Appendix A: Surveyed sand volume changes by analysis cell

Longshore zone	ID	AREA (m^2)	Volume (m^3) change (2018 base line) 1883	2002	2011	2018
Seven Mile Beach	SM-1-1	196,600	-	-	74,612	-
	SM-1-2	1,283,004	-	-	-438,762	
	SM_LS	1,267,989	-	-	-490,424	
Beaches of Broken Head Nature Reserve	BH-1-1	26,789	-	-	19,612	
	BH-1-2	271,822	-	-	-179,252	
	BH-2-1	53,500	-	-	1,754	
	BH-2-2	592,304	-	-	-371,630	-
	BH-3-1	43,555	-	-	24,547	
	BH-3-2	666,323	-	-	-222,285	-
	TB-1-1	37,822		-	49,119	-
	TB-1-2a	229,577	-	116,325	111,284	-
	TB-1-2b	395,103	-	-16,981	-355,799	-
	BH_LS	1,340,780	-	-	-638,505	
Tallows Beach	TB-2-1	190,560	-	-	125,763	-
	TB-2-2	1,721,984	-	470,973	966,121	-
	TB-3-1	163,835		-	78,987	-
	TB-3-2	1,319,176		347,345	691,965	-
	TB-4-1	165,091		-	29,264	-
	TB-4-2	1,183,935		-432,172	-201,141	-
	TB-5-1	81,470		-	-39,618	-
	TB-5-2	432,181		-355,884	-403,998	-
	TB_LS	8,549,119		247,498	-1,969,648	-
Cape Byron	CaB-1-1	324,169		-190,993	-414,107	-
	CaB-2-1	236,256		62,517	-112,635	-
	CB-BYPASS	337,923		-213,771	-451,643	-
	CB-LS	334,319		-89,667	-113,074	-
Southern Byron embayment	WB-1-1	26,753		-	10,409	-
	WB-1-2	162,695		50,591	145,271	-
	WB-1-3	382,316	545,339	-49,943	144,432	-
	CB-1-1	78,613	-23,861	-	60,984	-
	CB-1-2	215,344	-2,091	70,320	145,892	-
	CB-1-3	553,955	433,116	27,562	-14,681	-
	MB-1-1	79,953	89,665	-31,707	22,209	-
	MB-1-2	128,193	294,031	-39,506	178,608	-
	MB-1-3	552,848	304,427	-41,123	5,412	-
	BB-LS-1A (15m)	1,766,200	2,687,996	41,507	120,828	
	BB-LS-1B (15-20m)	2,402,219	4,249,167	-546,284	272,416	-
Nouthern Byron embayment	BB-1-1	91,903	173,631	-	-18,513	-
	BB-1-2	116,600	361,079	-158,144	6,097	-
	BB-1-3	476,481	284,555	32,700	-31,066	-
	BB-2-1	52,954	109,063	-	-51,043	-
	BB-2-2	122,725	244,720	-142,113	3,593	-
	BB-2-3	243,663	175,684	-58,968	-33,464	-
	BB-3-1	70,600	138,853	-	-108,286	-
	BB-3-2	112,075	241,749	-51,968	-49,266	-

Longshore zone	ID	AREA (m^2)	Volume (m^3) change (2018 base line) 1883	2002	2011	2018
	BB-3-3	187,576	231,029	- 8,307	- 62,985	-
	BC-1-1	45,685	120,282	-	- 24,871	-
	BC-1-2	67,891	134,619	8,731	- 31,281	-
	BC-1-3	121,461	160,971	48,314	17,784	-
	BB-LS-2A (15m)	2,380,000	1,348,208	102,408	73,589	
	BB-LS-2B (15-20m)	1,197,255	644,956	- 166,021	230,278	-
Tyagarah Beach	TY-1-1	93,701	187,389		- 92,389	
	TY-1-2	528,376	724,412		- 46,351	
	TY-2-1	746,000			- 387,044	
	TY-2-2	3,649,186			423,502	
	TY_LS-1	2,216,783			- 25,429	
	TY_LS-2	6,716,730			- 1,804,141	
Brunswick Heads	BrH-1-1	117,591	-	-	- 79,962	
	BrH-1-2	391,508	-	-	3,937	
	BrH-2-1	163,486	-	-	68,085	
	BrH-2-2	997,565	-	-	6,702	
	BrH_LS-1	630,532	-	-	- 103,155	
	BrH_LS-2	1,333,210	-	-	- 159,258	
New Brighton Beach	NB-1-1	721,944	-	-	6,497	
	NB-1-2	2,593,201	-	-	580,877	
	NB-LS	4,359,700	-	-	80,349	

The analysis cells (IDs) for each longshore zone are described in Section 4.2.1 and are presented geographically in Figure 109 to Figure 112.

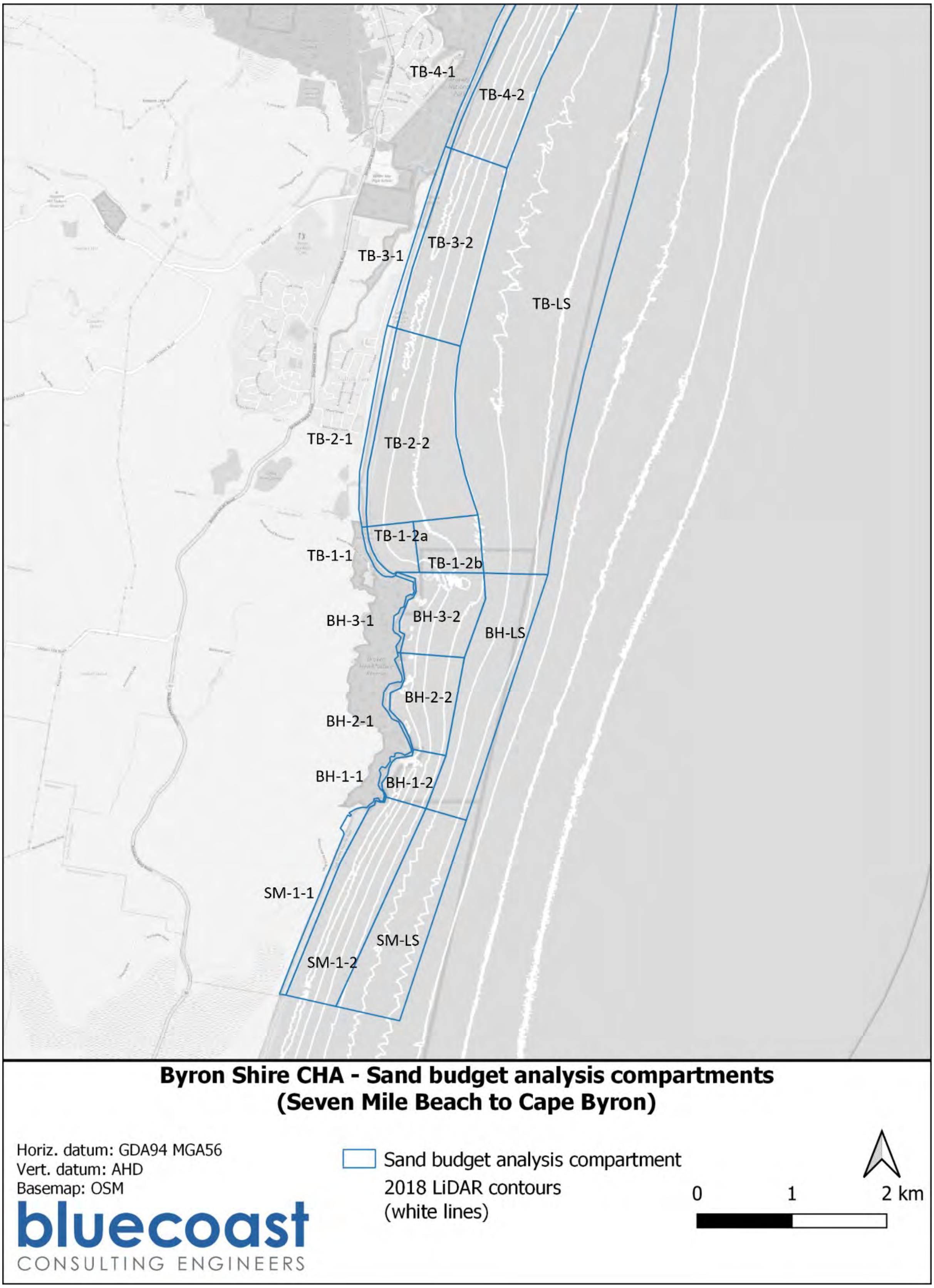


Figure 109: Sand budget analysis cell for Seven Mile Beach to Cape Byron.

