredging, interpreting historical aerials in relation to infilling of Horseshoe Beach, measuring tidal and wave driven currents along the inside of the southern breakwater and obtaining additional long term bathymetric survey coverage over Nobby Beach and the sand lobe.

6.1.3 Hunter River

The Hunter River does not supply significant quantities of terrestrial sourced sand to the coast/ocean (Roy, 1977). As discussed above, the Hunter River has acted as a sink for marine sand up until dredging started, with the lower estuary filled with a flood tide shoal and low sand islands. 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.

6.1.4 Capital and maintenance dredging

Port dredging commenced in 1859, operating near continuously for more than 160-years, removing an estimated 140 million cubic metres of sediments (clay, silt and sand). The dredged sediment has historically comprised mostly silts and clays (i.e. fine sediments less than 0.073mm grain size). The quantity of sand (or coarser sediment) has been typically less than 30% (by weight) and often less than 10% (Patterson Britton and Partners, 1989). Until 2009, almost all dredge material has been dumped at an offshore spoil ground (i.e. removed from the active system) and a minor quantity of sand was used for land fill. Since 2009, an average annual quantity of 34,000m^3/yr of clean sand that was dredged from Area E (entrance) has been placed in the nearshore at Stockton Beach.

A summary of dredging within the port has been compiled from available records covering the years 1860 to 2020 and is presented in Figure 82. The sand only dredging and placement history is also shown by assuming sand on average comprises 25% by volume of the maintenance dredging (after Patterson Britton and Partners, 1989) and adopting the reported sand quantity in the 1977 to 1983 channel deepening project as well as recent sand placement records. Figure 82 also includes a time series of the volume change in compartment 3 (entrance area) derived from hydrographic surveys.

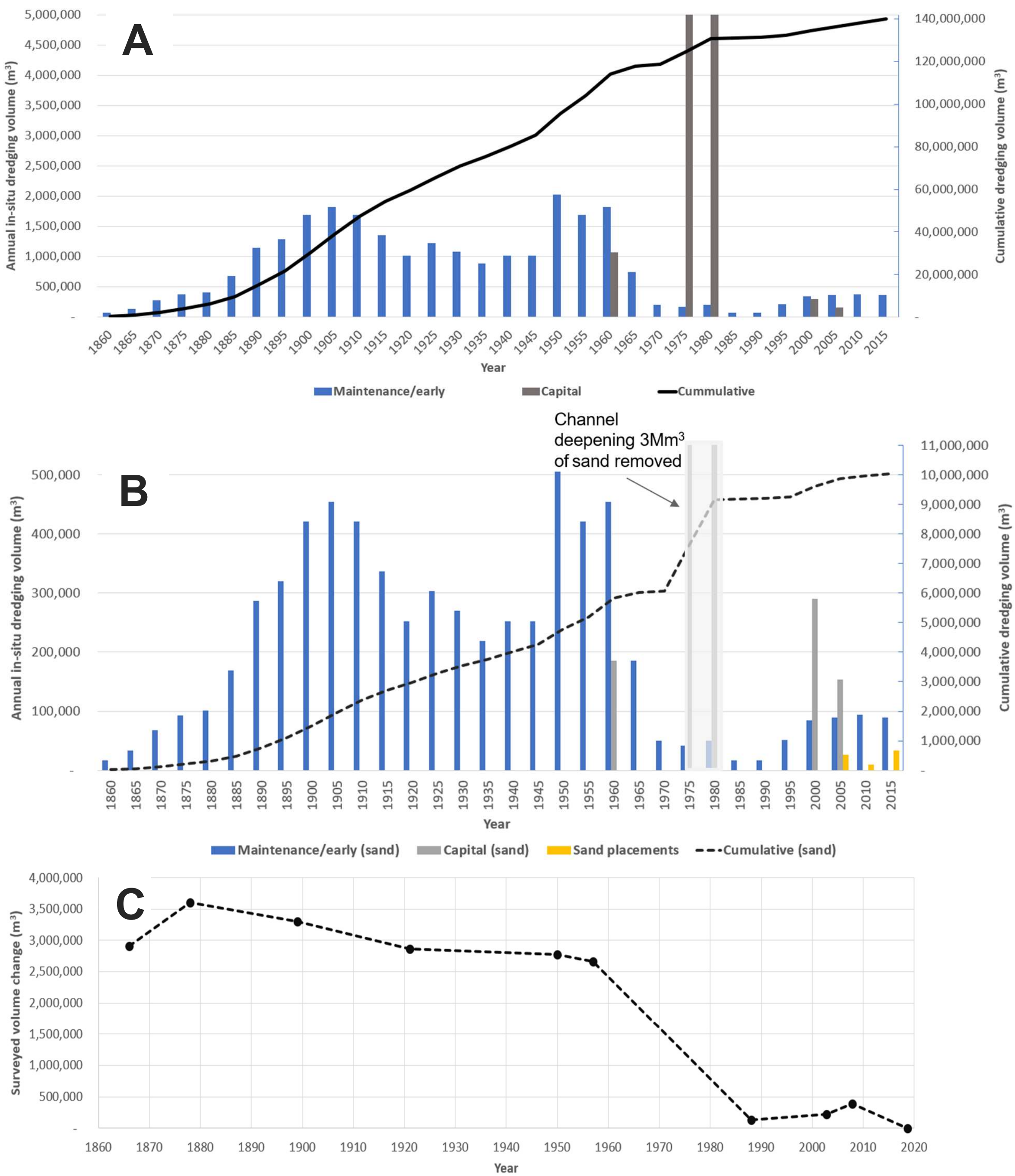


Figure 82: Dredging history at the Port of Newcastle.

Notes:

1. Panel **A** is based on dredging records gathered from PBP (1989), NPC (2013), PoN and other sources.
2. Panel **B** plots sand only dredging and placement history based on a 25% sand content in maintenance dredging and 3M m^3 of sand in the 1977 to 1983 channel deepening quantity after Umwelt (2002).
3. **Panel C** plots the surveyed change in the volume of sand within compartment 3 relative to 2018 (see Section 5.2.1).
4. Not shown above is the NCIG dredging in the South Arm in 2010-2011. Approximate 3M m^3 of sand was removed from the river and reused to create NCIG's coal stockpile areas on Kooragang Island (WorleyParsons, 2012). Another 600,000m^3 of clean sand was removed from the river and dumped offshore outside the active coastal sand transport system (Brian Cole 2011 pers. comm. cited in WorleyParsons 2012).

Maintenance dredging

The total annual volume of material dredged from the port varied from approximately 236,100m^3 to 670,000m^3 between the years 2000 and 2012 (NPC, 2013). This is substantially less than pre-1988 (channel deepening) when the average dredging quantity was slightly over 1Mm^3. Most of this material is fine sediments (silts and clays) but a proportion is sand. Previous literature has reported the content of sand ranging from 10% to 30%. As discussed above a contemporary figure of the sand content in maintenance dredging would assist the understanding of sand movements into the Bight's sediment compartment.

Sediment sampling from maintenance dredge areas within the port (see Figure 83) shows sand content in samples increases closer to the port entrance, ranging from <1% to 80% in Area A, B, C and D (NPC, 2013). Sediments in Area E are predominantly sand with a content ranging from 70% to 84% (NPC, 2013). Roy (1997) reports relict deposits of shelly, quartz-rich marine sand, muddy sand and sandy muds occurring in the lower 9.5km of the Hunter River estuary. The sand deposits were derived from the open coast and transported into the river mouth by waves and tidal currents during and since the post-glacial transgression (Roy, 1997). The infilling of Horseshoe Beach provides evidence that this process is still active.

In May 2005, approximately 150,000m^3 of sand from Area E was dredged and dumped offshore (outside the zone of active sand movements) without any additional sand placements on Stockton Beach (WorleyParsons, 2009).

Figure 83: Newcastle port maintenance dredge areas (source: WorleyParsons, 2012).

Major capital dredging

Between 1979 and 1983, capital dredging was undertaken to deepen the channel. Approximately 2M m^3 of rock and 3M m^3 of sand and 5M m^3 of fine sediment (silt and clay) was dredged from the main entrance to the port and dumped offshore for a total cost of $103,300,000 (Umwelt, 2002 and NPC, 2014). It is also understood that no sand was placed on Stockton Beach during the capital dredging works.

Following a representation from Newcastle City Alderman, a report was prepared to examine the feasibility of using sand from deepening of Newcastle Harbour to nourish Stockton Beach (PWD, 1978). The report identifies that the deepening of Newcastle harbour work was to be undertaken by a dredging company under contract to Maritime Services Board (MSB) and that there was some 3M m^3 of sand to be dredged of which 0.5M m^3 was to be pumped to Kooragang Island. The report concluded:

> *"Due to the type of equipment available for use by the Dredging Contractor and the proposed method of operation of this equipment, suitable sand cannot easily be placed within the required limits of the beach profile without endangering the dredging equipment….In conclusion it can be said that under different operational and geological circumstances the proposal to use dredging spoils from the deepening project to nourish Stockton Beach would be sound in both terms of engineering practicability and also from an economic point of view. However, due to the Contractor's type of equipment, dredging methods and lack of suitable material of the correct grading, the proposal is not feasible in this particular instance."*

As noted in Section 2.2, there was also capital dredging works completed in the 1950's and between 1962 and 1966. There is an observed sand loss in compartment 3 of approximately 2.5 million cubic metres that occurred between the 1956 and the 1988 surveys. This difference can be accounted for by the dredging at the entrance of the harbour during the capital works.

6.1.5 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 (see Figure 84). South of the Hunter coast intermittent headland bypassing and predominately swash-aligned headland embayed beaches that are typical along the central and southern coast of NSW to occur. From the Hunter and north it is generally accepted that there is a net northward movement of littoral sand transport (Goodwin et al., 2020).

Consistent with this regional sand transportation system, and as shown in Figure 84, this study has found a net northward longshore sand transport to occur along the Stockton Bight. Apart from the very southern end of the embayment, the direction of transport is generally consistent with DHI (2006) as is the pattern of increasing northward transport until the Fort Wallace area. The net northward transport finding differs to the PWD (1977) report, however, it is noted that this study did not have the benefit of the contemporary datasets that have been used to construct the sediment budget for the Bight.

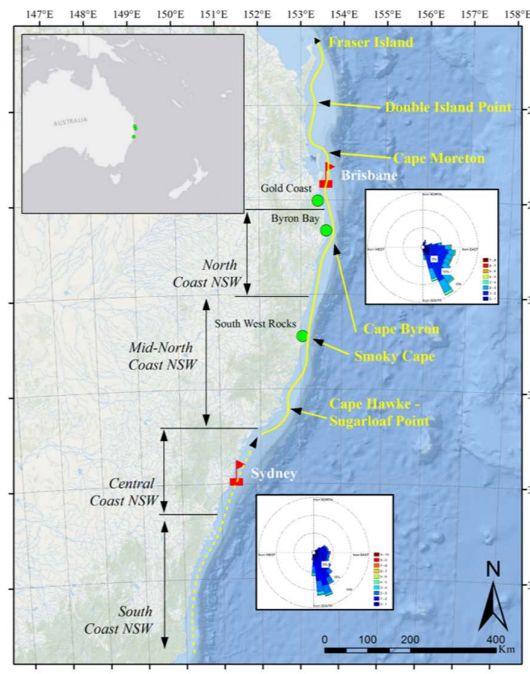


Figure 84: East Australian sand transportation system (source: Goodwin et al., 2020).

Note: 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.

A gradient in longshore transport rates was found to exist with a maximum rate around Fort Wallace with lower rates in the south due to the wave sheltering provided by the port's breakwater and in the north due to a much-reduced wave obliquity. This is supported by the gentle curvature of the Bight shoreline as demonstrated in Figure 85. The gradients in longshore transport rates explain the pattern of erosion observed over the southern Bight and the accretion observed in the northern Bight.

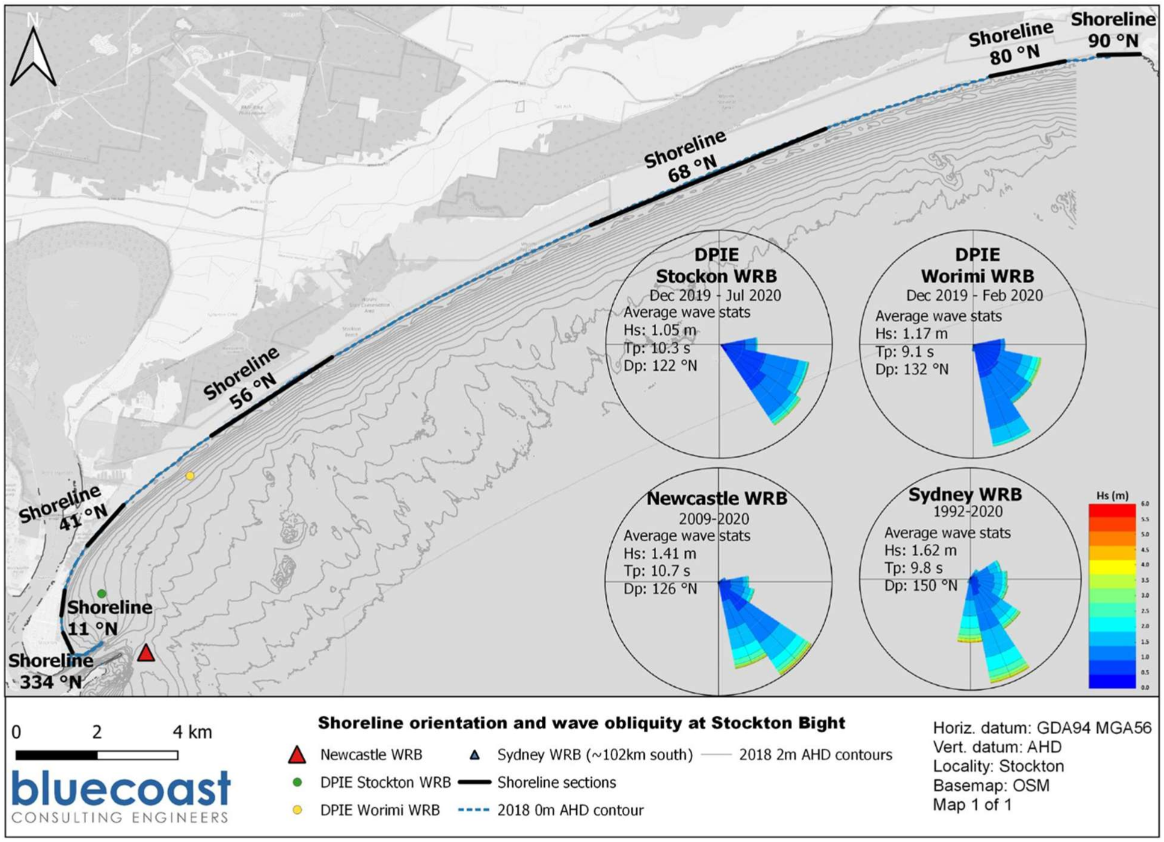


Figure 85: Shoreline orientation and nearshore wave climate along Stockton Bight.

The following observations provide further evidence of the net northward transport along the entire Bight:

- Review of historical and aerial photography either side of the Sygna wreck indicates longshore drift in a net northerly direction exists (see Figure 85). This wreck is located around 9 km downdrift (north) of the southern breakwater.
- Review of similarly satellite derived imagery, bathymetry and shorelines at Birubi Point indicate on-going accretion updrift of the rocky headland as well as bypassing of this headland to the east.

Figure 86: (left) Tombola formed following the grounding of the Sygna in 1970's and shoreline eitherside of the Sygna wreck in May 2016 (source: Nearmaps), both indicative of a net north-eastward longshore transport.

As noted above, while PWD (1977) study calculated a net northerly longshore transport, the study reasoned that the pattern in sand grain size distribution discussed in Section 3.3 implied that there was not significant net littoral transport along Stockton Bight. The findings presented herein rely on the volumetric analysis which do imply a significant net northerly transport. That stated the pattern of grain size distribution in the Bight (e.g. fining towards the north east) do require further explanation as they appear to be due to inherent factors at play within the Bight. It is possible these contrasting distributions reflect the different sediment histories during periods of lower sea-level (Thom et al, 1992). The band of coarse sand identified as a relic channel of the Hunter River along with winnowing by longshore transport and losses to the dunes may also be factors in explaining the pattern.

The exposed to the energetic and variable wave climate along with the long-curved shoreline of the Bight gives rise to both high gross longshore transport as well as periods of reversal of the net transport direction. PWD (1977) used empirical approaches to predicted gross annual sand movements along the Bight of some 2.5Mm^3/yr to one order of accuracy. DHI (2006) calculated a gross littoral drift at ‘Point 2’ near the Hunter Water treatment ponds of 800,000m^3/yr. The large variability in the littoral transport was also evident in DHI’s analysis (see Figure 87). It is important that the large gross transport rates and high variability be considered when developing coastal management strategies. Section 6.2 provides analysis around the role of storm focused on observations in the southern embayment.

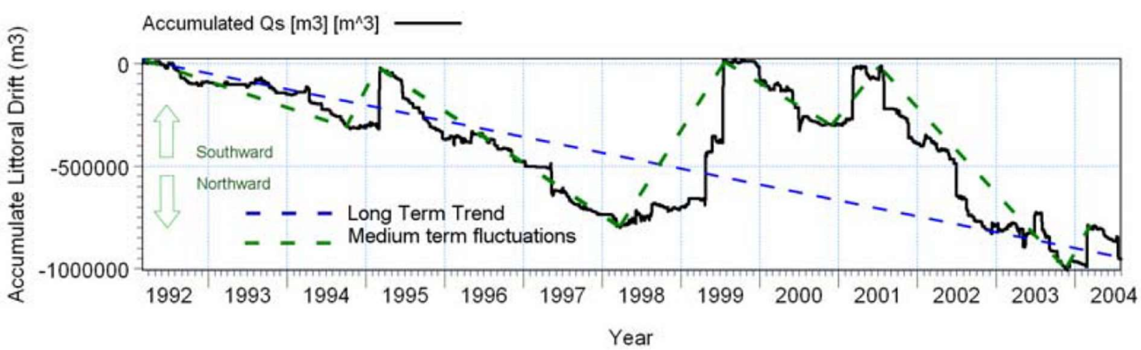


Figure 87: Littoral transport predicted by DHI (2006).

Note: the blue dashed line shows the long-term net northward direction whereas the dashed green line shows the medium-term variability and reversal of net transport direction.

6.1.6 The deepening and realignment of the southern embayment

Observations presented herein show a long-term deepening of the upper shoreface (subaqueous) in the southern Bight embayment (see Figure 51 and other information in Section 5.2). More recently a landward realignment of the shoreline in the southern embayment between the northern breakwater and Fort Wallace (see Section 5.2) has also been observed. Prior to the recent realignment and based on observations between 1952 and 1995 Stockton Beach had experienced episodic storm erosion (e.g. 1946, 1952 and 1995) without long-term shoreline recession[7] (DLWC, 1995). The observed long-term coastal erosion[8] presenting as erosion of the upper shoreface[9] while not evident as recession of the subaerial beach is demonstrated in Figure 88. Also notable is the recession of the subaerial beach, with limited recovery following the erosion in 1995 followed by the more recent reduction observed since 2016.

This section explores the possible explanations for these observations.

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[7] The term long term shoreline recession is used here to describe a net loss of sand based on analysis of data (beach volumes or shorelines) from the subaerial beach above 0m AHD.

[8] Defined here as net loss of sand from the coastal profile from +6-8m AHD down to -15m AHD.

[9] Defined here is as the subaqueous beach between 0m AHD and -12 to -15m AHD.

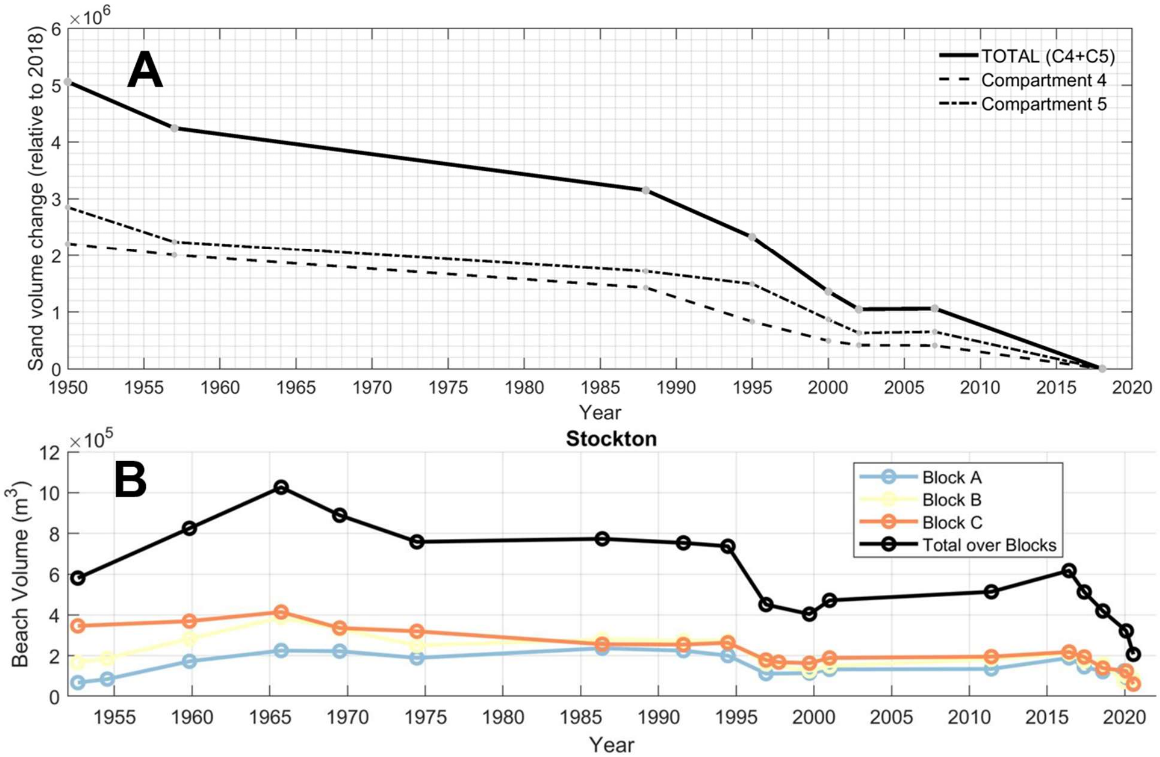

*Figure 88: Timeseries of sand volume changes since 1950. **A** long term erosion of the upper shoreface in compartments 4 and 5 based on bathymetric survey and **B** beach volumes above 0m AHD based on photogrammetry.*

The Bight's southern embayment and river entrance is a complex natural system which has been subject to breakwater construction, significant harbour dredging and coastal protection works. It is difficult to separate the natural processes from man-made impacts and there are a few possible explanations for these observations. Based on the review herein, the below presents a sequence that provides the most likely explanation:

1 Pre-European settlement there was an extensive ebb tide delta fronting Stockton Beach (see Figure 2 and Section 6.1.2). The large ebb delta at Stockton was formed by onshore sand supply, sand bypassing from the south and tidal and fluvial processes of the untrained Hunter River prior to breakwater construction (see Section 6.1.2). Sheltered by Coal Island and the associated reef system and with an active supply of sediment, the area was rich with marine sand which was mostly located in the subaqueous part. The ebb tide delta would have been highly dynamic responding to waves, tides and flood events. The main navigation access, however, was to the north of Nobbys Head and to the south of the ebb tide delta (Oyster Banks), implying that the shallow area at the end of the Stockton peninsula had a semi-permanent nature (i.e. a dynamic equilibrium). The extensive and active shoals would have made the entrance to the Hunter River dangerous for vessels. Lieutenant Shortland on first encountering the Newcastle entrance remarked that anyone seeking refuge should avoid trying to cross the entrance bar unless there was no other option available. The ebb tide delta was located directly seaward of the present-day suburb of Stockton with similar longshore extents. The pre-European shoreline was much straighter than it is today.

2 The northern breakwaters and early harbour dredging introduced (i) a change in wave and current patterns (ii) reduced littoral sand supply to the southern embayment and (iii) a strong shoreline control

(northern breakwater) on the southern sand spit/peninsula at Stockton. The sand movement pathways and mechanisms were changed. The initial shoreline response was from a straighter (pre-breakwater) alignment to a more zeta-shaped embayment shoreline resulting in accretion of the southern end of the Stockton spit as the breakwater progressed (i.e. a new curvature of the beach was introduced at the southern end).

The initial response happened relatively rapidly and it is likely to have resulted in an overall net propagation of the shoreline position. The changed shoreline shape with most of the advance against the breakwater is illustrated in Figure 89. It is reasonable to assume this response was a result of the strong shoreline control provided by the northern breakwater, the sheltering provided by the breakwaters and the abundance of sand available in the now isolated ebb tide delta. It is likely that finer sand would have been preferentially moved into this southernmost area potentially explaining the southern fining in the 1km from the breakwater.

The town of Stockton was initially planned prior to the breakwater construction with building commencing prior to and during this initial period of shoreline adjustment. Land that did not exist prior to the harbour works was subdivided and developed. The alignment for Mitchell Street may have been planned to follow the originally shoreline but is now close to the coast north of Hereford Street and well back from the coast at the southern end.

During this initial shoreline adjustment period the ebb tide delta would already have undergone changes (deepening) in response to the earlier construction of Macquarie's Pier.

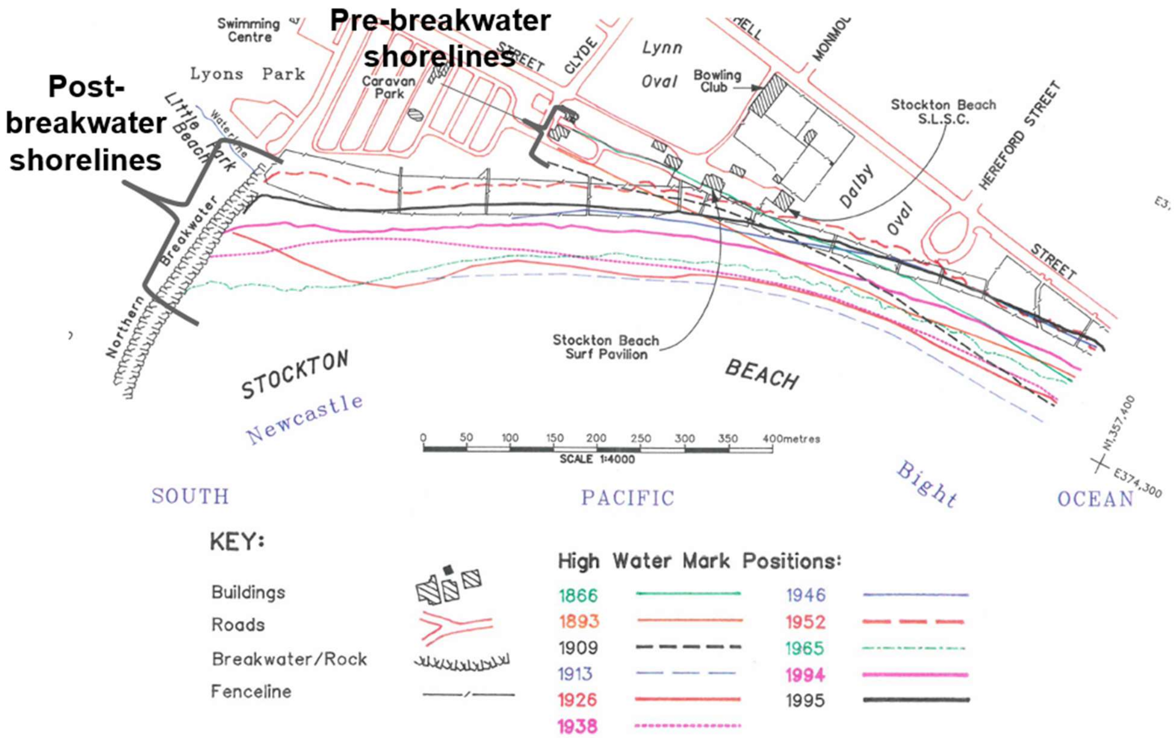

Figure 89: High water shorelines from 1866 to 1995 (source: DLWC, 1995).

3 Following the initial adjustment, the shoreline settled into a zeta-shape that was in equilibrium with the sand supply. This is evidenced by the relatively stable shoreline alignment and subaerial beach volume observed from the 1920's to 1995. However, a stronger more persistent change was continuing to take place on the former ebb tide delta. It was deepening, with the eroded sand feeding the shoreline and the associated northerly alongshore transport maintaining its relatively stable zeta-

alignment. That is, the gradual lowering of the delta is reasoned to have supplied sand to Stockton Beach over the past century, masking the underlying coastal erosion.

The existence of coastal equilibrium profiles that maintain their long-term average shape is widely recognised (Bruun, 1954, 1962, 1986; Dean, 1977, 1991). Following the isolation of the ebb tide delta, the coastal profile along the southern embayment was overfilled (overfit or positive) and in a state of disequilibrium. This is evidenced by the long history of bathymetric surveys which clearly show an evolution towards a deeper and steeper coastal profile shape (see Figure 93). The shoreface has deepened by as much as 6 or 7 metres. Based on the observed pattern of erosion (see Figure 56 to Figure 59), much of the deepening has occurred beyond the surf zone and in the lower shoreface when the closure depths for the Stockton embayment are considered (Bluecoast, 2020). The depth at which this erosion occurred and the wave climate may explain the length of time of which the lower as occurred.

Normally where sand is moving onshore under the action of waves, an increase in the beach width would be expected on the shoreline. For example, when the Shoalhaven River flooded in 1978 it deposited a large ebb tide delta off the entrance (positive profile) which took several years to migrate onshore and, in the process, widened the beach by 10’s of meters. As such, it is difficult to reconcile the observations at Stockton. It is reasoned that the lack of propagation is a result of a balance between the rate of northerly longshore transport out of the system (in the surf zone) and the rate of onshore supply (from below the surf zone).

Patterson and Nielsen (2016) documented similar observations from the northern Gold Coast when the migration history of the Nerang River mouth has formed a disequilibrium shoreface lobe that was observed to be evolving towards an equilibrium profile shape, without any corresponding propagation of the shoreline. While this paper offers similar (but not identical) observations over a 46-year period the differences in the coastal setting must be recognised with the northern Gold Coast being a straight open coast beach with very high longshore transport rates.

Like other NSW open coast locations, this stretch of shoreline was still subject to episodic variation (i.e. storm erosion and recovery cycles). It is unclear what effect, if any, the disequilibrium profile had on the storm erosion response of the profile.

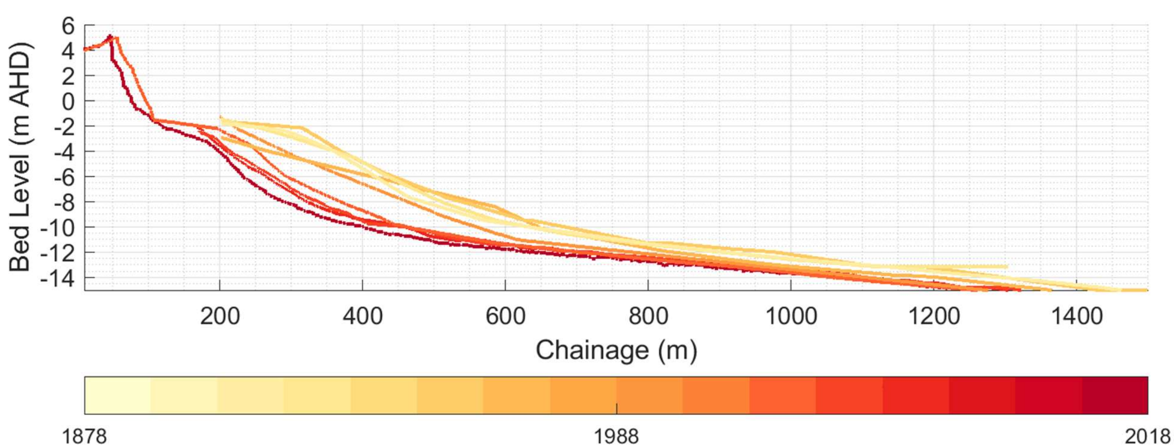

Figure 90: Time history of coastal profile evolution within the southern embayment (profile 4, see Figure 50).

4 As the persistent deepening on the disequilibrium coastal profile continued, it is likely to have reached equilibrium and then became negative. This is reasoned to correspond to a slowing or cessation of the shoreface sand supply to the shoreline. As the rate of onshore sand supply slowed the coastal erosion has manifested on the shoreline, i.e. the entire coastal profile is now moving landwards

because of a net sand loss driven by the on-going northerly longshore transport (see Figure 91). This last phase corresponds to the present-day situation where the observed landward movement of the shoreline is now realigning to a new zeta-shape with limited sand supply.

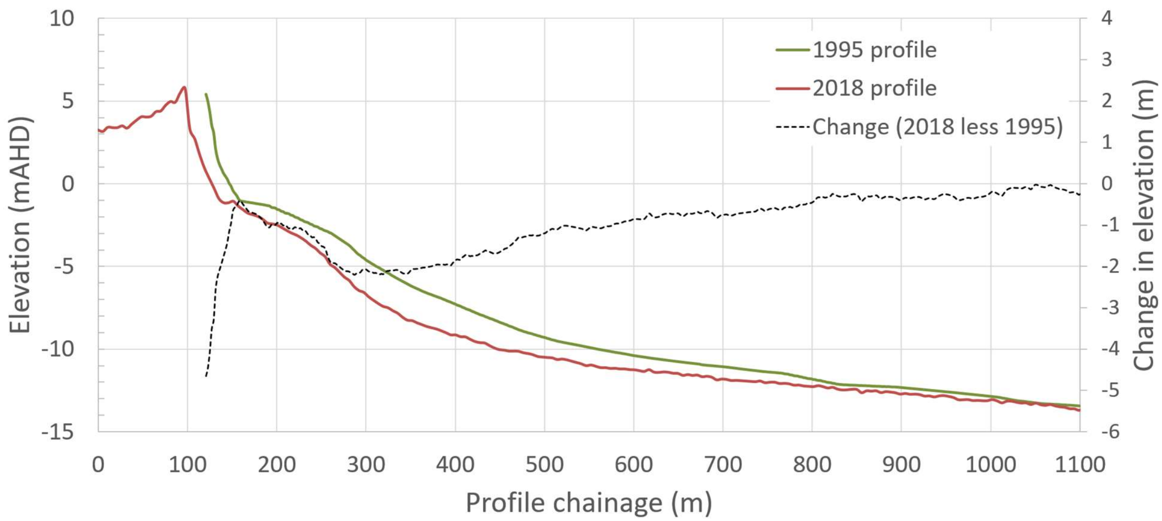

Figure 91: Coastal profile within the southern embayment showing the 1995 and 2018 survey showing overfilled area at relict ebb tide delta and the deepening and steeping of the profile.