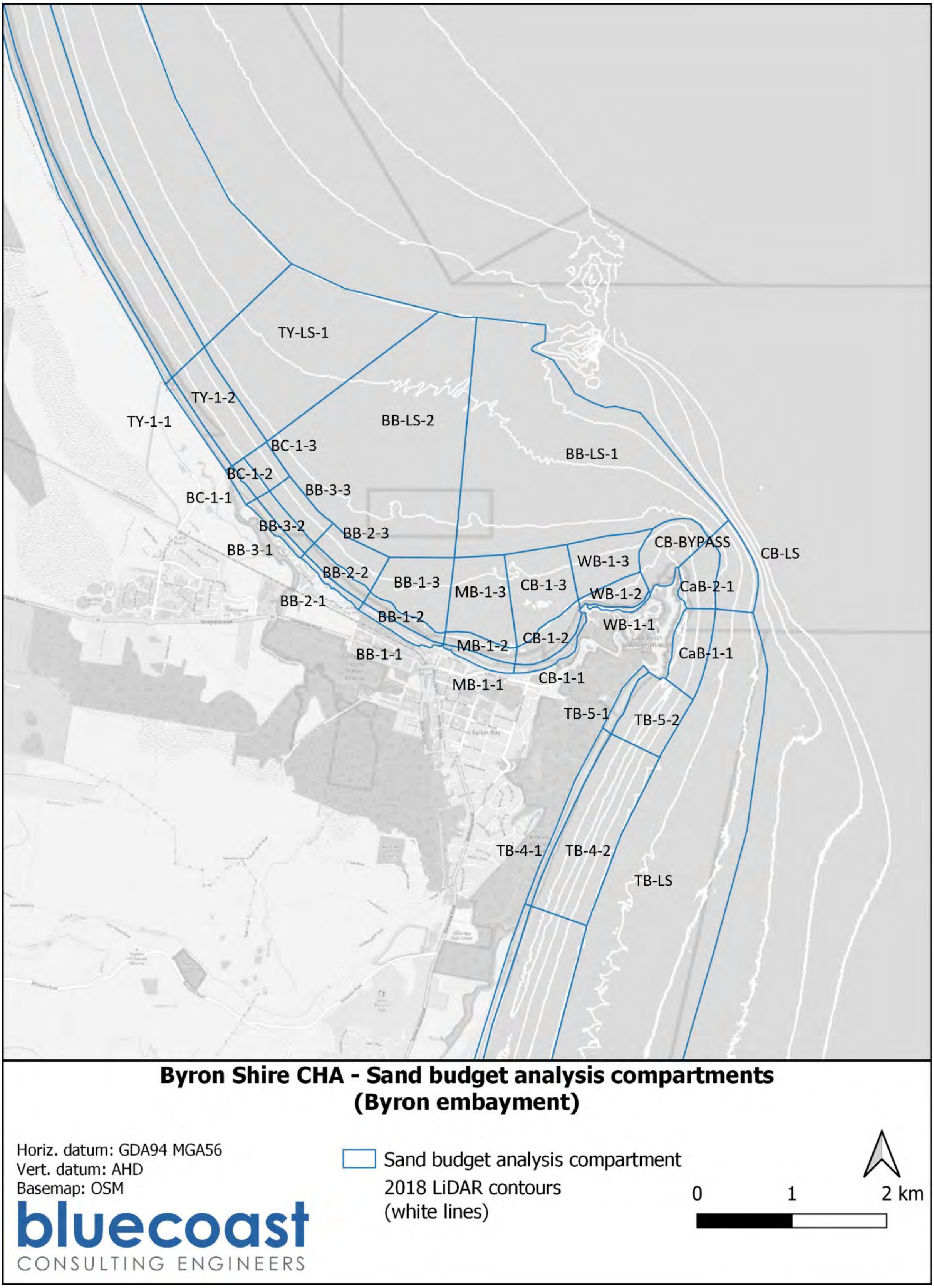


Figure 110: Sand budget analysis cell for the Byron embayment.

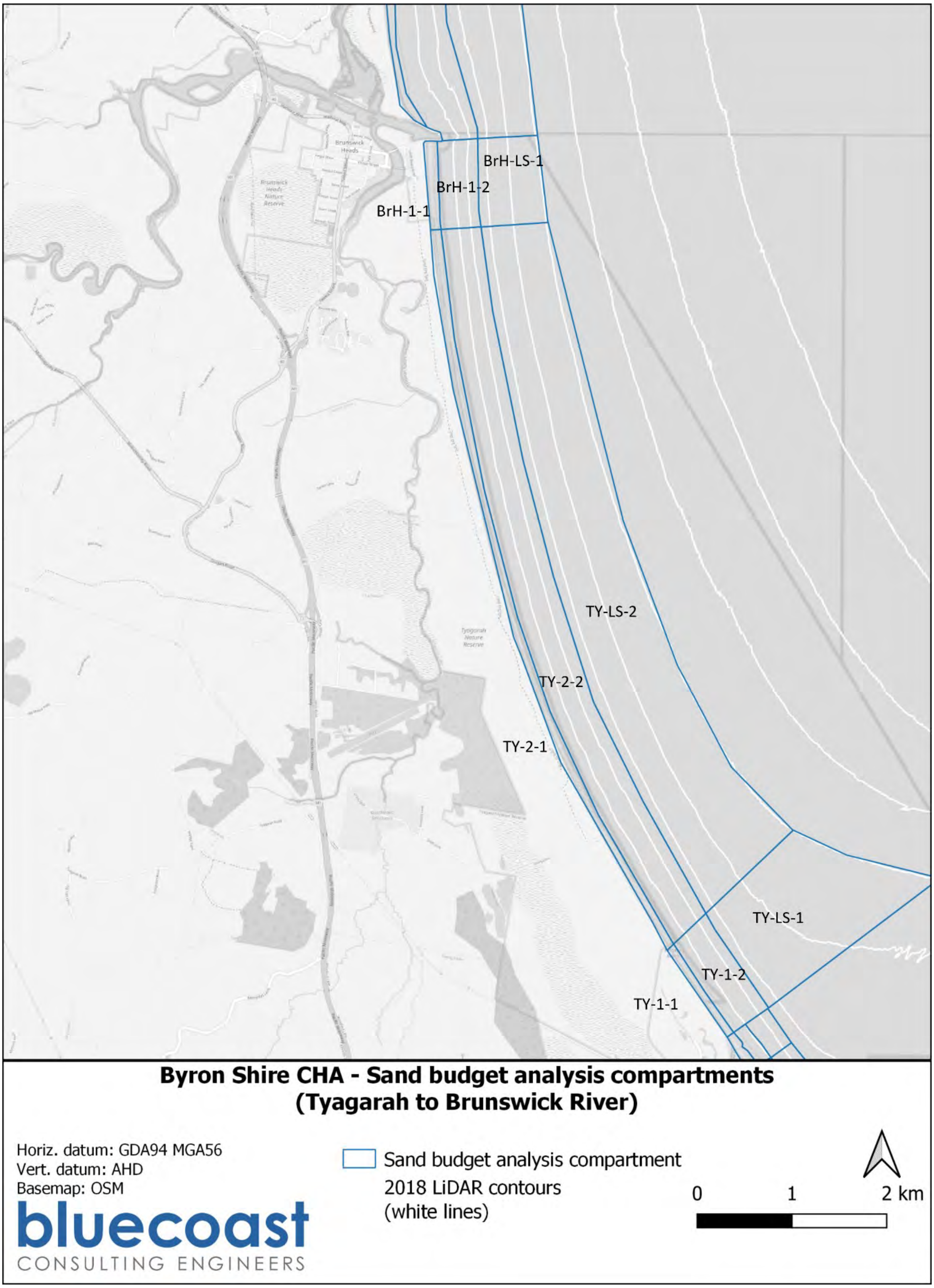


Figure 111: Sand budget analysis cell for Tyagarah to Brunswick River.

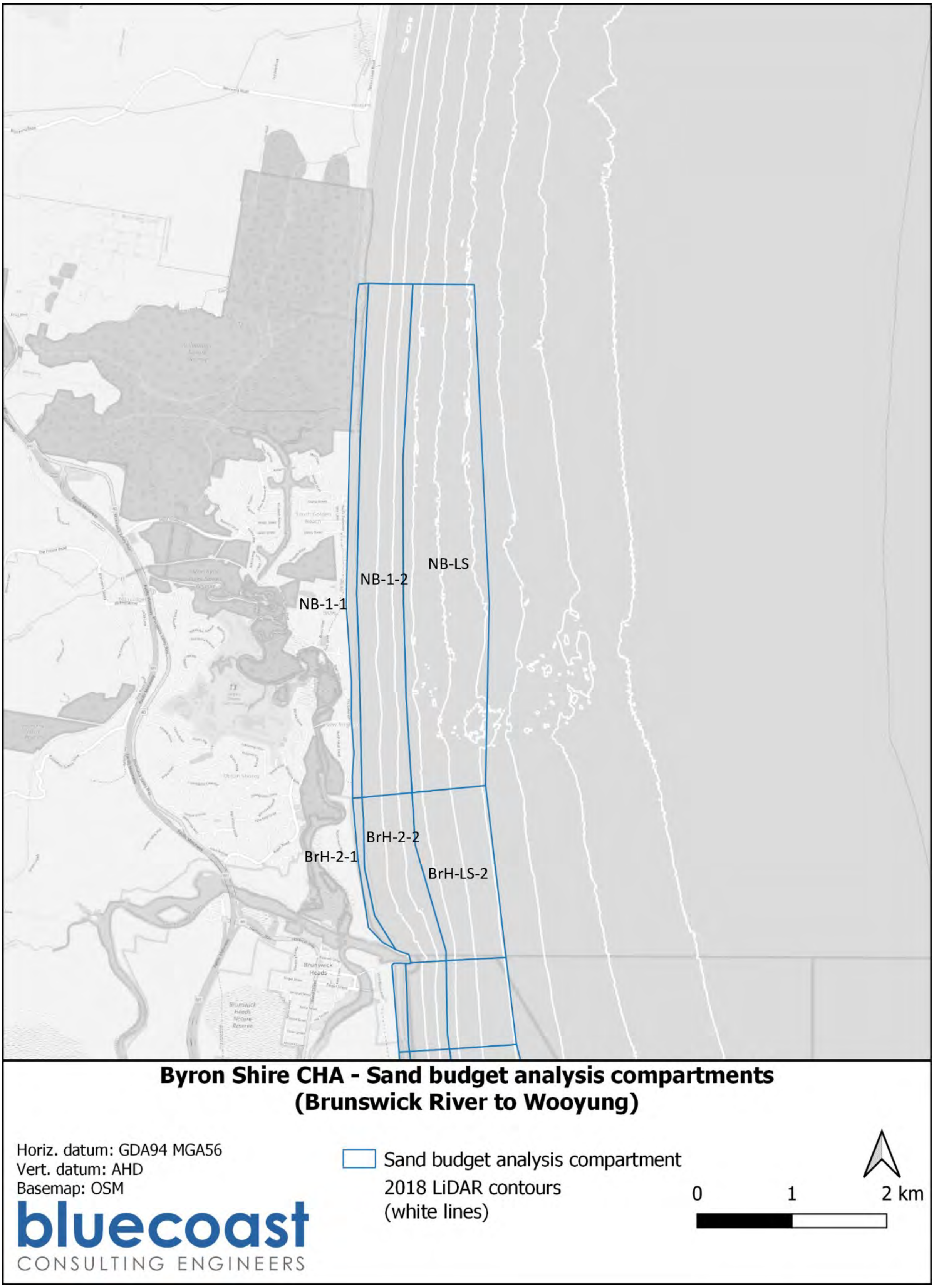


Figure 112: Sand budget analysis cell for Brunswick River to Wooyung.

Appendix B: Local context for hazard assessment

Seven Mile Beach to Cape Byron

Beach compartment overview

Table 29: Overview of Seven Mile Beach to Cape Byron beach compartment.

Characteristic	Seven Mile Beach (Byron Shire LGA)	Broken Head Nature Reserve	Broken Head to Tallow Creek	Tallow Creek to Cape Byron
Beach type	Semi-embayment (headland control to north)	Embayment (full headland control)	Semi-embayment (headland control to south)	Semi-embayment (headland control to north)
Sandy beach length	2,100m (Byron Shire LGA) 8,400m (total embayment)	120m (Whites Beach) 240m (Brays Beach) 190m (Kings Beach)	4,400m	3,070m
Orientation	South-east	South-east (Whites Beach) East (Brays & Kings Beach)	North-east to east	South-east
Coastal land-use / Resilience SEPP mapping	Isolated residential properties and resorts Littoral rainforest Coastal wetland	Nature reserve	Nature reserve Township of Suffolk Park Littoral rainforest Coastal wetland	Arakwal National Park State conservation area (Cosy Corner)
Key morphological features	Jews Point headland to the north	Pocket beaches along Broken Head headland Bedrock outcrops on beach and nearshore	Broken Head headland to the south Entrance to Ti-Tree Lake at northern end of Broken Head beach Entrance to Tallow Creek to the north	Cape Byron headland to the north Entrance to Tallow Creek to the south
Coastal structures	None	None	None	None

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

Long-term beach volume and shoreline change

Shoreline behaviour

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2020 were analysed. Results showing the historic shoreline behaviour within the Seven Mile Beach to Cape Byron beach compartment are presented in Figure 113 to Figure 115.

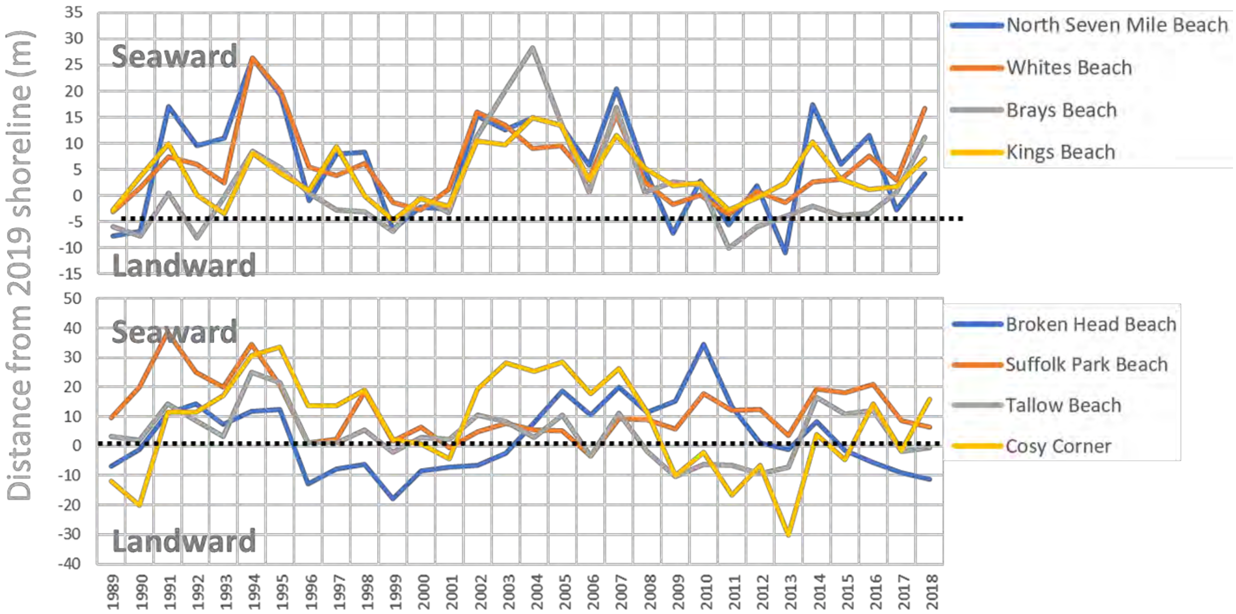


Figure 113: Observed change in mean annual shoreline positions relative to 2019.

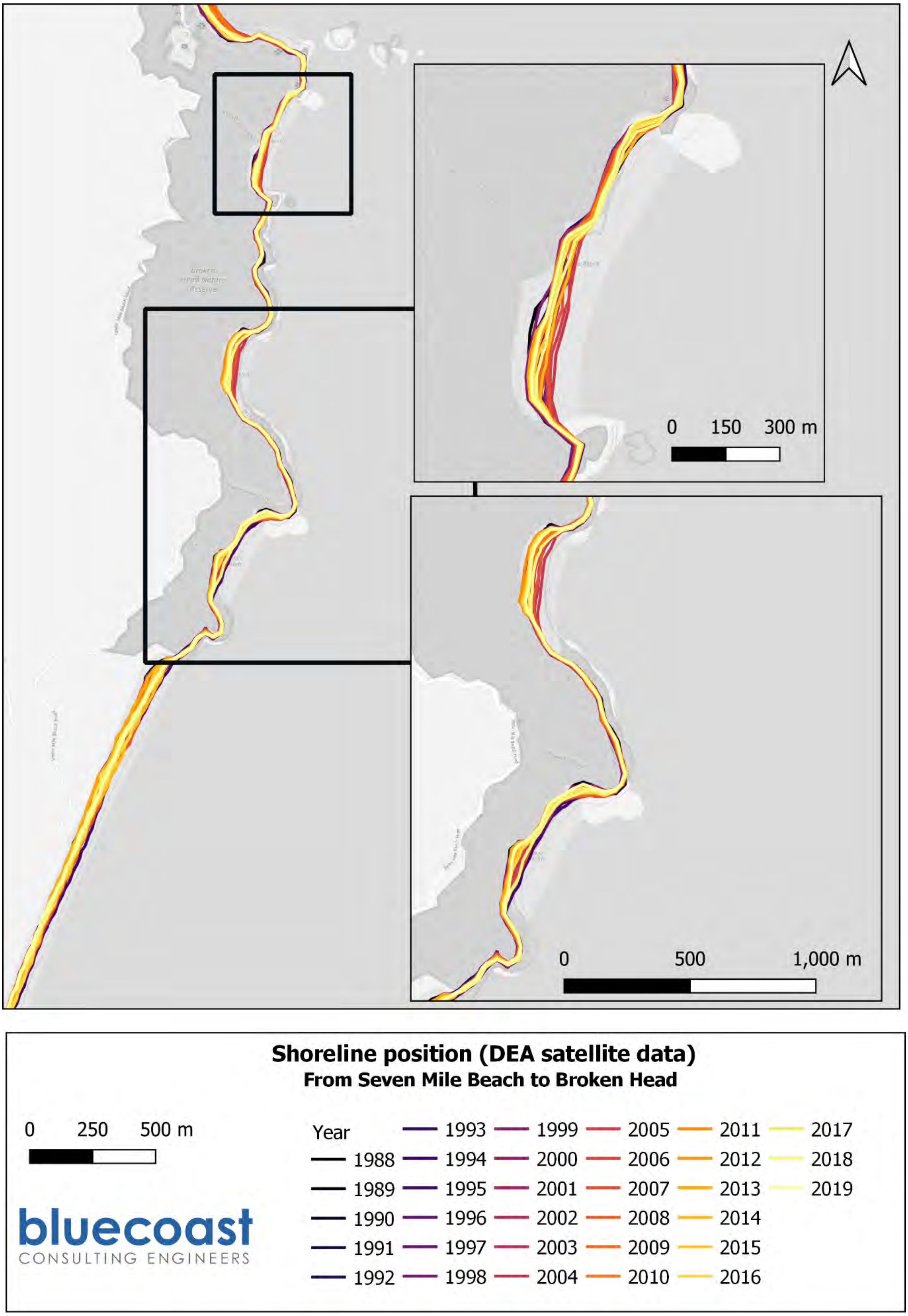


Figure 114: Mean annual shorelines between Seven Mile Beach and Broken Head from 1988 to 2020.