The scenario laid out above is one plausible explanation that is in principle supported by the observations. Alternative explanations have been considered and where possible discounted if not supported by the factual data. For example:

- The deepening of the shoreface results from movement of sand southward or offshore. DHI (2006) predicted a nodal point and divergent net sand movement directions with a net southward transport in the southern embayment. A nodal point and net southerly transport imply a depositional area in the southernmost corner against the northern breakwater or in deeper areas north of the northern breakwater. No significant depositions are observed in the surveys in both these areas. Therefore, the DHI conceptual model of sand movement in the southern embayment is not supported by the observations. Alternatively, the sand may have moved into the deepened entrance channel and either been dredged and disposed offshore or moved further offshore by the ebb tide or flood flows. Again, dredging records of surveys, some of which extent beyond the 30m depth contour, do not support this notion.
- Sea level rise has been discounted as the underlying cause as the observed coastal erosion has been relatively localised and a rise in sea levels would be expected would be expected to results in both a landward and upward shift of the profile (not lowering of the shoreface).
- There is no record of significant quantities of dredging ever occurring in the southern embayment of Stockton Bight and this has therefore been discounted.
- The three seawalls along the Stockton shoreline have been discounted on the basis that the observed deepening commenced well before

As presented in Section 4.4, current measurements were undertaken in the nearshore area within 6-10m water depth which identified a net southward (low-magnitude) current that forms part of a secondary circulation pattern between the breakwater and the southern end of the Mitchell Street seawall. As found in the survey analysis and SWASH modelling undertaken for this study, the dominant sand transport in this area is forced by wave driven littoral currents (water depths less than 4m) in a net northward direction.

As discussed in Section 3, the northern Bight is characterised by the presence of a nearshore double-bar system while the southern Bight has a single semi-permanently attached bar. This plays an important role during storm waves, as the nearshore bars naturally offer protection of the coastline by wave breaking some distance from the shore while in absence of these bars larger waves impact the shore resulting in greater erosion, as seen during the recent storm erosion events at Stockton.

6.1.7 Port sand placements

The port's sand placement operations at Stockton have been described in Section 6.1.2. The placement location is in approximately 8m water depth relative to AHD, as shown in Figure 92. This placement area has been selected based on a constraints and opportunities analysis undertaken considering things such as the safe operations of the dredger the 'David Allen' as well as the location of shipwrecks and the like (WorleyParsons, 2009). The site is dispersive and is assumed that the bulk of the transport occurs firstly onshore and then into the littoral alongshore transport system with net northward movement. However, secondary sand transport pathway for the 2018 sand placement from the disposal site may be inferred from the surveys. It is recognised that these depend on the prevailing wave conditions at the time and alternative explanations may exist (e.g. the north-eastern area may be within the dredge placement box itself and the southern area could be related to cross-shore movement and not necessarily a transport pathway along the outer surf zone). However, if deemed to be significant these secondary dispersal pathways could be reduced by placing the sand in shallow depths (e.g. by rainbowing) which are beyond the reach of the existing capabilities of the 'David Allen'.

It is also noted that the 2018 survey was captured shortly after sand was placed at Stockton.

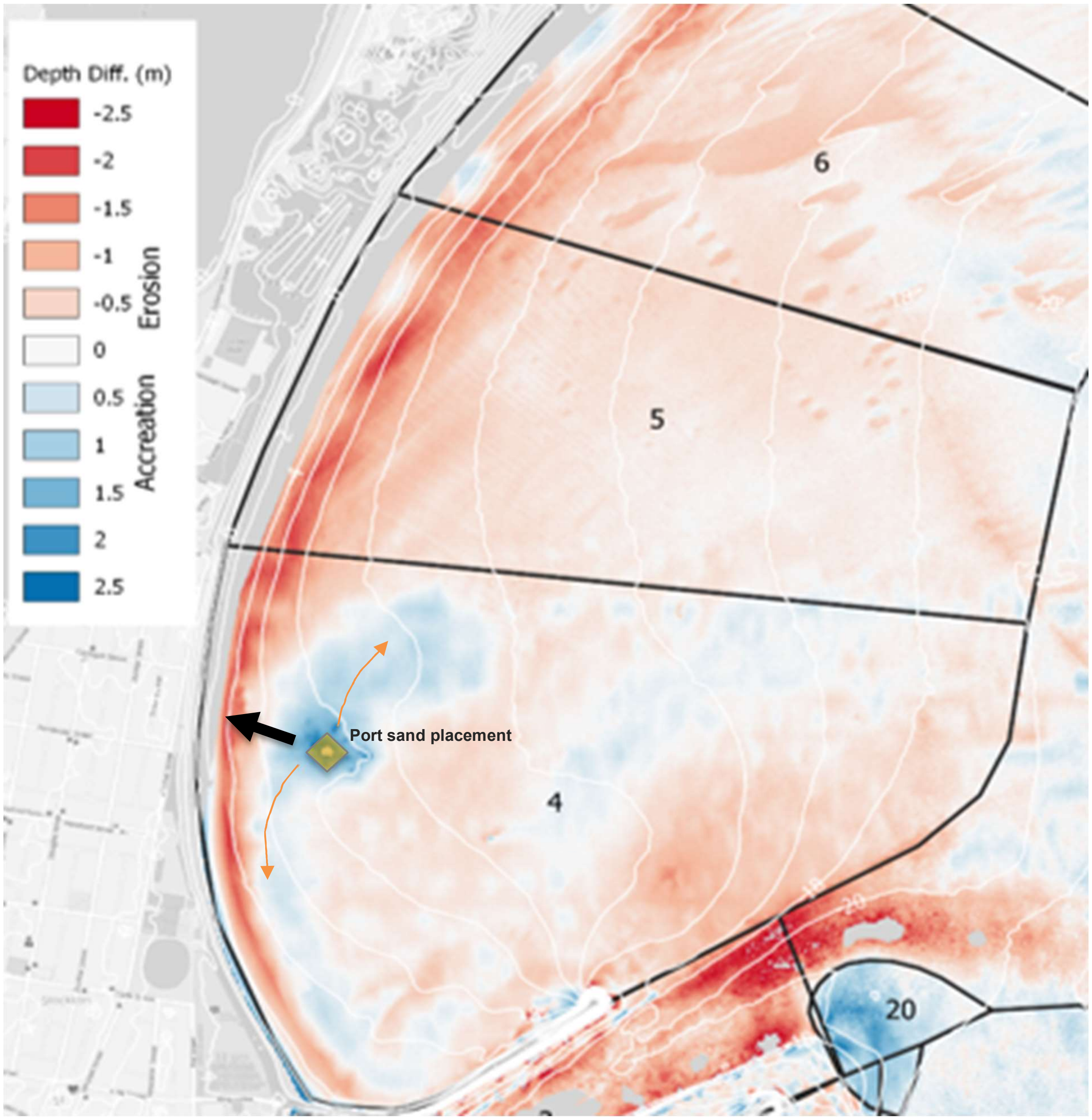

Figure 92: Seabed elevation difference between 2012 and 2018 showing dispersion of the port's sand placement in 2018.

6.1.8 Stockton dunes

The sand volume contained within the Stockton Bight transgressive dune sheet has increased over time. This has been quantified by the LiDAR survey comparisons herein as a net increase of 210,000m^3/yr (within analysis compartments) and around 400,000m^3/yr of sand being transported onto the dune sheet from the beach compartment. In line with previous literature, a net northward migration of the active transgressive dunes and alongshore (towards north-east) migration of the transverse ridges was identified. Given the seasonal and longer-term variations in the wind climate a reversal, slowing down or acceleration of the typically observed migration pattern may occasionally be observed. While dune sand is primarily transported by aeolian processes, the most seaward part of the foredune is considered in direct interaction with the beach and is subject to overwash and erosion processes by wave action. Mixing of windblown dune sand and littoral sand may occur as part of this two-way process, however, the dune sheet is considered a significant long-term sink for the beach compartment. Given, the ongoing (long-term) northward migration of the foredune and the stable (or prograding) shoreline provides evidence of a net influx of sand to the northern end of the Bight since the post-glacial sea level had reached its present position.

A long history of sand mining within the active (mobile) dune sheet as well as in vegetated areas exists along the Stockton Bight. While records and extraction limits exist for the quarries, the exact extraction locations and quantities could not be identified as part of this study.

6.1.9 Bight rotation

Rotation of embayed beaches is a cyclic phenomenon that can be observed along the Australian east coast and causes temporary changes in beach widths that range from a few metres to in excess of 10s of metres (Loureiro and Ferreira, 2020), for example at the Collaroy-Narrabeen embayment (Harley et al, 2015). The cyclic clockwise or anti-clockwise rotation of the beach (i.e. inverse change of beach width at opposing embayment extremities) is not typically considered a sink or a source as sand is maintained within a closed sediment cell. Typically, this occurs at embayed beaches of much shorter length (e.g. Collaroy-Narrabeen is less than 4km) compared to the 32km Stockton Bight, where alongshore distances are much greater. Still, this has been further assessed herein to provide context of cyclic processes for the identified long-term (net) sand pathways. Beach rotation can be observed over various time scales, defined as (Loureiro and Ferreira, 2020):

1. *Short-term:* Rapid beach rotation in the order of days–month, often as a response to storms.
2. *Medium-term (seasonal)*: Gradual rotation in the order of months–year, often with a strong seasonal signal.
3. *Long-term (interannual to decadal)*: Rotation with an interannual cyclicity (> 1 year), representing changes with yearly to decadal climate signals.

For this study, cyclic changes of the Stockton Bight shoreline position were assessed by using:

- 2011/12/13 and 2018 LiDAR elevation data (+1m AHD contour); and
- 32-years of shoreline positions derived from satellite imagery using CoastSat (Vos et al., 2019).

The analysis undertaken herein suggests that medium-term and event-based cyclic behaviour of shoreline positions is evident for periods of months and potentially over several years, however this is overruled by a dominant trend in long-term erosion in the southern Bight and net accretion in the northern Bight. The short- and medium-term cyclic events of clockwise and anti-clockwise shifts in shoreline positions along the Bight are likely explained by changes in wave climate linked to seasonal and yearly to decadal climate signals (e.g. ENSO). For example, during La Niña cycles, increased tropical and east coast cyclone activity may bring a higher number of swells from a north-easterly and easterly direction which can lead into a temporary reversal of the net sand transport pathways (see further discussion in Section 7.2) and exposure to waves (i.e. cross-shore transport). Given the length of the Bight, the behaviour of shorelines at each end are not dynamically coupled (e.g. temporary erosion at the northern end does not mean this material will result in accretion at the southern end).

The opposing long-term trend in beach width change is clearly shown in the comparison of shoreline positions at the southern and northern end of Stockton Bight in Figure 93 (derived from the available LiDAR data). However, as described in Section 6.1.8, the long-term accretion or stable position of the shoreline in front of the active dune system at the northern end of the Bight has been evident long before European settlement. In contrast, the sand loss from the full coastal profile along the southern Bight is evident since more recent anthropogenic modifications of the coastline. Given the relatively short time period of 5-7 years of available topographic data for this analysis, the relative changes in shoreline positions based on the 32-years' of CoastSat data have also been assessed and are presented in Figure *94*. In agreement with the other investigations herein, both analyses and assessed time periods suggest a long-term (non-cyclic) trend that results in a clockwise rotation of the shoreline within the Stockton Bight. It is noted that the horizontal accuracy of the satellite derived shoreline positions is around 10m which was deemed suitable for the purpose of this analysis.

Figure 93: Shoreline positions at the northern and southern end of the Stockton Bight derived from the available LiDAR data.

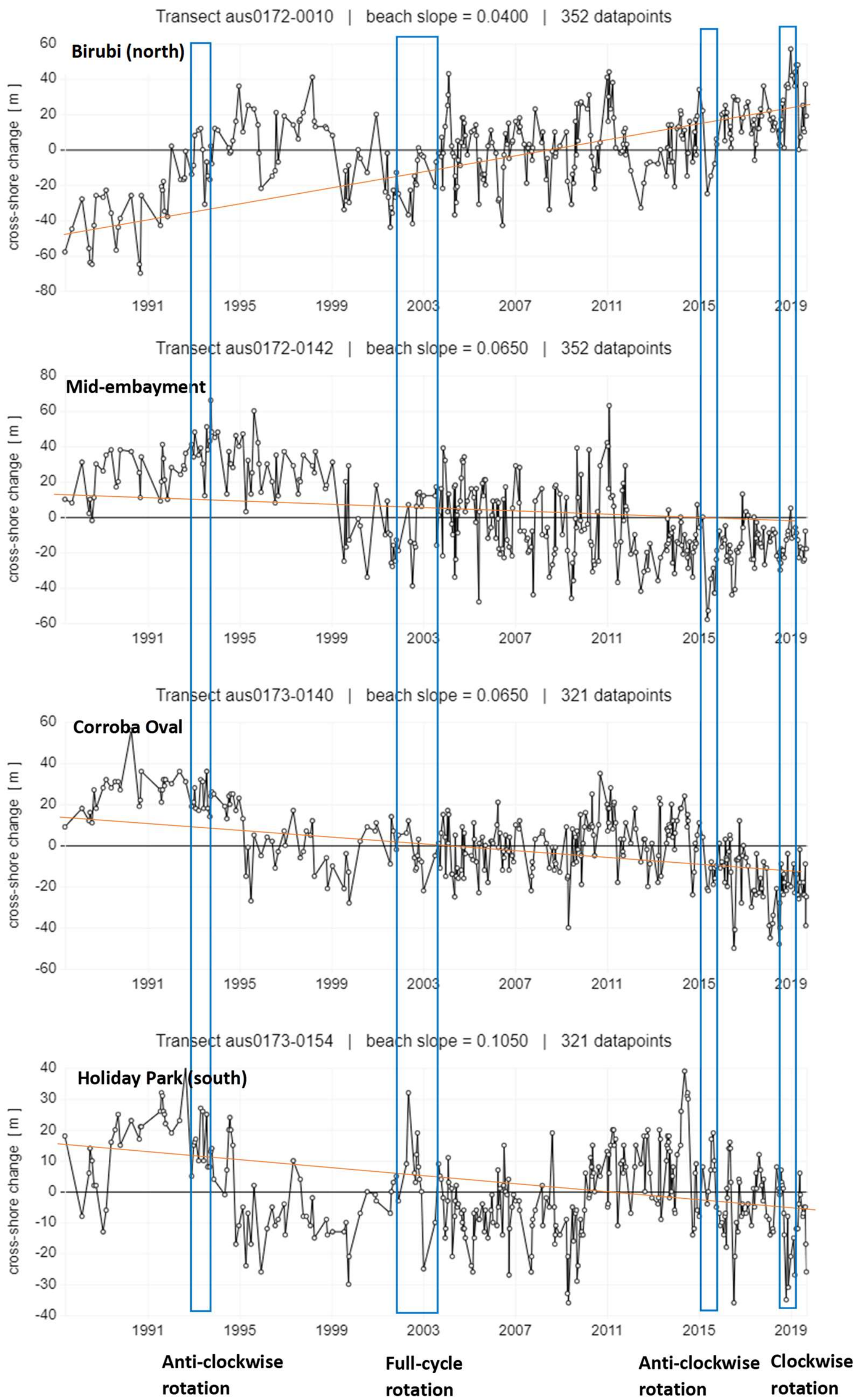

Figure 94: Changes in shoreline position at four cross-shore profiles (top to bottom – north to south) within Stockton Bight based on 32-years of satellite imagery. Note, trendlines are approximated.

6.2 Quantified conceptual model

Based on the Stockton Bight sand budget presented in Section 5 and explanation of each of the main sand sources, sinks and pathways provided in Section 6.1, Figure 95 shows graphical overview of the quantified conceptual model of sand movements (quantified model) in the Stockton Bight.

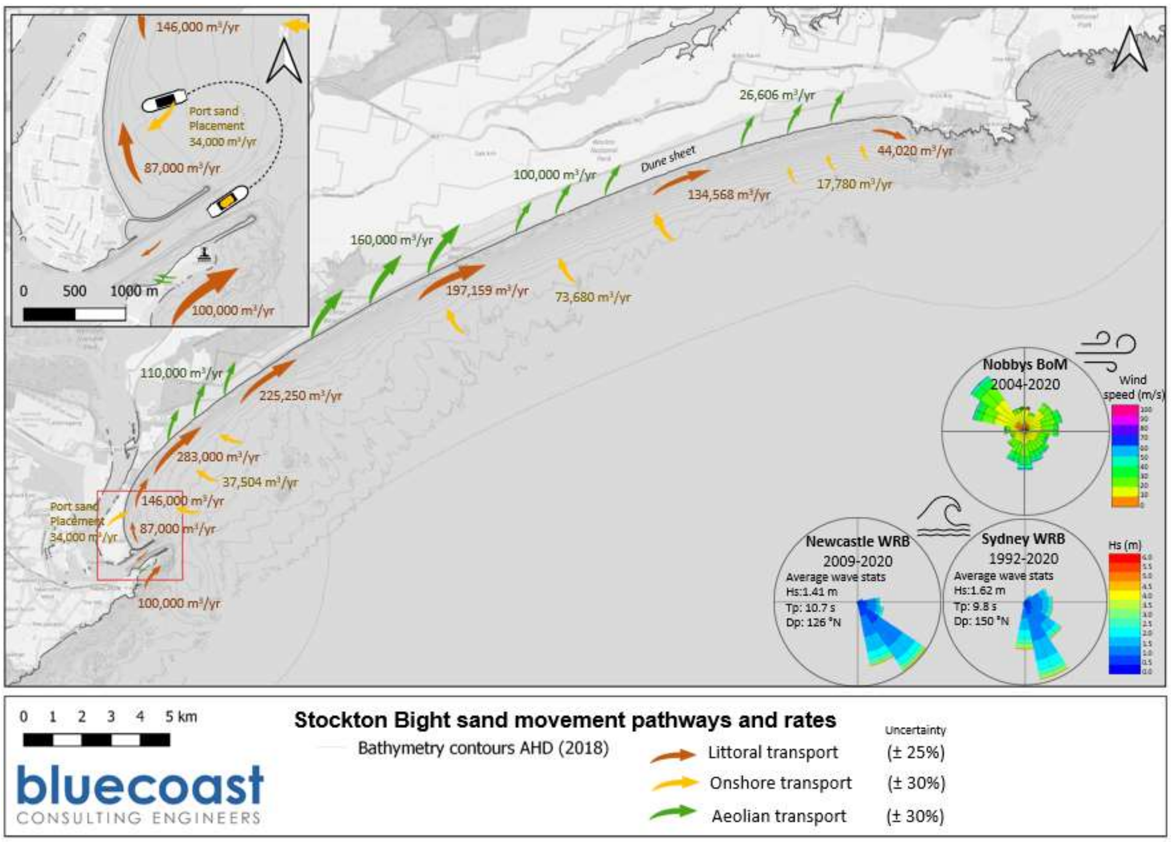

Figure 95: Quantified conceptual model of sand movements in the Stockton Bight.