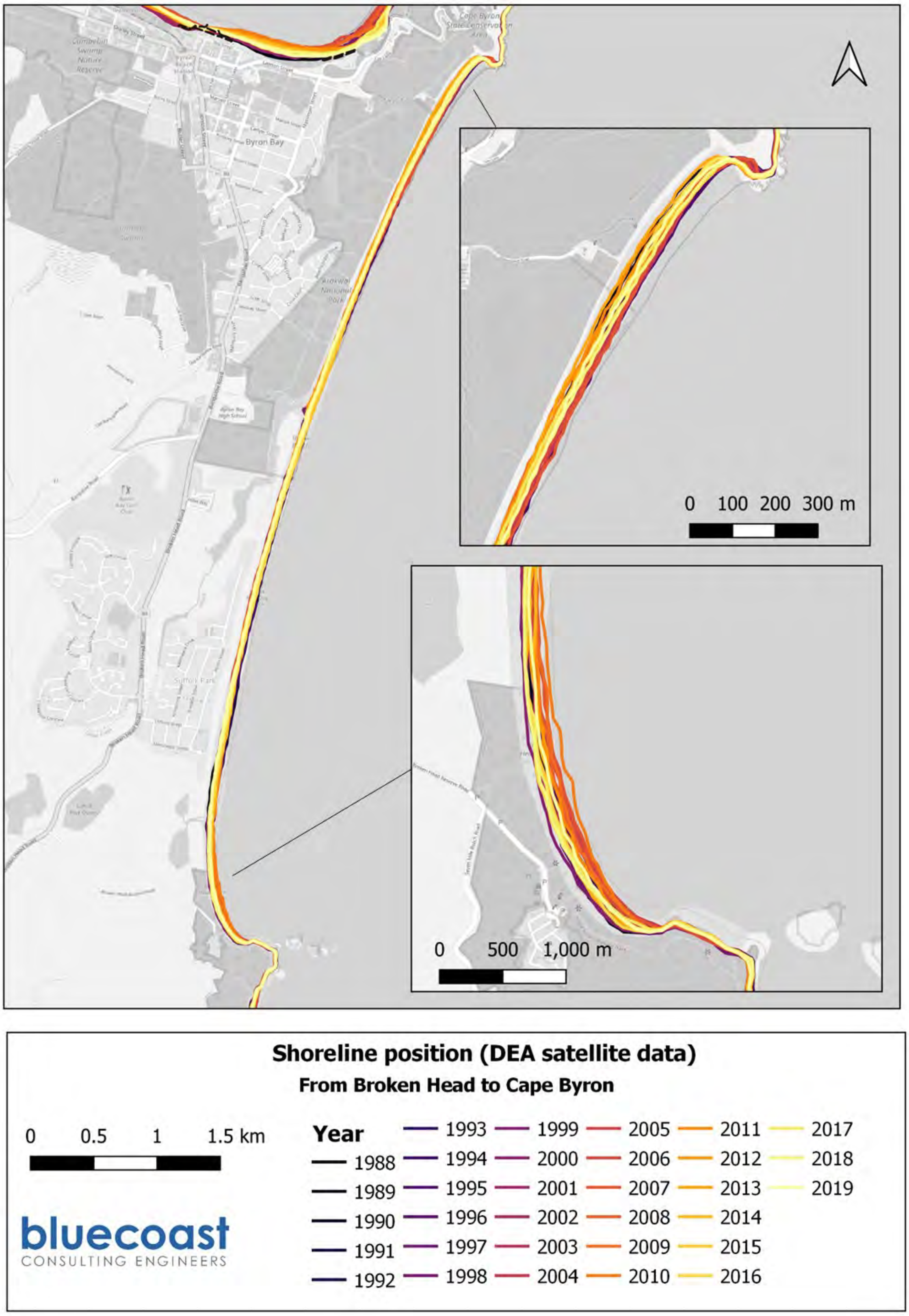


Figure 115: Mean annual shorelines between Broken Head and Cape Byron from 1988 to 2020.

Subaerial beach profile volumes

Beach profiles from the NSW Beach Profile Database were analysed for subaerial (above 0m AHD) sand volume changes[8]. A summary of the beach profile analysis is provided for representative sections of beach as follows:

- The alongshore rates of change in subaerial beach volume are shown in for three different periods.
- Timeseries of subaerial beach profile volumes and regression analysis for selected profile locations.

Seven Mile Beach

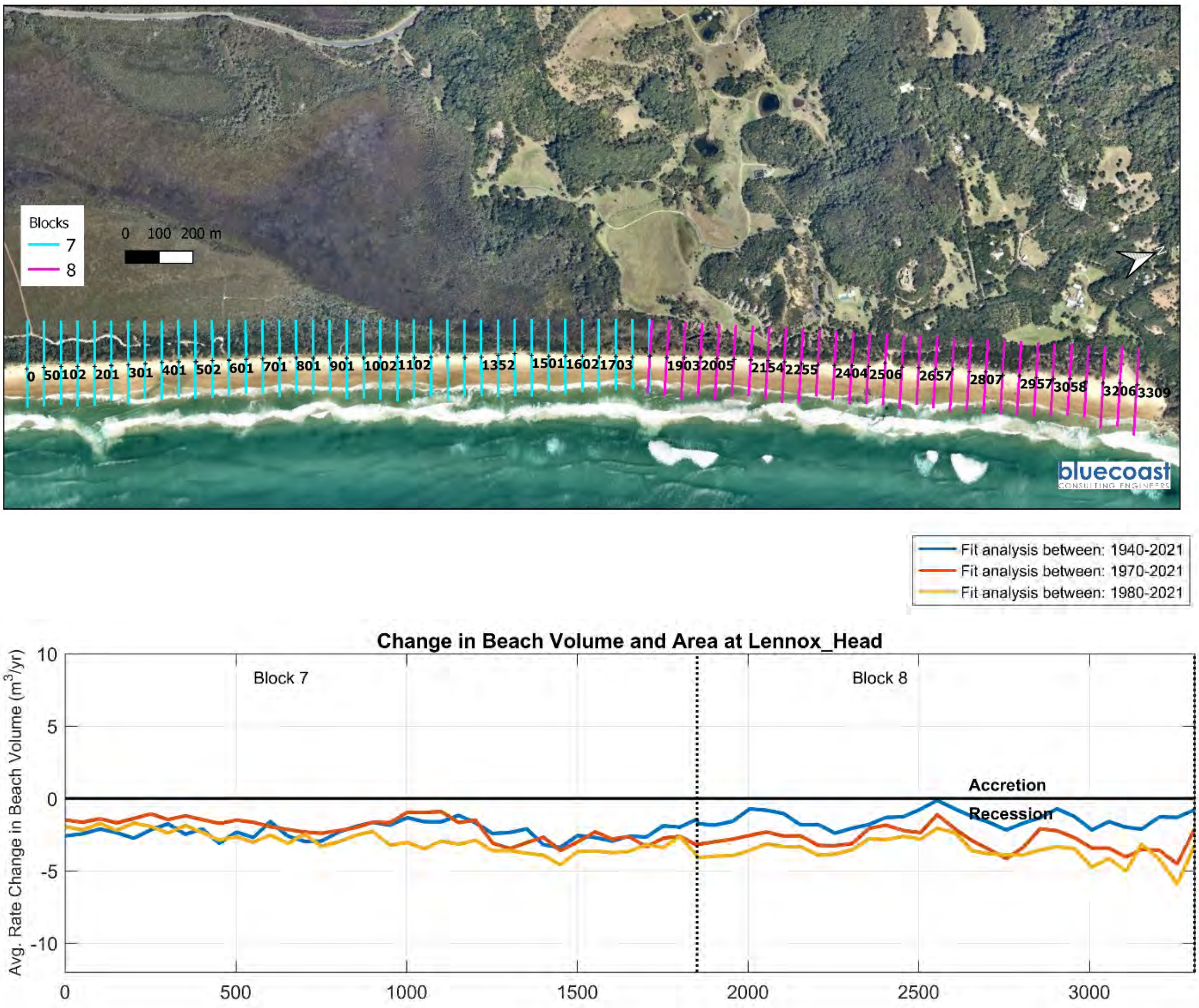


Figure 116: Alongshore rate of subaerial beach volume change at the northern end of Seven Mile Beach.

[8] Photogrammetry derived beach profiles present snapshots in time. The sparse temporal nature of the data can mask the true timing and magnitude of change in beach behaviour.

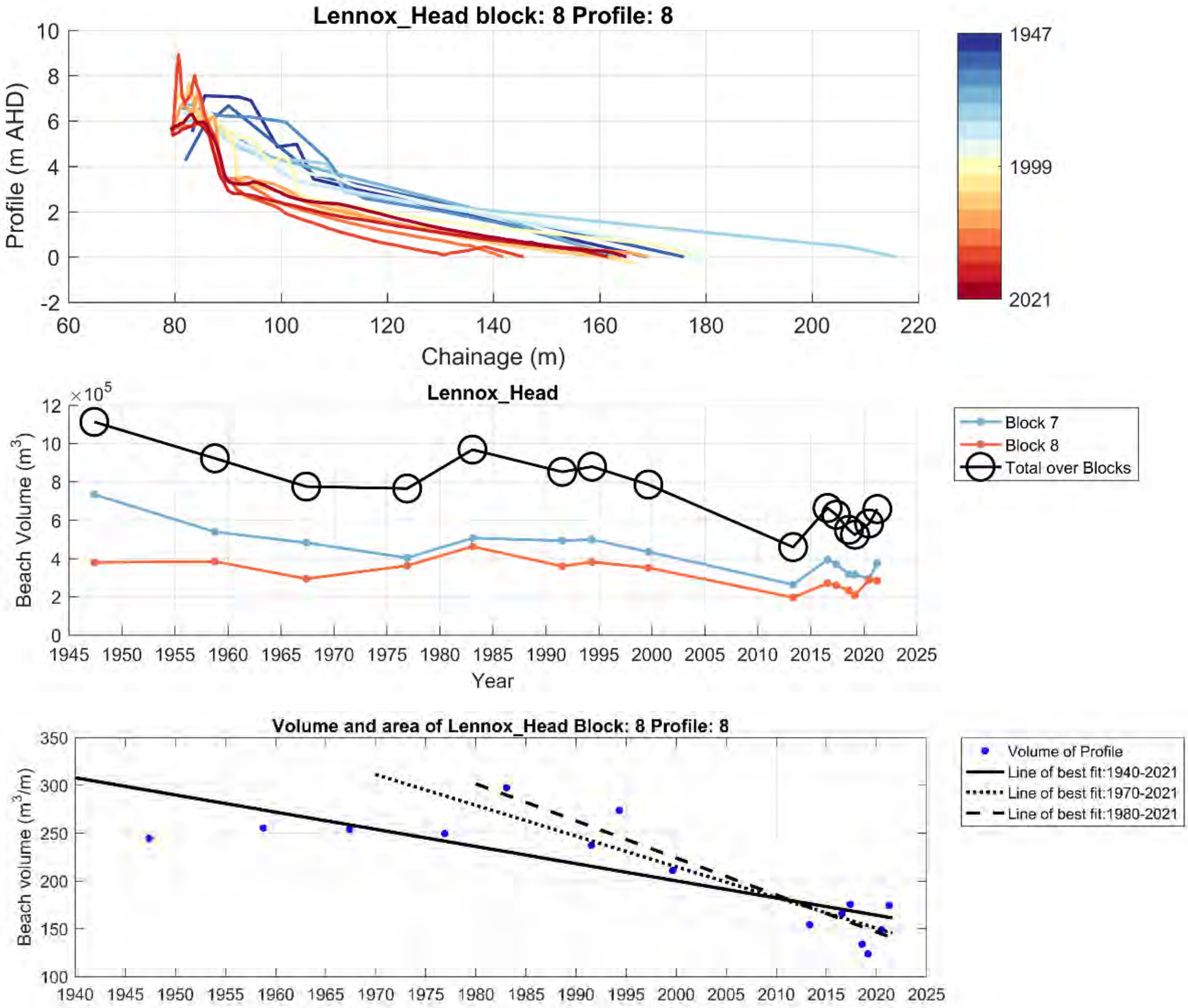


Figure 117: Timeseries of (top) beach profiles, (centre) calculated subaerial beach volume and (bottom) regression analysis.

Broken Head to Cape Byron

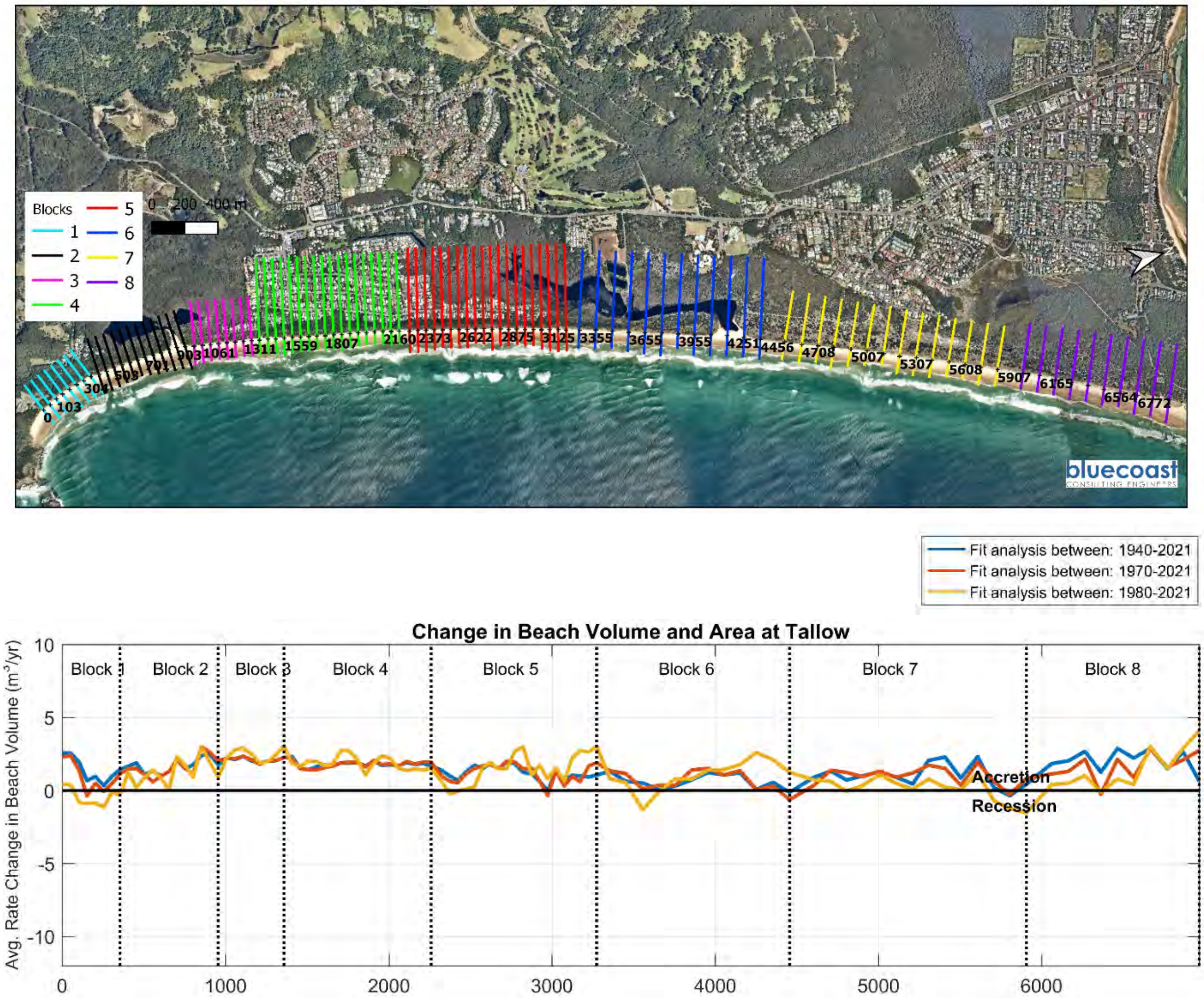


Figure 118: Alongshore rate of subaerial beach volume change along Tallow Beach.