The quantified conceptual sand movement model for the Stockton Bight can be explained by the following key concepts:

1. **Variable wave climate** - the Stockton Bight is exposed to a variable wave climate that drives variations in sand movement. Temporal variations in the wave climate act over seasonal to decadal and longer time frames. The Bight's seasonal wave climate is characterised by:

   - Summers with lower energy waves (seasonal mean significant wave height of 1.3m and peak wave periods of 9.7s) from more easterly direction (125°N) due to influence of north-east sea breezes and reduction in Tasman Sea and extra-tropical swells from the south. Spring is characterised similar as summer but with a transition towards winter conditions.
   - Winter is characterised by higher energy southerly swells (seasonal mean significant wave height of 1.49m, peak wave periods of 11.6s from more southerly mean direction of 137°N). Autumn is similar as winter but with a transition towards summer conditions.

   Longer term (decadal) variation in mean directional wave power are primarily associated with El Niño Southern Oscillation (ENSO) (Morlock and Goodwin, 2016). Shifts in the northerly alongshore transport regime of the Bight can be linked to directional variability in the regional wave climate with

ENSO (Goodwin et al., 2013). While shifts in the orientation of beach compartments are not observed along the 32km Bight as they are within shorter embayments (e.g. Collaroy-Narrabeen Beach; Harley et al., 2015), changes in the directional wave climate can result in periods of reversal of the net longshore transport direction creating a shift in sand volumes over sections of the Bight (DHI, 2006). Gordon and Roy (1977) noted rotation in wave directions of 13 degrees result in a reversal in the net sand movement direction.

2. **Alongshore sand transport –** driven by the obliquely aligned southerly wave climate a net northward longshore transport is experienced along Stockton Bight with significant alongshore variations in the rates. The highest rates longshore transport rate (280,000m^3/yr) occur around Fort Wallace with lower rates in the south due to the wave sheltering provided by the port's breakwater and in the north due to a much-reduced wave obliquity. The gradients in longshore transport rates explain the pattern of erosion observed over the southern Bight and the accretion observed in the northern Bight.
3. **Sand bypassing of the harbour entrance –** has been altered by the construction of the breakwaters and the deepening of the entrance to Newcastle Harbour. The natural sand bypassing rate pre-breakwater construction is estimated to be 100,000m^3/yr (±30%) as described in Section 6.1.2. Since breakwater construction was completed, shortly after the turn of the previous century (~1912), sand bypassing rates have been reduced and intermittent. Following the channel deepening project, which was completed in 1983, sand bypassing to Stockton Bight ceased. This is because the combined physical barriers of the breakwater and deep channel make it impossible for significant quantities of sand to move northward. Mechanical bypassing of a portion (~34,000m^3/yr, Section 6.1.2) of the natural bypassing was reinstated by the port's on-going dredge operations in 2009. The Hunter River is not a significant source of sand sized sediments.
4. **Deepening and realignment of the southern embayment –** as evidenced by historical surveys, the southern embayment has experienced on-going erosion and steepening and deepening of the shoreface (see Section 5.2.1). For the area fronting the suburb of Stockton the erosion has been exacerbated by the lack of sand supply from the south (i.e. due to the alteration of the natural sand bypassing) combined with the northerly littoral transport continuing to remove sand from the southern embayment (compartment 4 and 5). The net long-term erosion of the southern embayment, until recently, has not been readily observable on the shoreline or sub-aqueous beach. This is because the erosion has mostly occurred as deepening on the overfilled nearshore (i.e. the relict ebb tide delta had been supplying sand to maintain a relatively stable average shoreline along Stockton).
5. **Dune sand supply –** around 60% of the sand transported from the southern embayment, along with onshore sand supply from the inner continental shelf is transported by wind into the dune sheet that backs Stockton Beach.
6. **Rotation of the Bight –** The net north-eastward movement of littoral and aeolian transport has been observed to result in a long-term clockwise rotation of the Bight with an accretion trend observed in both coastal and dune compartments around Birubi Point and a sand deficit in the southern Bight resulting in shoreline recession. A low net eastward flow of sand bypassing the headland at Birubi Point with an annual average rate of 44,000m^3/yr (±30%) has been estimated.

6.3 The role of storms

The dominant coastal response to large storm waves is beach erosion (during the event – typically days) followed by beach recovery (typically months) during the following lower wave energy conditions. This erosion and accretion cycles primarily involve cross-shore sand transport with the amount of beach erosion 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. When the wave direction during the storm event is oblique to the shoreline orientation, alongshore sand transport can be significant.

Several significant storm events at Stockton have resulted in sand being removed from the beach face at Stockton Beach, the sand volumes removed during these events is the storm demand volume.

6.3.1 Northerly swell event

From the 8th to 9th of February 2020 a north-easterly swell event and spring tides resulted in extensive beach erosion at Stockton Beach. RHDHV (2020) recorded wave heights and currents during the event (displayed in Figure 96) which measured inshore significant wave heights larger than 2.5m, inducing significant offshore and southerly (alongshore) current which had the potential to transport sediment within the system.

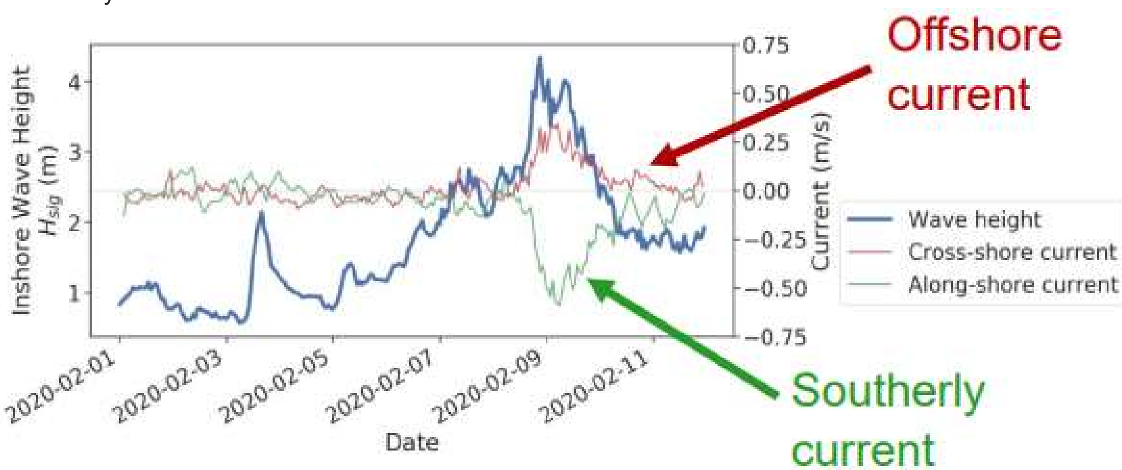

Figure 96: Measured currents and waves during the storm event on the 8th-9th February 2020 at Stockton Beach (Source: RHDHV, 2020).

Survey of the beach (terrestrial UAV/drone) was collected as part of the sand placement trial (see Section 6.4 for sand placement trial description) on the 5th February 2020 (post placement survey) and on the 18th February 2020 (storm event monitoring). The beach surveys have been used to examine sand movement during northerly swell event conditions. A snapshot from the UAV flight displayed in Figure 97 shows the shoreline on the 18th February 2020, after the storm event. Figure 98 displays the changes in seabed levels between the two surveys relative to the 18th February 2020 and is limited by the northerly extent of the 5th February 2020 survey. Within the map, red indicates areas where the seabed has lowered by erosion and the blue areas indicate areas of accretion. The majority of the beach was lowered by erosion between the two survey dates with the largest cutbacks being at the northern end of the SLSC seawall and directly in front of the caravan park at Stockton Beach, this aligns with the areas in the aerial images in Figure 97. The volume difference between the surveys was a net loss of 11,600m^3 of sand from the beach and foredune.

Figure 97: Storm damage to shoreline of Stockton Beach and SLSC seawall from CN UAV flight on the 18th February 2020.

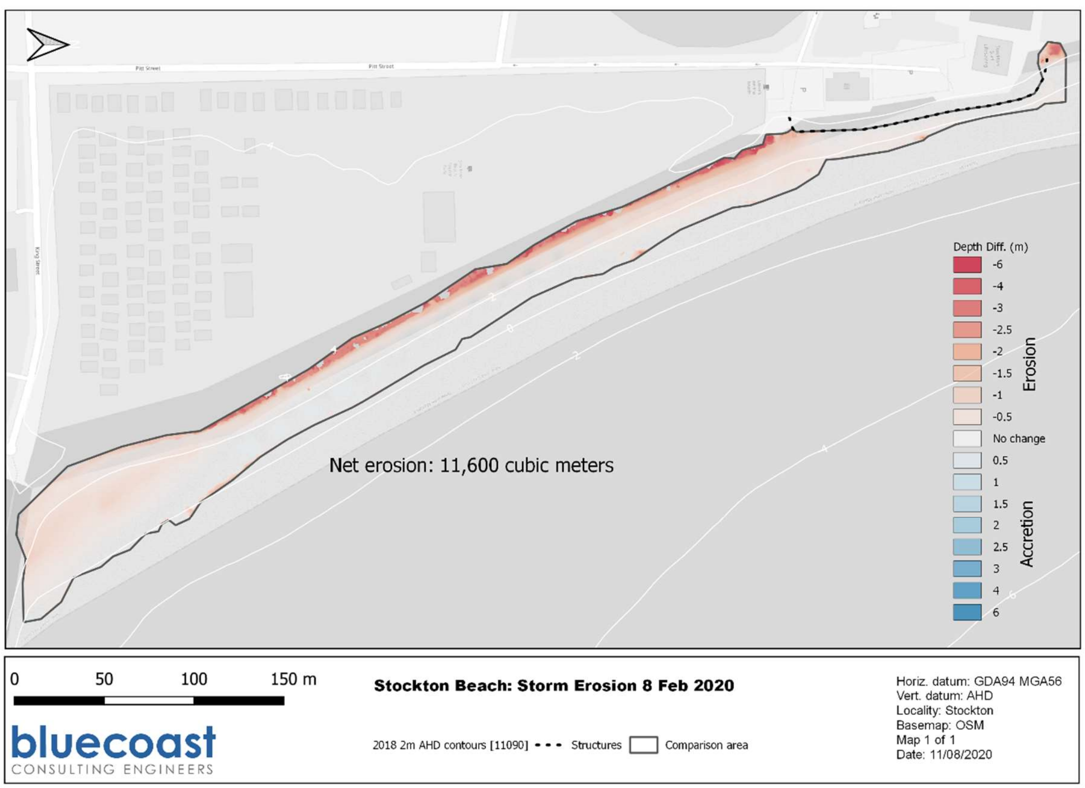

Figure 98: Survey difference map for 18th Feb 2020 relative to 5th Feb 2020 for northerly swell event on the 8th - 9th Feb 2020.

6.3.2 Southerly swell event

A southerly swell event occurred on the 13th of July 2020 and impacted a large portion of the NSW coastline. Terrestrial (UAV) surveys of the subaerial beach profile of Stockton Beach from the northern breakwater to the southern end of the Hunter Water seawall were undertaken after the event on the 20th July 2020. The surveys were compared back to pre-storm conditions on the 28th May 2020. Bathymetric (jetski) surveys of the subaqueous beach profile were undertaken on the 13th of July before the event, and a post storm comparison survey is available from the 24th July 2020. Due to the extents of the surveys, there is a section along the beach face between the subaerial and subaqueous datasets that does not have survey coverage. Figure 99 displays the cutback of the shoreline to the north and south of the sandbag protections at Griffith Ave taken during drone surveys on the 6th April and 20th July 2020 (before and after storm event). Figure 100 displays the changes in seabed levels between the re and post storm surveys relative to the 20th July 2020 (sub-aerial) and 24th July 2020 (subaqueous), with red indicating areas where the seabed has lowered by erosion and the blue areas indicate areas of accretion.

Comparisons for the southerly event show the largest changes in shoreline position occurred at the southern end of Mitchell Street seawall (bottom map in Figure 100) and between Mitchell Street north and the Hunter Water seawall. This is in keeping with the erosion of the shoreline seen in the aerials at Griffith Ave in Figure 99. The net volume of sand lost between the surveys in the subaerial beach profile was 116,000m^3. Of this net volume loss, approximately 36,000m^3 of this was lost from the section of shoreline north of Mitchell Street seawall. In the comparisons of the surveys in the subaqueous beach profile there was a net accretion of 182,000m^3 in the area surveyed out to the 10m contour. Although there is no survey comparisons available for this northern section of Stockton Beach for the northerly swell event on the 8th February 2020, it is expected that there would have been greater erosion of these shorelines during a southerly storm event due to their orientation of approximately 11 °N compared to southern Stockton Beach at 334°N. Erosion at southern end of Stockton Beach during the southerly event on July 13th (Figure 100) resulted in a sand volume loss of 8,900m^3 whereas the volume of sand lost in the same area during the northerly event on 8th February (Figure 98) was 11,600m^3. These differences in sand loss volumes are likely due to the orientation of the storm event, with south Stockton Beach being slightly protected by the port breakwaters during the southerly event.

Figure 99: Shoreline position at Griffith Ave (north of the Mitchell Street seawall) before and after the 13th July 2020 storm from CN UAV flights on the 6th April 2020 and 20th July 2020.

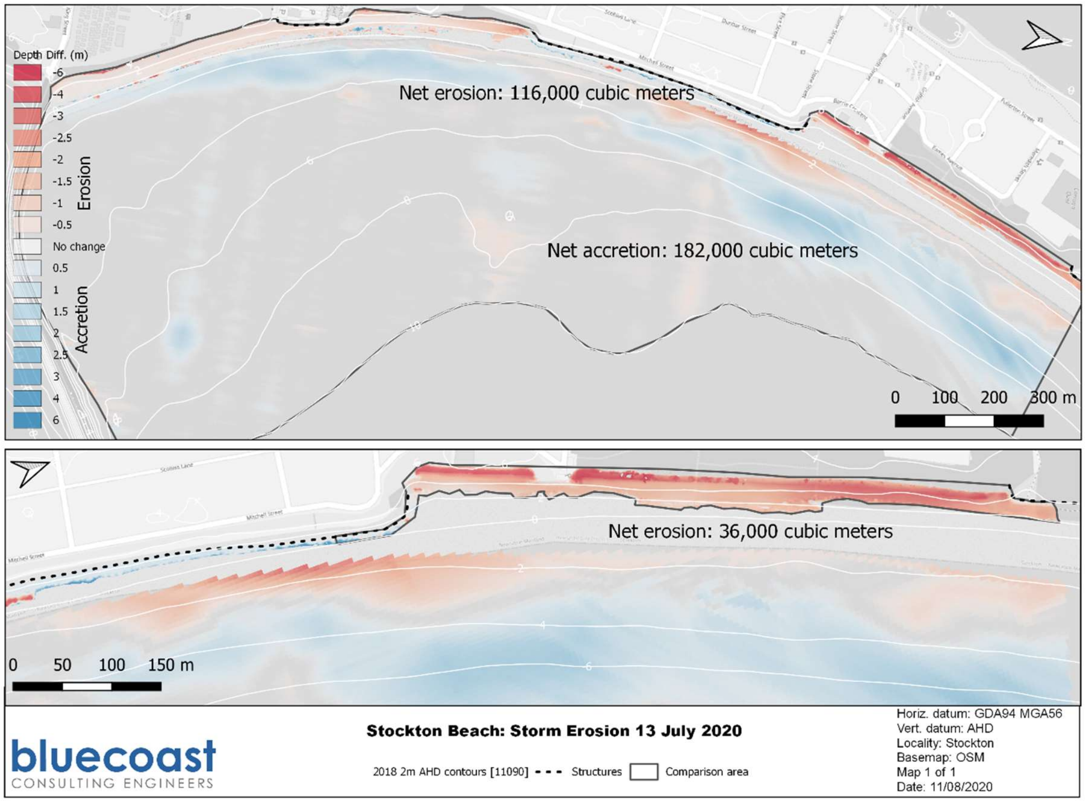

Figure 100: Survey difference map at Stockton Beach for southerly swell event on the 13th July 2020 with comparisons in the subaerial on the 28th May 2020 relative to 20th July 2020 and the subaqueous on the 24th July 2020 relative to the 13th of July 2020.

As noted previously in the description of the surveys, due to the survey extents there is a section along the beach face between the datasets that does not have survey coverage. The gap of undefined elevations is largest north of Mitchell Street seawall and is between approximately the 2m to -2m AHD 2018 contours (seen in Figure 100). As the areas immediately above the 2m contour and below the -2m contour have a net erosion and knowing the shape of a typical beach face profile for the area, it can be assumed that the gap between the surveys can be interpolated to estimate the full profile. Figure 101 displays the profiles taken just north of the Mitchell Street from pre- and post-storm surveys for the east coast low on the 13th July 2020. Interpolation across the survey gap show this section of the beach face underwent erosion during the storm event and a net erosion value was estimated. The lack of data within this gap would have reduced the net erosion volume given in Figure 100 and the missing section of erosion volume may account for the overall net accretion calculated between the surveys.

Adjacent to the northern end of the Mitchell Street seawall significant erosion of the seabed was observed. The post-storm survey showed depths nearby the toe of the structure (~8m) to be up to -4.8m relative to AHD (Figure 102). This is likely to be caused by the strong alongshore littoral currents observed in the area during the event (pers. coms R. Boyd) and enhanced by the alignment of the seawall relative to the shoreline. This scour is a risk to the stability of the structure as well as for wave overtopping, particularly given the on-going nearshore deepening and shoreline realignment/recession.