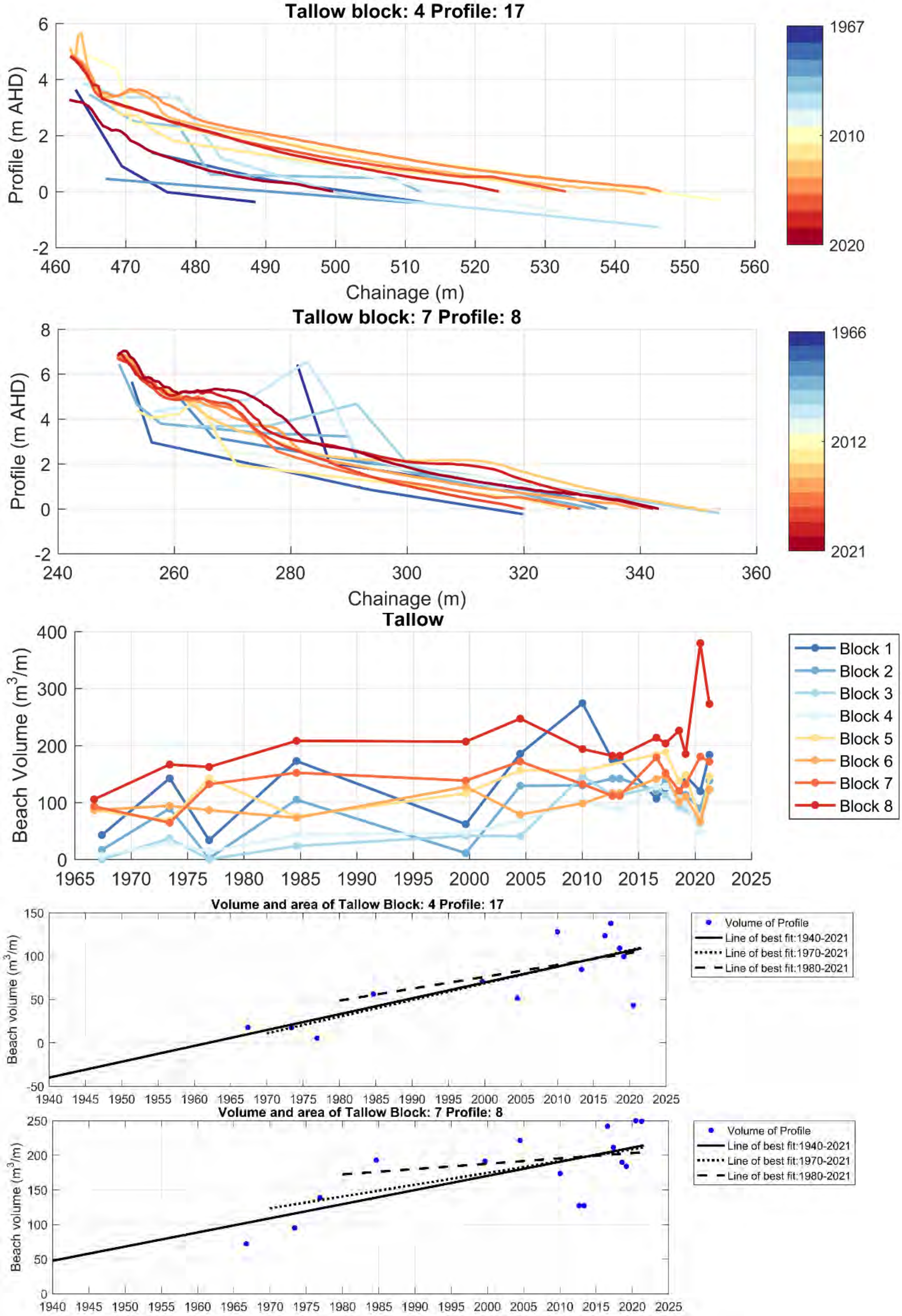


Figure 119: Timeseries of (top) beach profiles, (centre) calculated subaerial beach volume and (bottom) regression analysis.

Beach erosion

Storm demand volumes were estimated by analysis of subsequent dates in the NSW Beach Profile Database for a range of storms. The following storm events have been analysed (where data was available):

- Tropical Cyclone Dinah 1967
- Tropical Cyclone Wanda 1974
- East Coast Low in 1996
- East Coast Low in 2009
- Tropical Cyclone Oma 2019

The alongshore distribution of storm demands is presented in Figure 120 and Figure 121. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

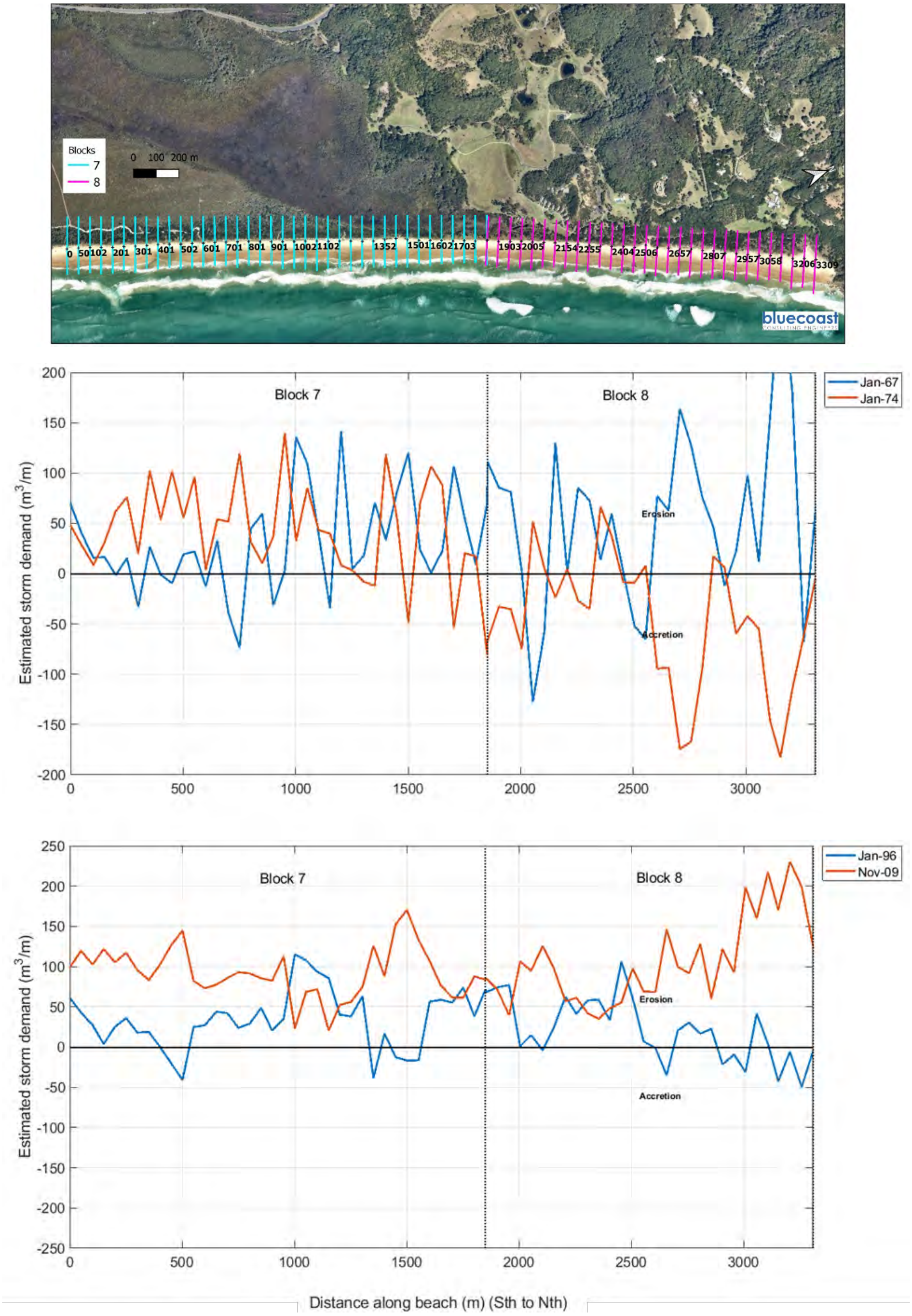


Figure 120: Seven Mile Beach - alongshore storm demand estimates derived from NSW Beach Profile Database for storms in 1967, 1974, 1996 and 2009.

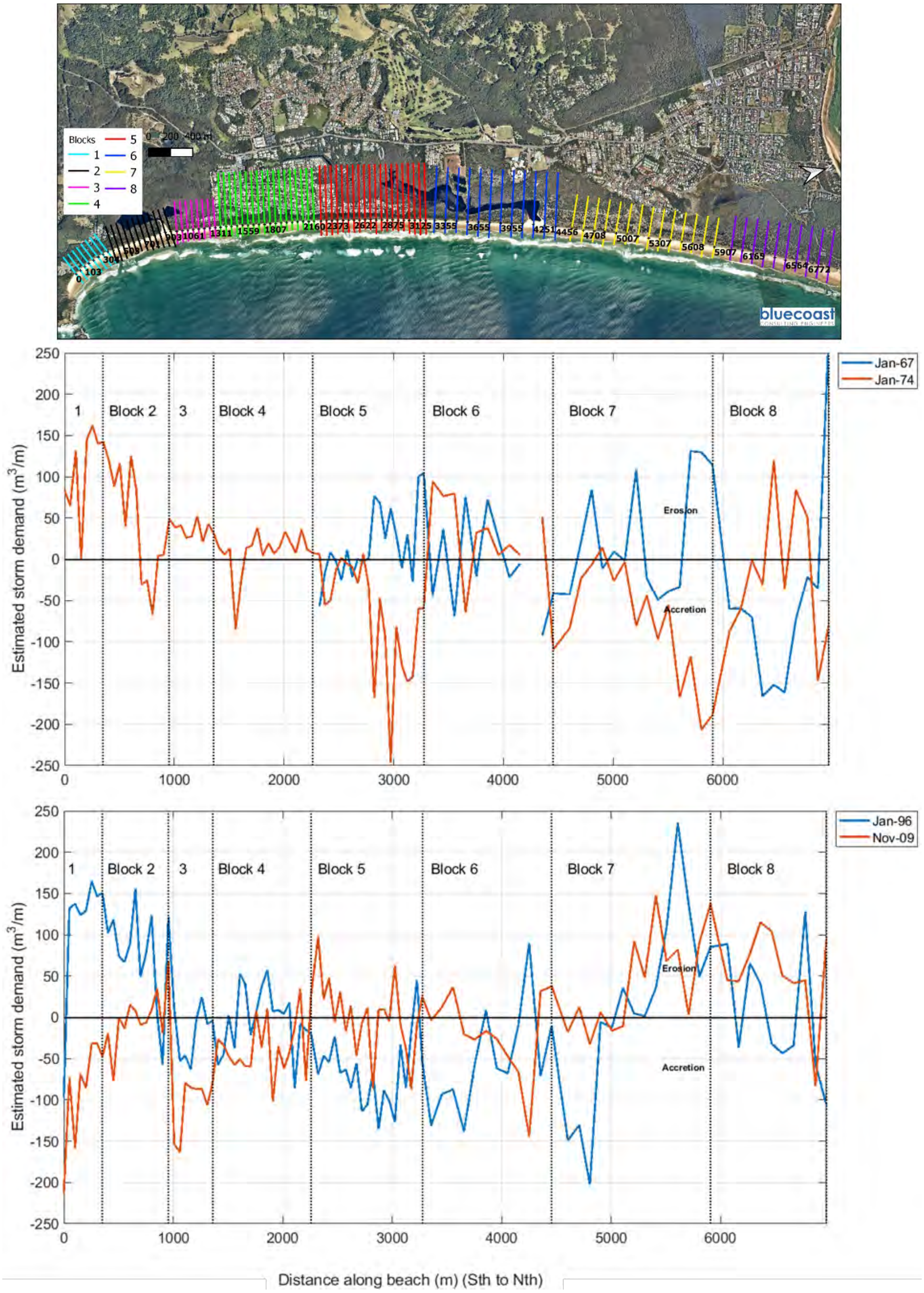


Figure 121: Tallow Beach - alongshore storm demand estimates derived from NSW Beach Profile Database for storms in 1967, 1974, 1996 and 2009.