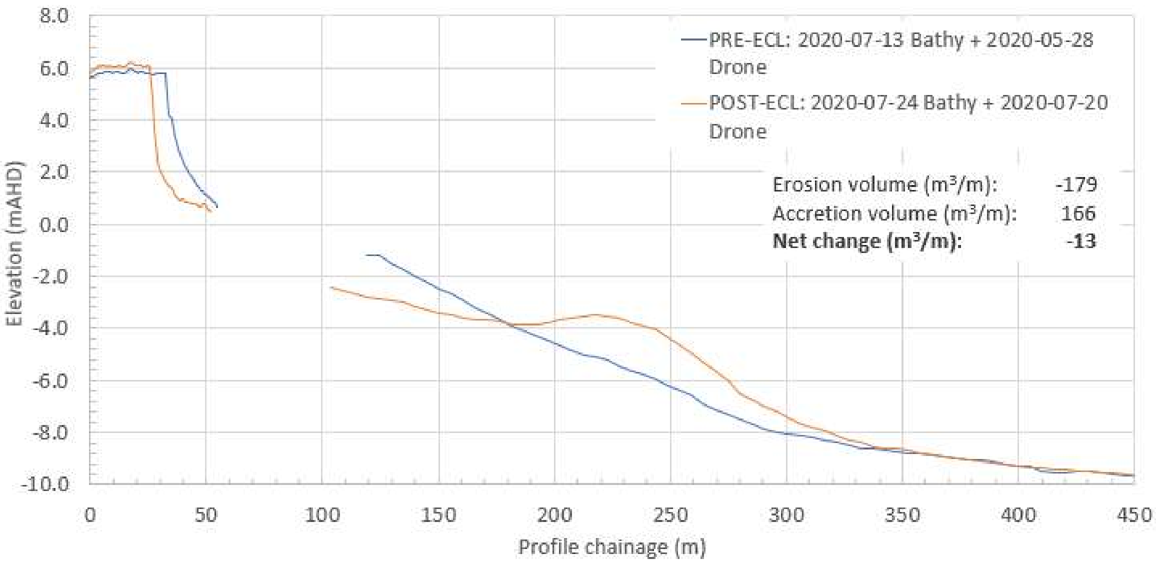

Figure 101: Coastal profiles from pre- and post-storm surveys for the east coast low on the 13th July 2020 taken just north of the Mitchell Street seawall.
Note: the discontinuity in the coastal profile is related to the gap in the survey around in inner surf and swash zone.

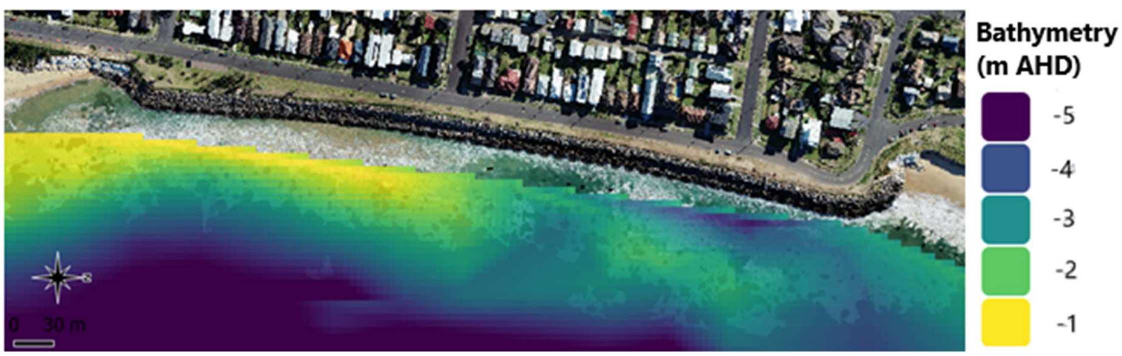

Figure 102: Post-storm seabed levels adjacent to the Mitchell Street seawall (colour bar in m AHD).

6.4 Trial sand placement exercise

Between the 9th – 12th of December 2019 the City of Newcastle placed terrestrial sourced sand onto the beach face along southern Stockton Beach. The relatively small sand placement volume of 5,644m^3 is Stage 1 of the two staged sand placement works proposed (RHDHV, 2020). The objective of the sand placements was to improve beach amenity and safety of the most popular section of the beach over the summer holiday period. The campaign was also intended as a pilot project and monitored with the intent of inform future management of the beach (CN, 2019b).

The 5,664m^3 of sand was placed in front of the Holiday Park and the SLSC revetment (see Figure 103). The nourishment was limited to the 25m width of subaerial beach above 0m AHD and a longitudinal extent of approximately 200m (RHDHV, 2020). Suitable sediment for a nourishment campaign is sand that has similar physical and chemical characteristics of the native beach sand. The section of Stockton Beach in the Stage 1 placement area (Figure 103) is comprised of medium to coarse sand (97% sand on average) with an average grain size of 0.37mm with typically less than 4% fines and less than 1% gravel content (WorleyParsons, 2012). The nourishment material was from a sand source with a median grain size (D50) between 0.35mm to 0.4mm, a fines fraction (< 75 microns) of less than 5%, no more than 2% of the sample being very coarse sand (> 2mm) and no organic content (RHDHV, 2020).

The monitoring required for the placement campaign involved surveys and measured waves and currents. Bathymetric (jet ski) and terrestrial (UAV/drone) surveys were undertaken before and after the sand placement, with ongoing surveys at 3-month intervals for monitoring as well as surveys taken pre and post any storm event that may occur to assess the impact of large events on the beach profile. Currently the surveys undertaken at Stockton are:

- 4-5th December 2019 – Pre sand placement
- 19th December 2019 - Post sand placement
- 5th February 2020 – Three monthly monitoring (used as pre storm survey event on 8th February)
- 18th February 2020 – Post storm survey, terrestrial only (event on 8th February)
- 6th April 2020 – Three monthly monitoring, terrestrial only
- 28th May 2020 – Three monthly monitoring, terrestrial only
- 13th July 2020 – Pre storm survey, bathymetry only (event on 13th July)
- 20th July 2020 – Post storm survey, terrestrial only (event on 13th July)
- 24th July 2020 – Post storm survey, bathymetry only (event on 13th July)
- 3rd August 2020 – Three monthly monitoring, terrestrial only.

A spotter buoy was deployed offshore of the placement zone to measure nearshore wave heights from the 27th November 2019, the location is displayed in Figure 30 (Wave buoy RH). An ADCP was deployed in the nearshore (Figure 30 – ADCP RH) to measure ocean currents and waves from surface elevations. Measurements from the various deployments of the ADCP are available between 3rd December 2019 and 12th February 2020. Measurements of the wave conditions immediately after placement up until the post placement survey (12th to 19th December 2019 in Figure 96) showed ambient wave conditions with wave heights less than 1.5m (Hs), mean wave periods between 5s – 7s from the E to ESE. During the same period, low near-bed current velocities were measured with magnitudes too low to be suspended sediment or generate alongshore transport (RHDHV, 2020).

RHDHV (2020) compared the elevation from the placement of the nourishment sand and found that only the upper 5m width of beach retained the nourished sand. A depth of sand of up to 1m was lost from the lower 20m beach width that underwent nourishment, returning to the pre nourishment beach profile. A general reduction in sand volume was evident in the nearshore zone and minimal difference in seabed levels was noted beyond the surf zone. Further afield, there was minimal change south of the Stage 1 nourishment area (Figure 103) and to the north nourishment area there were gains and losses of up to 0.5m but minimal net volume change (RHDHV, 2020).

Figure 103*: Stage 1 sand placement works showing (top left) the extent, (top right) works underway on 10th Dec 2020, and (bottom) a typical design profile (Source: RHDHV, 2020).*

6.4.1 Sand movements during ambient summer wave conditions

Survey of the beach (terrestrial UAV/drone) and bathymetry (jetski) that was collected as part of the sand placement trial from the 19th December 2019 and 5th February 2020 (RHDHV, 2020) has been used to examine sand movement during ambient summer wave conditions. The post sand placement survey on the 19th December includes the sand placement volumes and no placement activities took place between then and 5th February which was the first monitoring survey was undertaken. The survey datasets cover both the beach above 0m MSL and out to approximately the 10m AHD depth contour 600m offshore. The wave conditions during this period showed ambient wave conditions with wave heights less than 1.5m (Hs), mean wave periods between 4s – 8s from predominantly the E with some from ESE. During the same period, low near-bed current velocities were measured with magnitudes too low to suspend sediment or generate alongshore transport (RHDHV, 2020).

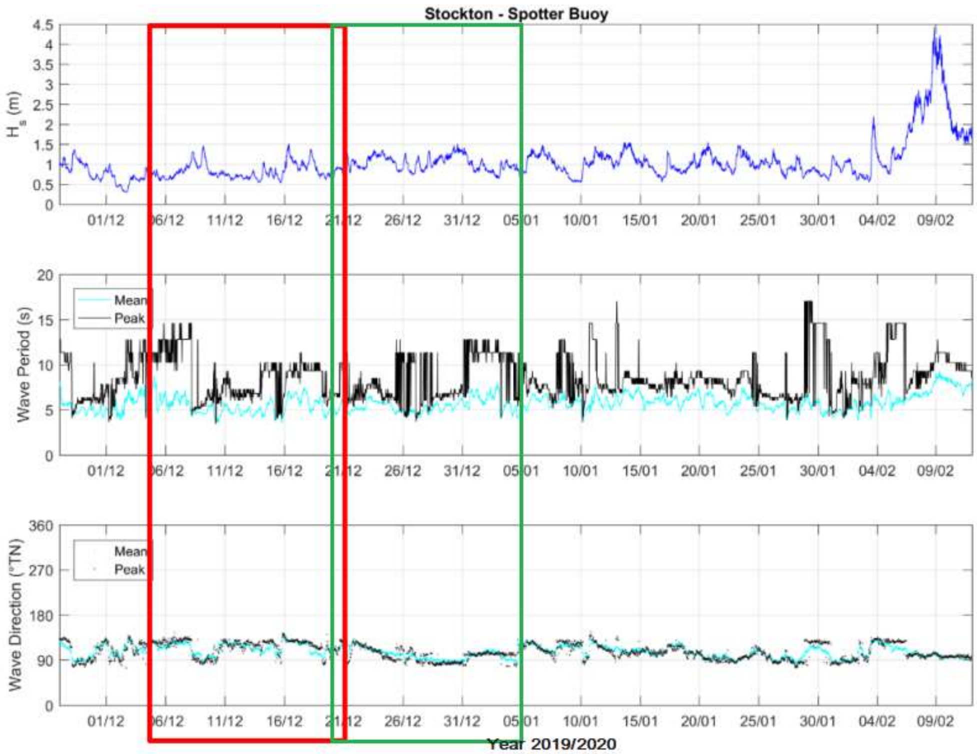

Figure 104: Measured wave data from spotter buoy showing (red) the period between the pre and post sand placement surveys and (green) the period between the post placement and first monitoring survey. (Source: RHDHV, 2020).

A volume analysis was undertaken on the layers to determine the volume lost or gained within the surveyed area. The analysis area included the entire extent of the surveyed area where there was adjacent beach and bathymetric survey out to approximately the 4m contour as beyond these depths there was minimal to no change. Figure 105 displays the changes in seabed levels between the two surveys relative to 2020 assuming a survey error of 0.1m. Within the map, red indicates areas where the seabed has lowered by erosion and the blue areas indicate areas of accretion. Areas of accretion are either formed by deposition of sediment (e.g. accumulation of littoral drift) or by sand placement activities (e.g. the effect of the beach nourishment placements at Stockton Beach).

Between 19th December 2019 and 5th February 2020 there was 6,828m^3 of sand loss and 11,617m^3 gained within the area. Figure 105 shows the pattern of transport was mostly erosion of the subaerial beach profile with accretion in the nearshore zone. Overall, there was a net gain within the area of 4,789m^3 and as there was no sand placement activities between the survey dates, the gain can be mostly attributed to the transport of sediment from the north. During the ambient wave conditions much of the sand that was placed on the subaerial beach was moved into the nearshore zone.

Figure 106 displays the change in the shoreline (of Stockton Beach) based of the measured contour positions on the subaerial beach profile in relation to the photogrammetry profiles. The analysis confirms that pattern of erosion of the subaerial beach profile at Stockton Beach between the surveys during ambient conditions.

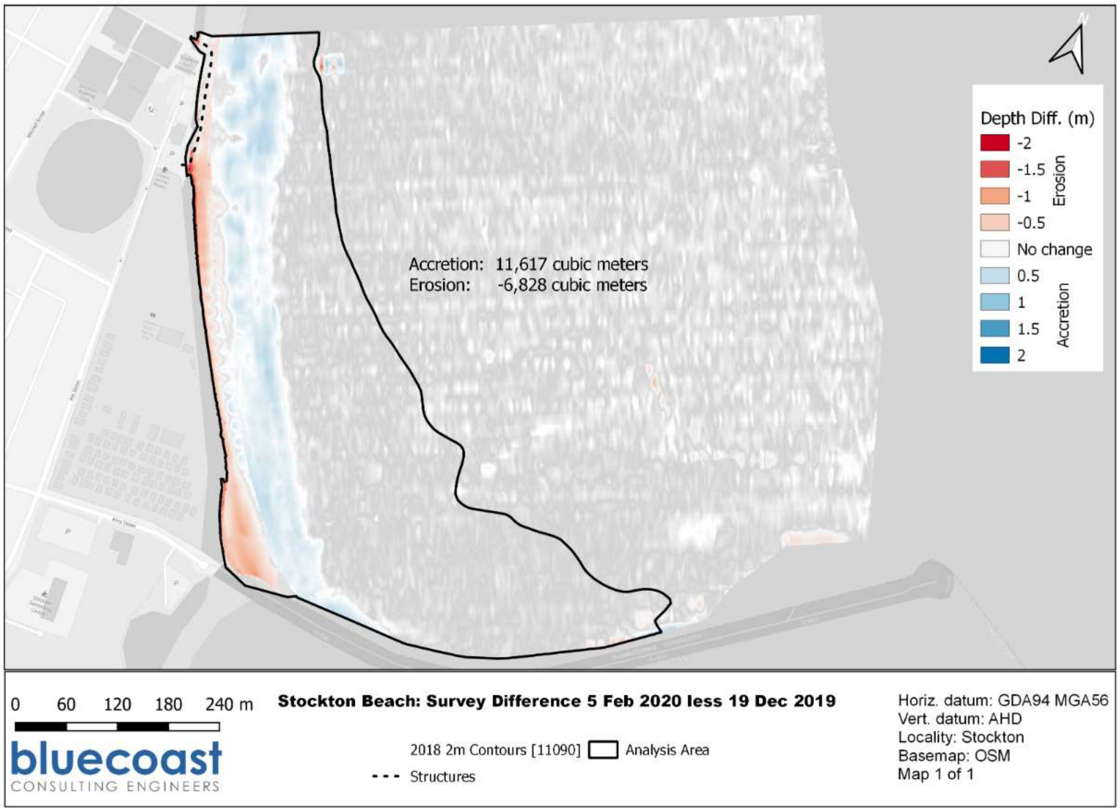

Figure 105: Survey difference map for 19th Dec 2019 relative to 5th Feb 2020 with volume difference calculations for zone 1 and the smaller extent of zone 2.out to the 4m contour (based on 2018).

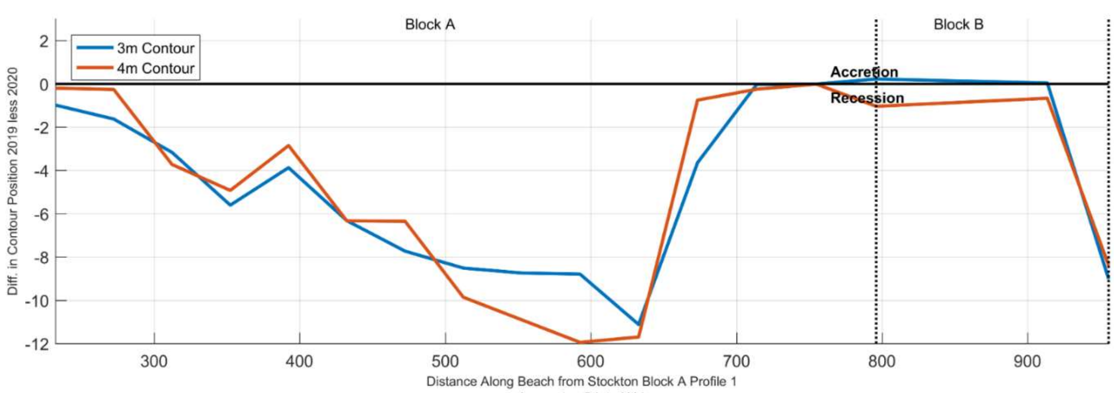

Figure 106: Shoreline change rates based off changes in contour positons between 19th Dec 2019 and 5th Feb 2020 along Stockton Blocks A and B.

7 Climate change assessment

7.1 Sea level rise

Climate change results in sea level rise (SLR) around Australia as the sea level changes in response to fluctuations in ocean mass and the expansion of water as it warms. The contribution of melting of ice sheets is also predicted to increase into the future. Shoreline recession can occur because of SLR as the increase in water level leads to a landward adjustment of the upper shoreface.

The latest advice from IPCC (2019) on sea level rise calls for increases to the allowances in previous documents. The latest global SLR (above 1986 - 2005 baseline) projections for the 'likely' scenario are 0.43m and 0.84m (i.e. 0.1m higher than AR5 projections in IPCC, 2013) by 2100 for RCP2.6 and RCP8.5, respectively (see Figure 107).

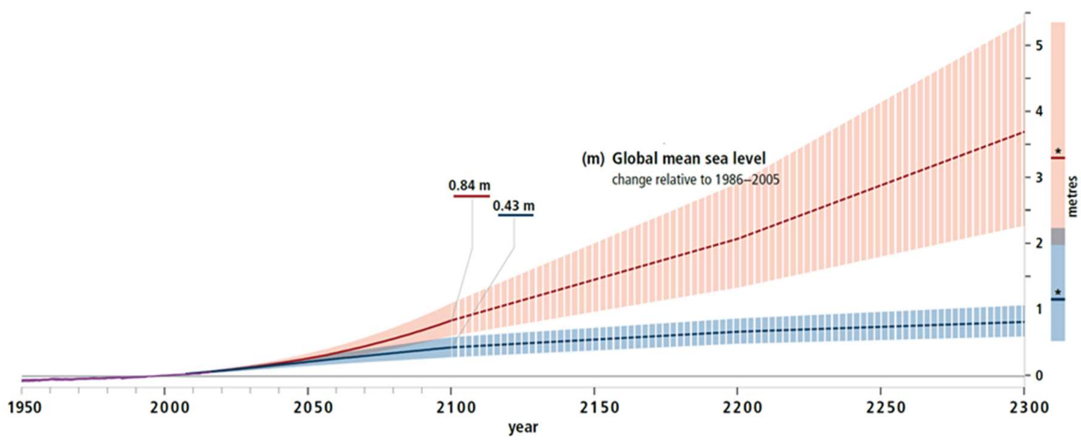

Figure 107: Global sea level rise projections above 1986 to 2005 baseline (IPCC, 2019): (blue) low (RCP2.6) and (red) high (RCP8.5) greenhouse gas emission scenarios.

SLR induced shoreline recession can be estimated using a simplified predictive equation termed 'the Bruun Rule' (Bruun, 1962 and 1983). The Bruun Rule is 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. This profile is re-established by shifting it landward and upward. It is noted that the application of the Bruun Rule is a highly simplified method to estimate SLR recession and its use in complex coastal processes areas such as the southern end of Stockton Bight and its proximity to the entrance is challenging. While it is common practice in NSW to adopt this approach, careful consideration of the input parameters and engineering judgement is required.

Shoreline recession due to sea level rise will be calculated as part of the Newcastle CMP's coastal hazard assessment being undertaken for the Bight's southern embayment.

7.2 Changes in storm and wave patterns

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. The directionality of the modal wave climate is well correlated with ENSO which significantly alters the wave climate in both direction and intensity (Mortlock and Goodwin, 2016). Typically, during La Niña events waves 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.

Due to shoaling in the nearshore zone, shifts in offshore wave direction with ENSO have limited impacts on wave directions near the coast. When waves are coming from the south east (clockwise of shore normal at Stockton) a 55° shift in wave direction is needed to see a 1° shift in wave direction in the centre and south nearshore zones. Whereas when the average offshore wave direction is southerly (anti-clockwise of shore-normal at Stockton) only a 30° change is needed for the 1° change in the surfzone. However, observations along the south east Australian coastline show shifts in the orientation of headland-bay beach compartments with the ENSO variations in wave climate. Figure 108 shows the surf zone morphology and wave directions for various ENSO seasons and the location of the nodal point along these embayments. ENSO wave climates that are from the northeast to south east (plots a, c, b and f in Figure 108) typically have a rhythmic bar and beach morphology, especially during La Niña east to northeast wave conditions. Measured shifts in modal wave direction with ENSO at Collaroy-Narrabeen Beach and Palm Beach resulted in a clockwise rotation of the embayment during El Niño events and an anti-clockwise rotation during La Niña events (Ranasinghe et al., 2004). The rotations of embayments with ENSO has been found to be more frequent over the last decade and studies suggest this may continue with climate change (Mortlock and Goodwin, 2016). The variations in weather patterns and intensity will have implications for shoreline stability and beach rotation at Stockton, which may further enhance the observed long-term clockwise rotation of the Bight.

The poleward expansion of the tropics impact storm type distribution, headland bypassing and regional longshore transport. 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). Figure 109 shows the potential storm driven longshore transport along the southeast coast of Australia if a 2-2.5° poleward shift of the tropics would occur. The expansion of the tropics with warming climate will lead to a poleward shift in storm type, with more tropical origin storms than extra-tropical storms with a southern origin (ETL and SSL in Figure 109, respectively). The reduction in extra-tropical storms with shore-oblique waves reduces the headland bypassing events along the southeast Australian shelf. Together with an increase in tropical storms that are shore normal, a poleward shift may result in a reduction in northward longshore transport and efficiency in headland sand bypassing (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.

Regionally, a study on the future change in climate within NSW undertaken by CSIRO in 2004 (Hennessy et al, 2004) found that in NSW average wind speeds and extreme monthly winds increased across most of the state. The study included analysis on extreme weather patterns and found that during the summer half of the year the frequency of ECLs and in turn the number of days with extreme winds decreased from 19% to 9% by 2070. During the winter half of the year the ECLs and frontal systems and the resulting extreme winds increased in frequency from 26% to 31% by 2070 and 25% to 29% by 2070 for ECLs and frontal lows, respectively. The storm systems that generate the highest storm surge and high wave activity in NSW which are typically ECL or cut-off lows showed small increases through all seasons. This may lead to the exacerbation of extreme winds and sea levels along the NSW coastline (Hennessy et al, 2004). The Newcastle coastline has been impacted with ECL events, with the 2019 -2020 period causing significant coastal erosion at Stockton Beach for the events on 8th February 2020 (see Figure 97) and 13th July 2020 (see Figure 99). An increase in the frequency of such storms could increase the rate of erosion of the beach at Stockton.

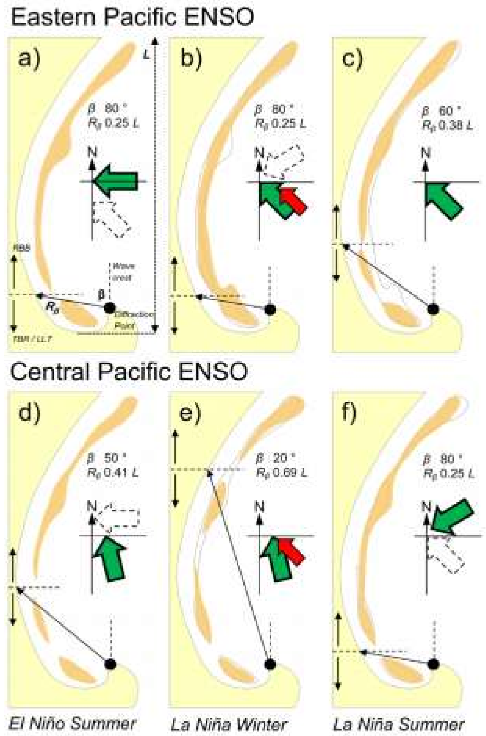

Figure 108: Model of the surf zone wave direction and embayment morphology during a summer-to-summer El Niño/La Niña cycle where the arrows are (red) mean storm wave direction in La Niña winter, (green) the dominant modal wave power, (white) the sub dominant wave power, the black dashed line is the nodal point and the morphology is shown by areas of accretion (orange) (source: Mortlock and Goodwin, 2016).

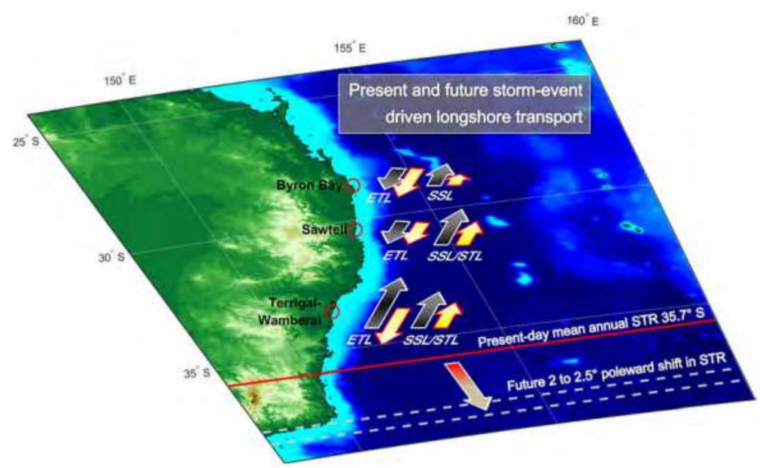

Figure 109: Storm driven longshore transport with a 2-2.5 degree poleward shift for (black arrows) present day and (yellow arrows) future day easterly trough lows (ETL) and southern secondary lows (SSL) (source: Goodwin et al., 2016)

8 Summary and recommendations

8.1 Summary

Stockton Beach is located on a sand peninsula immediately north of one of NSW's largest coastal rivers, the Hunter River. It is a highly dynamic coastal environment and has experienced numerous coastal erosion events requiring, the construction of a range of temporary (e.g. sandbagging) and permanent protection measures. While historical analysis of erosion at Stockton suggested a cyclic nature of beach erosion and recovery, in recent years erosion has progressed beyond the extents of historical cycles. The erosion is impacting beach amenity and coastal assets. In recognition the NSW Government has declared Stockton Beach a 'Significant Open Coast Location' or coastal erosion 'hot-spot'. The governments (local and state) are seeking a long-term solution to coastal management at Stockton Beach.

Coastal management strategies are often expensive and robust scientific knowledge is essential for effective coastal planning. To fully appreciate the dynamics at the southern end of Stockton Beach, an understanding of the entire sediment compartment is needed. A sand movement study of the entire Stockton Bight sediment compartment has been completed in accordance with the NSW *Coastal Management Act 2016*. This technical study forms a major part the Newcastle CMP's Stage 2 investigations as outlined by the NSW Coastal Management Manual.

The report covers a 32km long beach (NSW's longest beach), the largest active dune system in Australia, one of the highest wave energy beaches in NSW and a beach that grades from highly developed in the south to natural along its central and northern sections. It is a beach that is impacted by waves, tides, river flows, wind and human modification, all of which vary alongshore. Combined, these present an extremely complex and dynamic natural system that within and through which, there is considerable sand movement.

The study adopts a data-driven approach. At its centre is an analysis of the Bight's sand budget, which maps historical sand volume changes in ten beach and three dune sediment cells (Section 5). These are used to infer the rates and directions of sand movements. The most likely drivers for the observed sand volumes changes are described based on observational data, previous literature, state-of-the-art numerical modelling 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. Recommendations are made where this uncertainty could be reduced with improved data which would in turn would improve the quantification of the sand budget.

A quantified conceptual sand movement model was developed to link together the drivers and volumes of annual sand movement (see Figure 95). A net northerly longshore transport is fitted to explain the contemporary observations of sand volume changes. The southern Stockton Bight compartments (compartments 4 to 7) show a net erosive trend while the northern compartments (9 and 10) and dune compartments show a net gain in sand volumes. The pivot point of this trend was found approximately mid-way along the Bight, within compartment 8, where the shoreline turns more to the east. The highest annual net north-eastward sand transport rates were found adjacent to Fort Wallace which are gradually decreasing with alongshore distance in updrift and downdrift direction. Bypassing of sand around Birubi Point at Anna Bay was estimated to be around 44,000m^3/yr.

The most complex part of the system is the southern area around the river entrance, Nobbys Head and Stockton Beach area. Considerable attention has been paid to sand sources and sinks including the impact of the entrance training breakwaters, channel deepening and sand placements. Observations presented in Section 5.2 show a long-term deepening of the nearshore and a more recent realignment of the shoreline in the southern embayment between the northern breakwater and Fort Wallace. This agrees with the processes described in Section 6.1 that no natural sand bypassing from Nobbys Beach (northward) occurs and a net northward longshore transport or loss of sand occurs in the southern embayment of Stockton Beach. In contrast, previous literature (DHI, 2006) predicted a nodal point and divergent net sand movement directions with a net southward transport in the southern embayment. A nodal point and net southerly transport imply a depositional area in the southern corner against the northern breakwater or in deeper areas north of the northern breakwater. No significant depositional area is observed in the survey analysis and therefore the DHI (2006) conceptual model of sand movement in the southern embayment is not supported by the observations.

The observed deepening and realignment of the southern embayment is partly attributed to a significant reduction in the rate of sand bypassing the river entrance due to the construction of the breakwaters and deep navigation channel which, when combined represent a physical barrier to natural sand movement. The downdrift starvation of the southern embayment, until recently, is reasoned to have not been readily observable on the shoreline due to most change being attributed to the deepening of the nearshore and onshore sand supply to the Stockton shoreline from the relict ebb tide delta. The downdrift starvation is compounded by a second and more persistent pattern of coastal erosion/recession observed to the north of the southern embayment that is likely to be inherent to the Bight. The underlying cause of the inherent factors are reasoned to be the natural supply of marine sand to transgressive dune sheet. It is unclear if the clockwise rotation of the Bight is inherent or not.

Based on volumetric analysis of historical topographic and bathymetric surveys the long-term sand loss rate from the full coastal profile within the southern embayment of Stockton Beach (compartments 4 and 5 in Figure 50) is estimated as 112,000m^3/yr (±25%). This rate of sand loss is significantly greater than previously estimated and has implications for the on-going management of the coastal erosion issue at Stockton Beach. Without intervention the implications include chronic and worsening erosion which has already resulted in the loss of amenity and relocation of assets. There is a high potential for additional loss of amenity and assets. The scouring increases the risk of failure of the existing seawalls, wave overtopping of these seawalls and continued downdrift erosion as well as an increased risk of breakthrough of the peninsula.

The increased understanding of the Bight’s contemporary sand budget and sand movements provides the basis for improved evidence-based decision-making in coastal risk management and planning along Stockton Beach. The work can also be used to increase the confidence in shoreline change forecasts under future climate and sea level rise scenarios.

8.2 Key assumptions and uncertainties

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

- 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.
- Only limited survey data has been available for the mid and northern section of the Bight and survey analysis was therefore undertaken over shorter time periods which may result in higher uncertainties in estimated long-term averages.
- The rate of onshore sand supply has been assumed based on available literature.

- The records required to estimate the amount of sand of marine origin that enters Newcastle Harbour, mixes with fine sediment, and is then dredged and disposed at the offshore spoil grounds (i.e. outside the active coastal sand movement zone) during the port's maintenance dredging operations were not available to this study.

8.3 Recommendation

The Stockton Bight sand movement study presents a comprehensive review and analysis of available data and literature and is considered appropriate for the objectives of the study. As outlined above and throughout the report, limitations and assumptions have been noted with quantified errors (up to 30%) on some of the findings. Relevant uncertainties remain. The following lists identified areas where CN or other agencies could use practical approaches to improve the quantified conceptual sand movement model (i.e. by new or improved data or through further analysis):

- It has been necessary to infer the annual average quantity of marine origin sand that enters Newcastle Harbour, mixes with river silts and clays and is subsequently dredged and disposed of at the offshore spoil ground (i.e. marine sand that is removed from the active coastal zone). It is recommended that further effort is expended including obtaining and analysing the detailed maintenance dredging records, interpreting historical aerials and surveys in relation to infilling of Horseshoe Beach and measuring tidal and wave driven currents along the inside of the southern breakwater.
- Obtaining additional long-term bathymetric survey coverage over Nobbys Beach nearshore and the sand lobe would assist with quantifying sand impoundment and any offshore movements on the southern (updrift) side of the entrance.
- This study has focused on understanding historical patterns of change to infer future changes assuming no future human modifications, such as mass sand nourishment, terminal protection structures, groynes or artificial headlands or other significant coastal management actions. This lends itself to a data-driven approach. However, to predict the performance and impacts of significant coastal management actions, use of state-of-the art and well calibrated numerical and/or physical modelling is recommended prior to any major actions being implemented.
- It is recommended that CN and relevant state agencies consider the development and implementation of a coastal monitoring program to plan, priorities and co-ordinate the collection, analysis and storage of this coastal monitoring data. For example, this may consider:
    - Survey across the full coastal profiles with technique, frequency and extent to be determined with consideration for photogrammetry shore-normal profiles at northern Bight (minimum) or whole of Bight to build long term data set the use of used of satellite derived bathymetry for the northern bight and help monitor potential changes due to future changes in storm pattern and wave climate.
    - The direction of sand movements in the southern embayment is critical to effective management. For the avoidance of any remaining uncertainty the construction of a trial groyne or sand trap structure could be considered to estimate longshore transport rates north of Hunter Water site.
    - Nearshore current measurements around Birubi Point to quantify outflow.
    - Use of coastal imaging techniques to track the shoreline, nearshore wave conditions and other parameters at a high frequency.
    - Monitoring the effect of permanent and temporary coastal protection structures including their effect on beach widths.

9 References

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Appendix A - Metocean climate assessment

The following sections provide supporting material for the metocean climate assessment presented in the main report.

9.1 Wave climate

Offshore (regional) wave climate

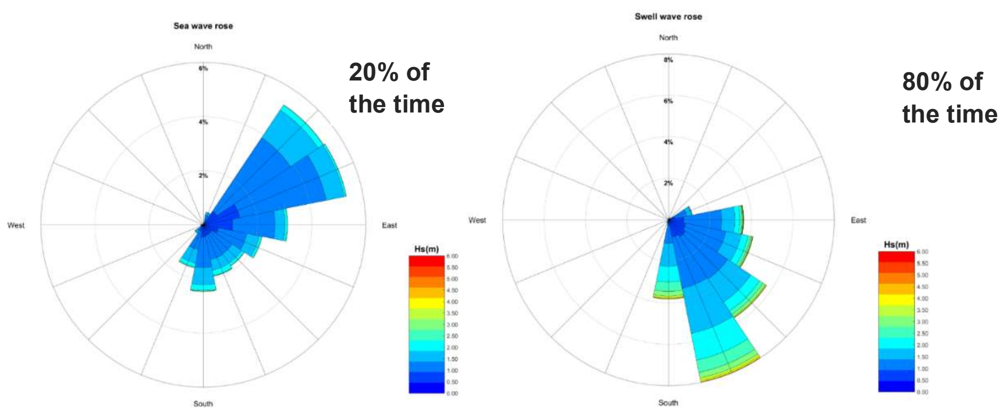

Figure 110: Long-term wave roses at Crowdy Head WRB for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from August 2011 to January 2020. The percentage occurrence of each sea state is annotated.