Cape Byron to Wooyung

Beach compartment overview

Table 30: Overview of Cape Byron to Wooyung beach compartment.

Characteristic	Cape Byron to Belongil Beach (Byron embayment)	Tyagarah Beach	Brunswick Heads to South Golden Beach	Wooyung
Beach type	Embayment (full headland control)	Open beach	Open beach	Open beach
Sandy beach length	140m (Little Wategos) 480m (Wategos Beach) 4,580m (The Pass to Belongil Creek)	9,200m	830m (Brunswick Beach) 5,600m (North Head to South Golden Beach)	7,800m
Orientation	North to north-east	East-north-east	East	East-south-east
Coastal land-use / Resilience SEPP mapping	Cape Byron State Conservation Area Littoral rainforest Coastal wetland	Nature reserve Coastal wetland	Nature reserve Townships of Brunswick Heads, New Brighton and South Golden Beach Coastal wetland	Nature reserve
Key morphological features	Cape Byron headland to the south Entrance to Belongil Creek to north Julian Rocks nearshore outcrop	Entrance to Belongil Creek to south	Entrance to Brunswick River between Brunswick Heads and North Head	-
Coastal structures	Clarkes Beach low-crested geobag revetment SLSC geobag revetment JSPW at Main Beach Mix of private and public protection structures along Belongil Beach	None	Brunswick River training walls	None

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

Long-term beach volume and shoreline change

Shoreline behaviour

Digital Earth Australia's (DEA) mean annual shorelines from for the period 1988 to 2020 were analysed. Results showing the historic shoreline behaviour within the Cape Byron to Wooyung beach compartment are presented in Figure 122 to Figure 125.

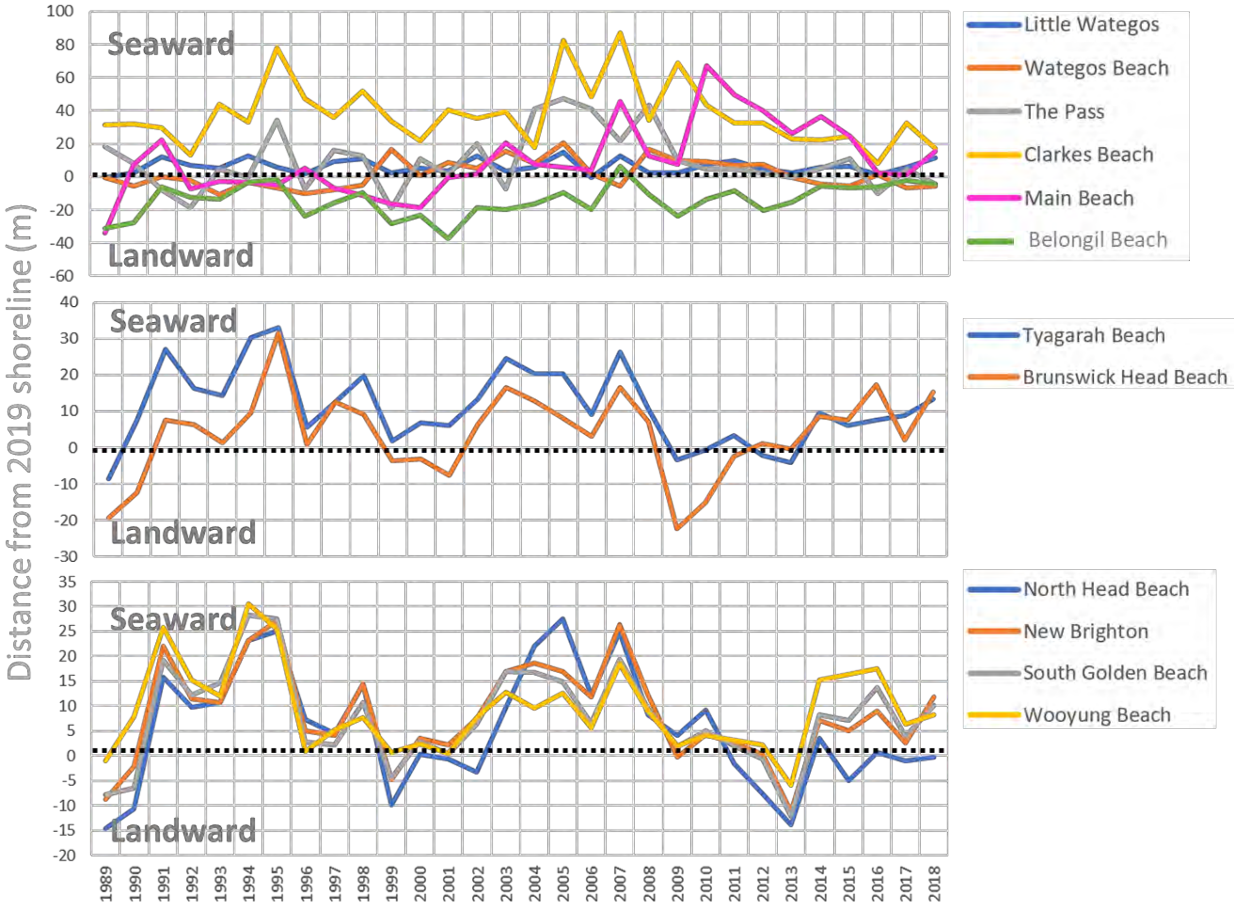


Figure 122: Observed change in mean annual shoreline positions relative to 2019.

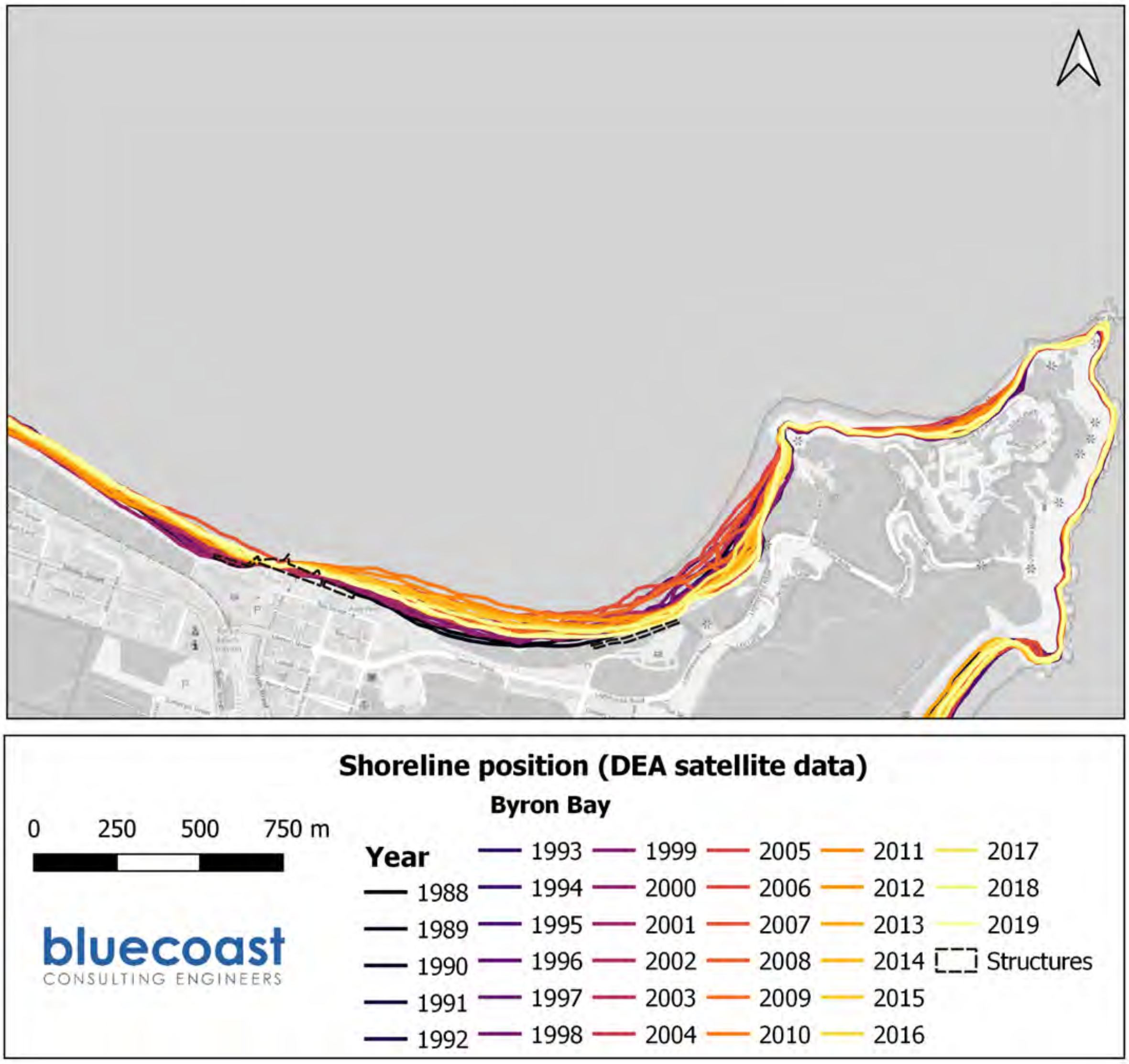


Figure 123: Mean annual shorelines between Cape Byron and Main Beach from 1988 to 2020.