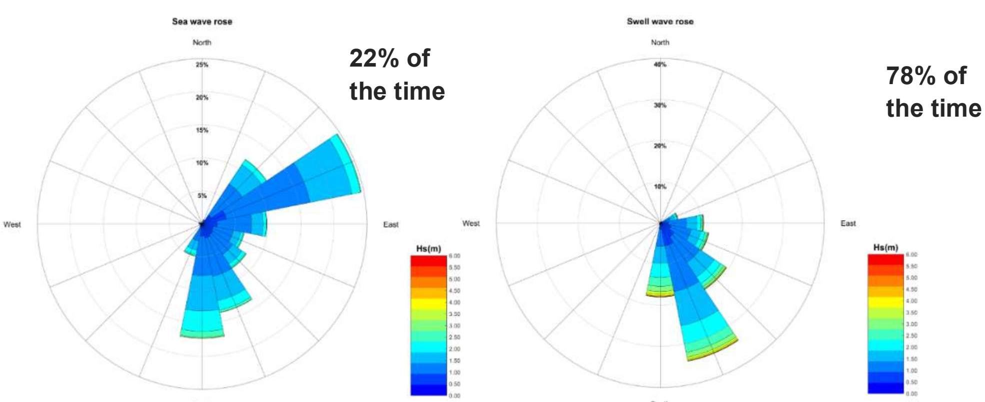

Figure 111: Long-term wave roses at Sydney WRB for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from March 1992 to January 2020. The percentage occurrence of each sea state is annotated.

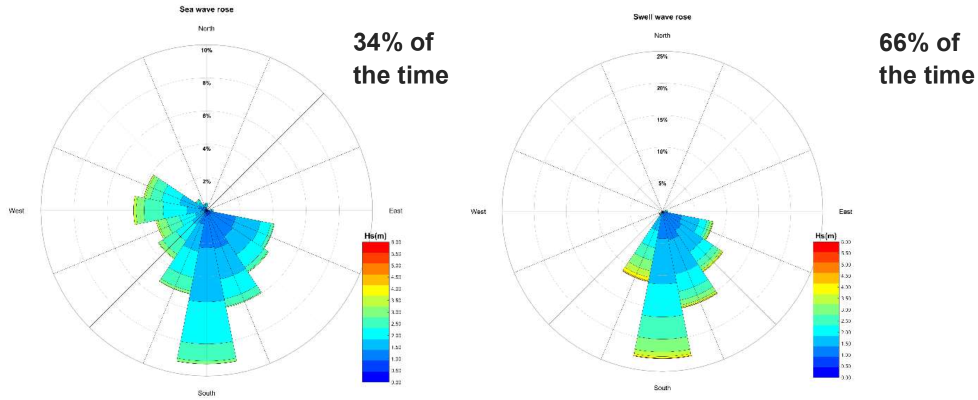

Figure 112: Long-term wave roses derived from the CAWCR Hindcast extracted at site A (further offshore) for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from 1979 to 2010. The percentage occurrence of each sea state is annotated.

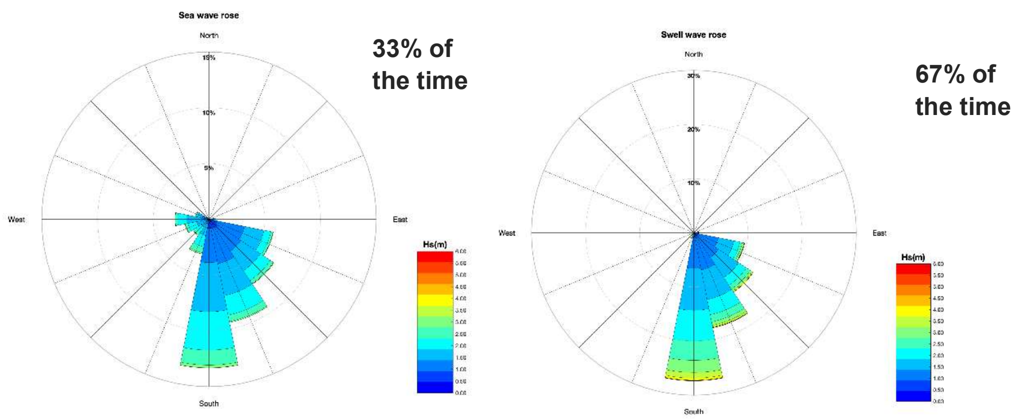

Figure 113: Long-term wave roses derived from the CAWCR Hindcast extracted at site B (closer to shore) for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from 1979 to 2010. The percentage occurrence of each sea state is annotated.

Table 9: Wave measurement statistics for the Crowdy Head WRB from August 2011 to January 2020.

Parameter	Statistic	Long term averages (10-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.56	1.65	1.52	1.51	1.56
	20%ile	1.05	1.04	1.05	1.06	1.05
	50%ile	1.40	1.47	1.39	1.35	1.41
	75%ile	1.84	2.02	1.79	1.72	1.86
	90%ile	2.42	2.65	2.31	2.25	2.43
	99%ile	3.80	4.17	3.37	3.76	3.74
	99.5%ile	4.19	4.45	3.58	4.27	4.09
	Max	6.62	6.62	4.81	6.40	5.15
Peak wave period (Tp) [s]	Mean	10.0	10.8	9.7	9.3	10.3
	20%ile	8.2	8.9	7.6	7.6	8.5
	50%ile	9.8	10.8	9.8	9.3	10.3
	75%ile	11.5	12.1	11.5	10.8	11.5
	90%ile	12.9	13.8	12.9	12.1	12.9
	99%ile	16.0	16.0	16.0	14.9	16.0
	% of time sea ($T_p < 8s$)	19%	11%	13%	27%	25%
	% of time swell ($T_p > 8s$)	81%	89%	87%	73%	75%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	146.4	150.7	152.8	133.5	146.5
	Mean	131.0	144.4	134.3	114.8	130.9
	Standard Deviation	37.7	32.5	41.1	37.5	33.8

Table 10: Wave measurement statistics for the Sydney WRB from March 1992 to January 2020.

Parameter	Statistic	Long term averages (29-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.62	1.65	1.59	1.58	1.66
	20%ile	1.05	0.97	1.06	1.06	1.06
	50%ile	1.45	1.43	1.43	1.43	1.48
	75%ile	1.93	2.01	1.87	1.87	2.02
	90%ile	2.55	2.78	2.44	2.44	2.62
	99%ile	4.17	4.65	3.96	3.59	4.10
	99.5%ile	4.64	5.18	4.43	3.93	4.62
	Max	8.43	7.76	6.22	5.53	8.43
Peak wave period (Tp) [s]	Mean	9.8	10.5	9.4	9.0	10.2
	20%ile	7.7	8.8	7.3	7.0	8.3
	50%ile	9.8	10.5	9.3	8.9	10.2
	75%ile	11.5	12.1	10.8	10.5	11.8
	90%ile	12.9	13.5	12.5	12.1	13.3
	99%ile	15.4	16.0	15.4	14.9	16.0
	% of time sea (T_p < 8s)	22%	12%	15%	34%	29%
	% of time swell (T_p > 8s)	78%	88%	85%	66%	71%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	150.4	154.3	153.6	141.9	147.5
	Mean	136.6	145.4	136.6	126.1	136.3
	Standard Deviation	37.4	32.1	40.1	40.4	34.9

Table 11: Wave statistics derived from the CAWCR 42-year wave hindcast from 1979 to 2010 (statistics only provided for CAWCR hindcast extracted closer to shore at site B).

Parameter	Statistic	Long term averages (42-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.85	1.82	1.87	1.85	1.85
	20%ile	1.29	1.22	1.27	1.37	1.29
	50%ile	1.71	1.69	1.73	1.73	1.70
	75%ile	2.20	2.20	2.27	2.16	2.18
	90%ile	2.77	2.80	2.82	2.68	2.78
	99%ile	3.99	4.07	3.96	3.79	4.06
	99.5%ile	4.28	4.37	4.25	4.09	4.33
	Max	6.68	6.50	5.99	5.54	6.68
Peak wave period (Tp) [s]	Mean	8.3	8.1	8.4	8.3	8.3
	20%ile	7.2	6.8	7.5	7.4	7.3
	50%ile	8.5	8.5	8.7	8.5	8.5
	75%ile	9.3	9.3	9.3	9.2	9.3
	90%ile	9.8	9.8	9.8	9.8	9.8
	99%ile	10.0	10.0	10.0	10.0	10.0
	% of time sea ($T_p < 8s$)	33%	35%	28%	35%	33%
	% of time swell ($T_p > 8s$)	67%	65%	72%	65%	67%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	166.4	171.5	162.3	160.1	169.8
	Mean	160.2	169.5	154.4	152.4	163.2
	Standard Deviation	32.9	39.3	30.0	27.1	29.5

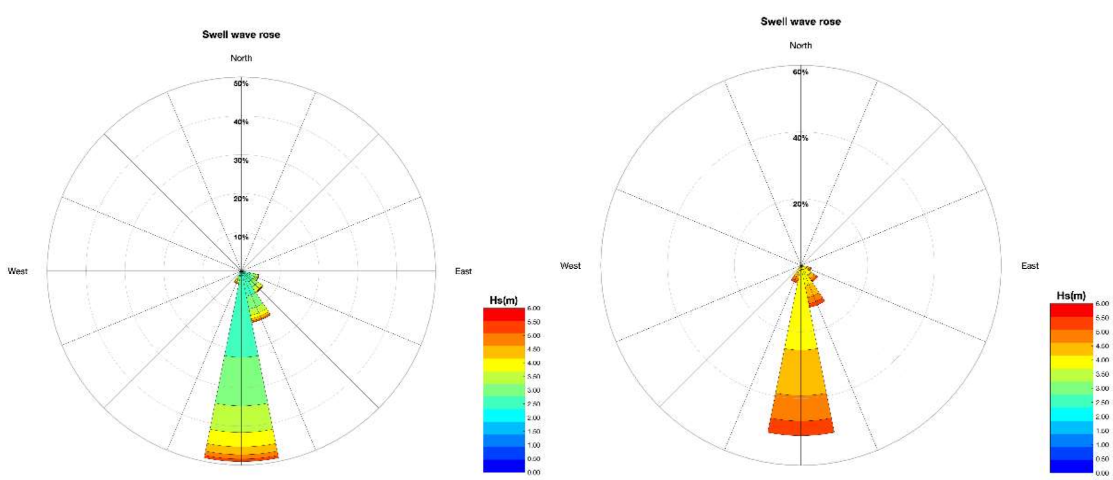

Figure 114: Long-term wave roses derived from the CAWCR hindcast extracted at site A (further offshore) for waves with (left) wave heights over 2.5 m and (right) over 4 m from 1979 to 2010.

<u>Nearshore wave climate</u>

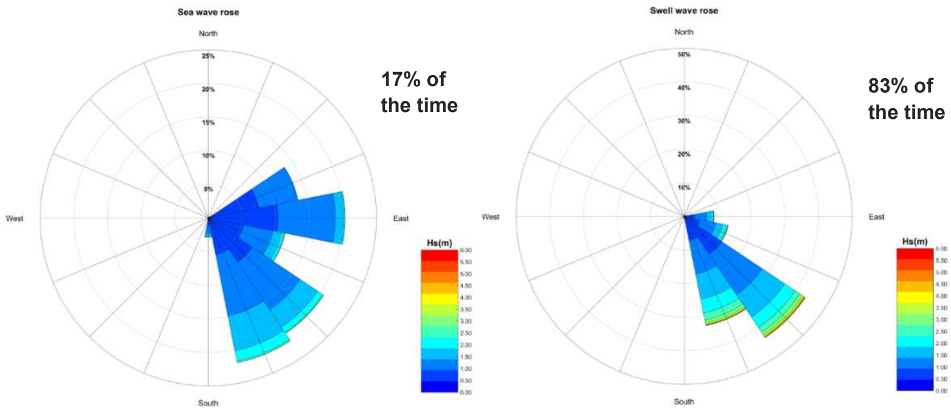

Figure 115: Long-term wave roses at Newcastle WRB for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) from November 2009 to March 2020. The percentage occurrence of each sea state is annotated.

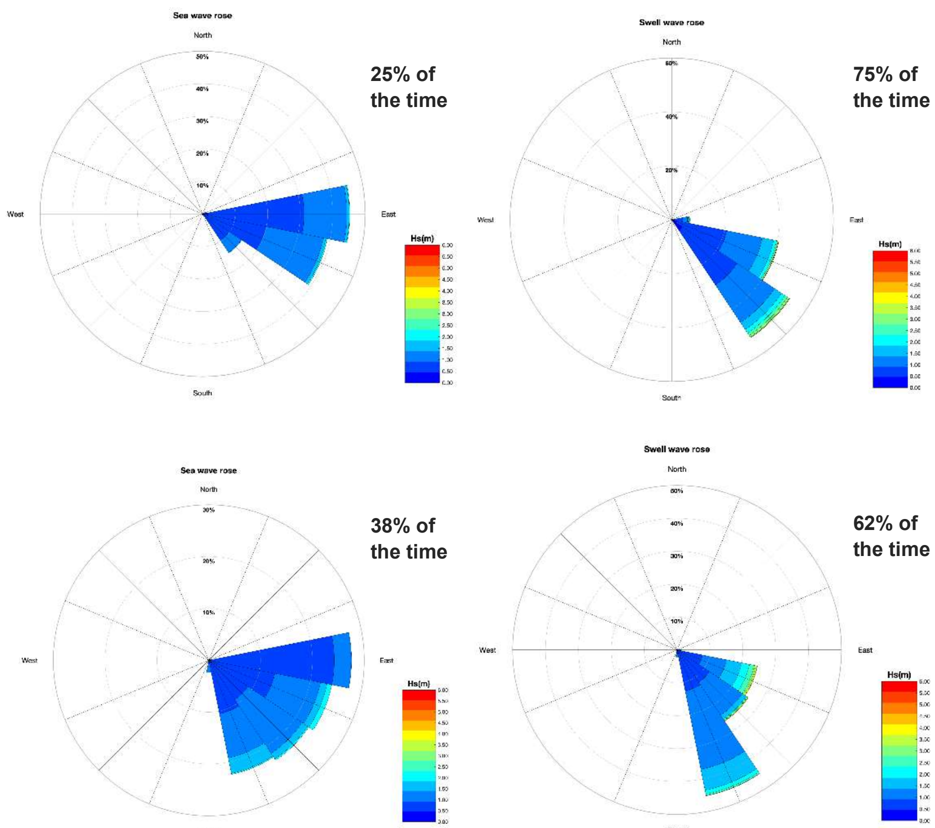

Figure 116: Short-term wave roses for sea conditions (Tp < 8sec) and swell conditions (Tp > 8sec) at (top) the DPIE WRB Stockton and (bottom) DPIE WRB Worimi. The percentage occurrence of each sea state is annotated.

Table 12: Wave measurement statistics for the Newcastle WRB from November 2009 to March 2020.

Parameter	Statistic	Long term averages (12-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.41	1.49	1.40	1.32	1.43
	20%ile	0.88	0.83	0.88	0.90	0.87
	50%ile	1.24	1.31	1.25	1.18	1.25
	75%ile	1.71	1.86	1.70	1.53	1.78
	90%ile	2.30	2.59	2.24	2.02	2.35
	99%ile	3.90	4.37	3.58	3.49	3.86
	99.5%ile	4.41	4.88	4.13	3.97	4.26
	Max	8.52	8.17	7.14	6.33	8.52
Peak wave period (Tp) [s]	Mean	10.7	11.6	10.6	9.7	11.1
	20%ile	8.5	9.7	8.2	7.5	8.9
	50%ile	10.8	11.5	10.7	9.7	11.0
	75%ile	12.6	13.0	12.6	11.5	12.9
	90%ile	13.9	14.6	13.9	12.9	14.3
	99%ile	17.1	17.5	17.0	15.9	17.4
	% of time sea (T_p < 8s)	16%	6%	18%	26%	11%
	% of time swell (T_p > 8s)	84%	94%	82%	74%	89%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	125.7	135.8	144.6	93.5	-
	Mean	133.4	136.7	137.5	125.8	133.9
	Standard Deviation	23.1	19.2	22.6	27.2	20.9

Table 13: Wave measurement statistics for the DPIE WRB, spanning 30th December 2019 to 13th July 2020 (only summer, autumn and winter averages available).

Parameter	Statistic	Long term averages (<1-year)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.05	0.98	-	1.03	1.09
	20%ile	0.69	0.64	-	0.73	0.66
	50%ile	0.95	0.92	-	0.92	1.00
	75%ile	1.21	1.25	-	1.14	1.28
	90%ile	1.55	1.47	-	1.41	1.67
	99%ile	3.11	2.20	-	3.04	3.32
	99.5%ile	3.50	2.69	-	3.59	3.61
	Max	4.57	3.37	-	4.27	4.57
Peak wave period (Tp) [s]	Mean	10.3	11.2	-	9.1	11.0
	20%ile	7.9	9.3	-	6.8	8.5
	50%ile	10.2	11.4	-	8.5	11.4
	75%ile	12.8	12.8	-	10.2	12.8
	90%ile	14.6	14.6	-	12.8	14.6
	99%ile	17.1	17.1	-	17.1	17.1
	% of time sea (T_p < 8s)	25%	8%	-	42%	17%
	% of time swell (T_p > 8s)	75%	92%	-	58%	83%
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	121.7	124.2	-	110.7	127.0
	Mean	117.6	121.6	-	113.3	119.6
	Standard Deviation	14.8	11.4	-	16.7	13.4

Table 14: Wave measurement statistics for the DPIE WRB WORIMI, spanning 6th December 2019 to 25th February 2020 (only summer average available).

Parameter	Statistic	Long term averages (<1-years)				
		All seasons	Winter	Spring	Summer	Autumn
Significant wave height (H_s) [m]	Mean	1.17	-	-	1.17	-
	20%ile	0.83	-	-	0.83	-
	50%ile	1.06	-	-	1.06	-
	75%ile	1.32	-	-	1.32	-
	90%ile	1.65	-	-	1.65	-
	99%ile	3.01	-	-	3.01	-
	99.5%ile	3.55	-	-	3.55	-
	Max	4.11	-	-	4.11	-
Peak wave period (Tp) [s]	Mean	9.1	-	-	9.1	-
	20%ile	6.8	-	-	6.8	-
	50%ile	9.3	-	-	9.3	-
	75%ile	10.2	-	-	10.2	-
	90%ile	12.8	-	-	12.8	-
	99%ile	14.6	-	-	14.6	-
	% of time sea (T_p < 8s)	38%	-	-	38%	-
	% of time swell (T_p > 8s)	62%	-	-	62%	-
Peak Wave Direction (Dp) [˚TN]	Weighted Mean	132.3	-	-	132.3	-
	Mean	134.1	-	-	134.1	-
	Standard Deviation	22.7	-	-	22.7	-

Wave direction

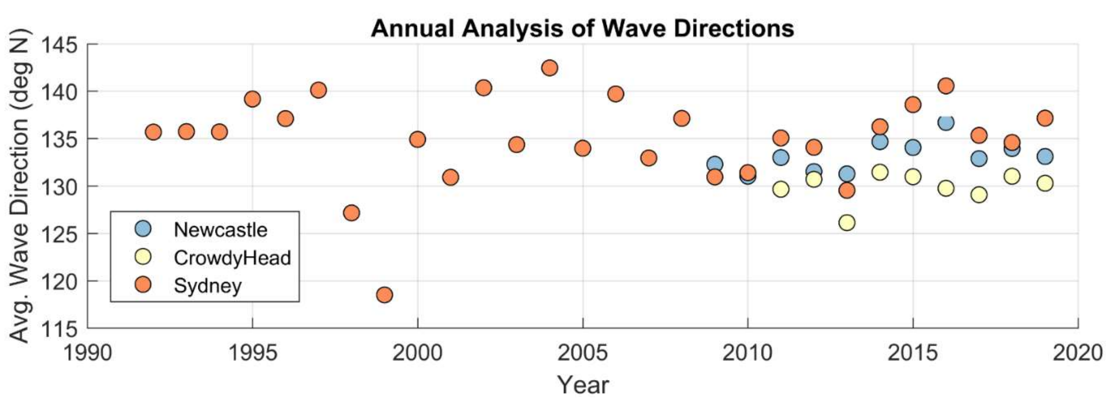

Figure 117: Annual average wave direction at Newcastle, Crowdy Head and Sydney WRB.

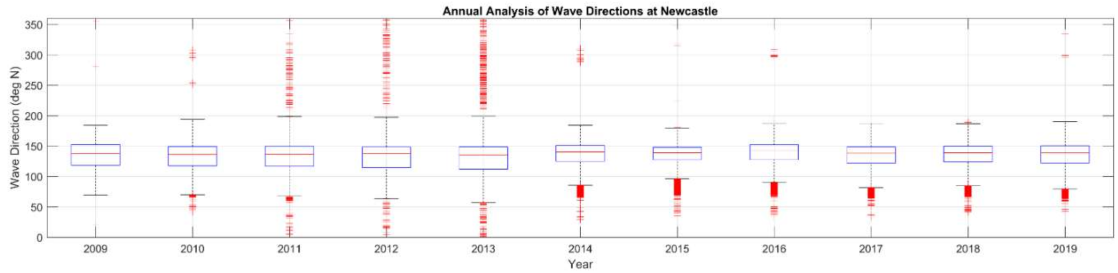

Figure 118: Annual wave directions at Newcastle WRB.

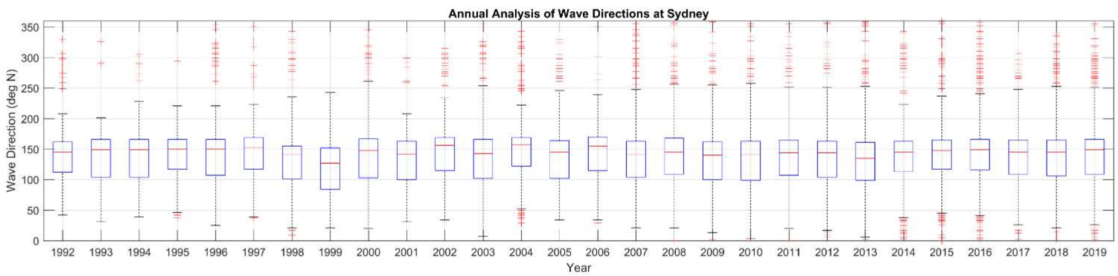

Figure 119: Annual box plots of wave directions at Sydney WRB.

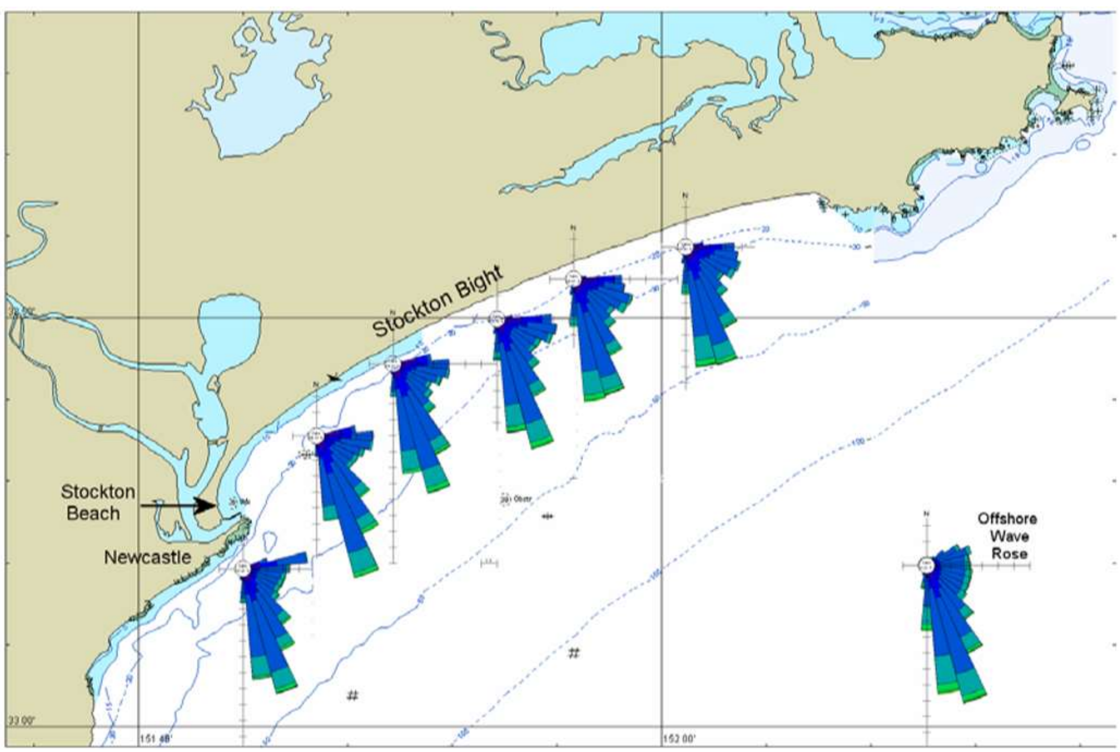

Figure 120: Wave roses from 12 years of transformed offshore measured wave data (Source: DHI, 2006).

Extreme wave events

At the study site, extreme wave events are usually associated with east ECL weather systems. An Extreme Value Analysis (EVA) of the Newcastle WRB spanning the 12 years of available data was undertaken. A peak over threshold analysis of the measured wave heights identified the extreme events

(Figure 121). A Weibull distribution was fitted to the extreme wave heights to provide the ARI wave heights in Table 15.

Table 15: Average recurrence interval (ARI) wave heights for Newcastle WRB from the Port of Newcastle.

ARI (year)	Hs (m)	98% Confidence Limits (m)
1	6.25	5.87 – 6.63
5	7.58	6.99 – 8.17
10	8.11	7.41 – 8.82
25	8.80	7.91 – 9.68
50	9.30	8.26 – 10.35
100*	9.80	8.58 – 11.01

*Values should be used with caution given the analysis is based on a 12-year wave height record.

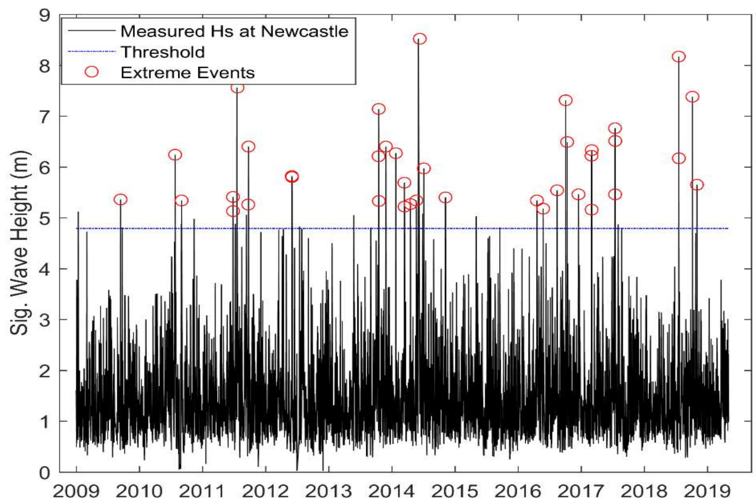

Figure 121: Identification of extreme wave events in measured wave heights at the Newcastle WRB managed by Port of Newcastle from all wave directions.

9.2 Wind climate

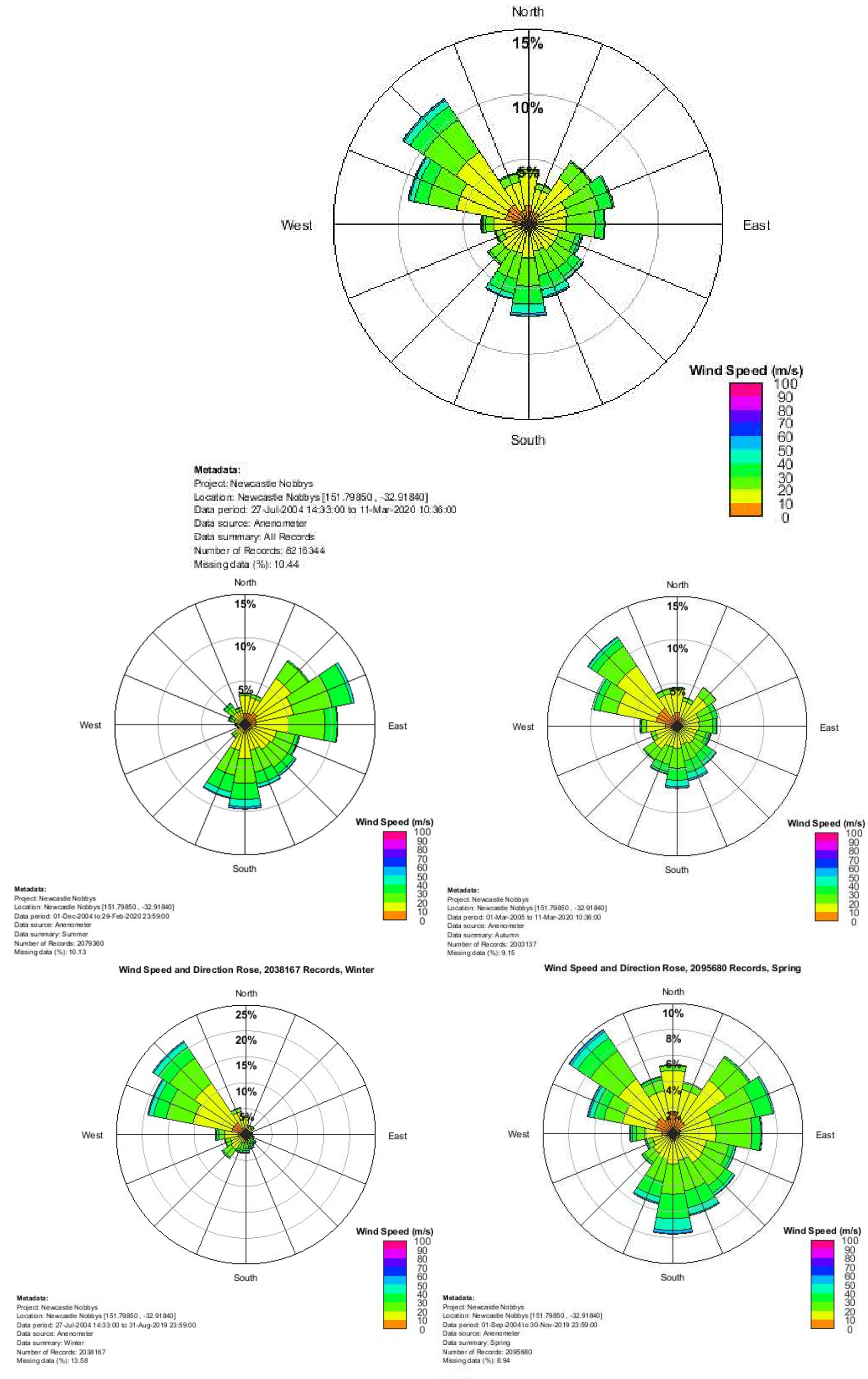

Figure 122: Annual (top) and seasonal wind roses at Nobbys Newcastle BoM station from one-minute data between July 2004 and March 2020.

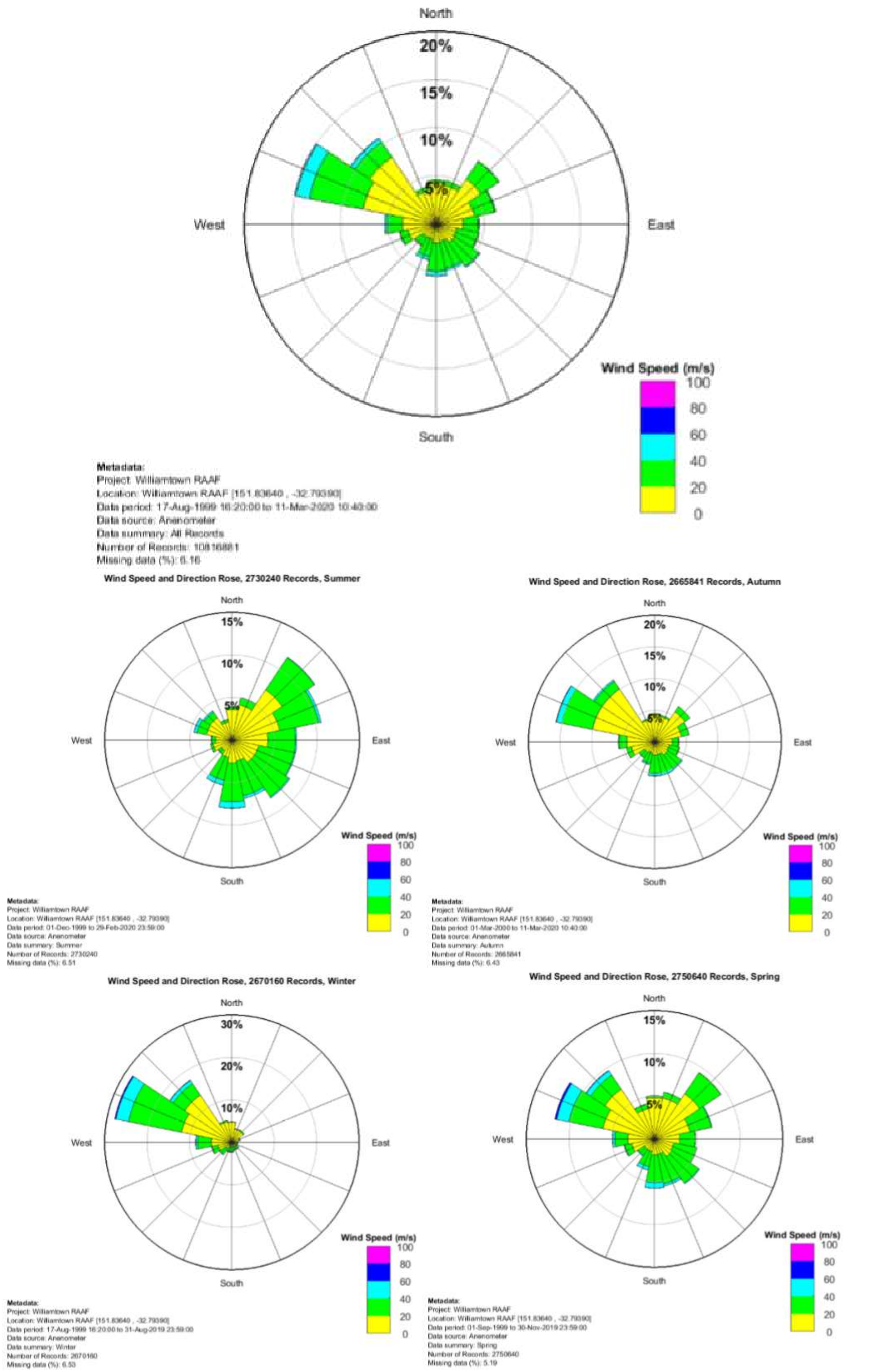

Figure 123: Annual (top) and seasonal wind roses at Williamstown BoM station from one-minute data between August 1999 and March 2020.