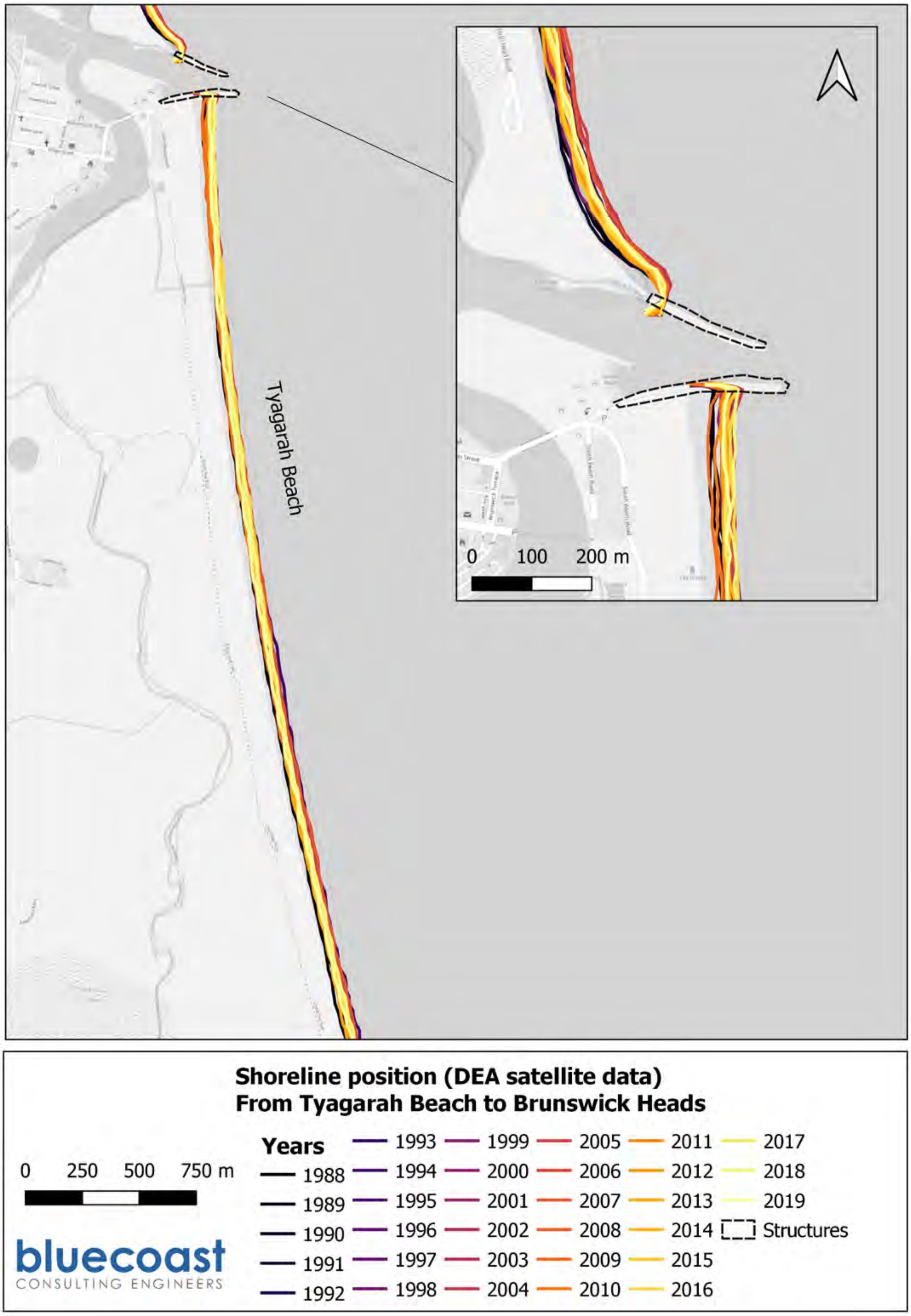


Figure 124: Mean annual shorelines between Tyagarah Beach to Brunswick Heads from 1988 to 2020.

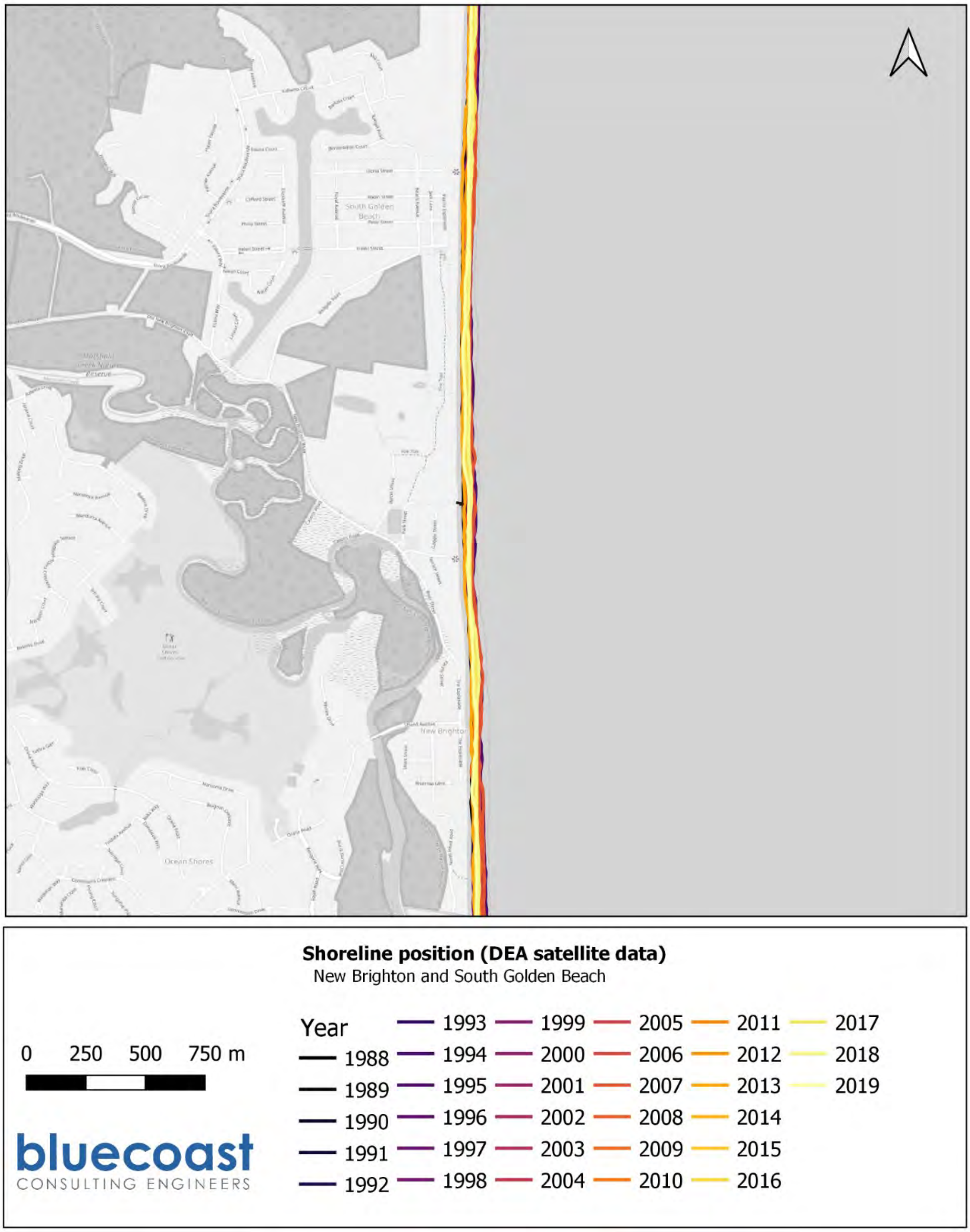


Figure 125: Mean annual shorelines between New Brighton and South Golden Beach from 1988 to 2020.

Subaerial beach profile volumes

Beach profiles from the NSW Beach Profile Database were analysed for subaerial (above 0m AHD) sand volume changes[9]. A summary of the beach profile analysis is provided for representative sections of beach as follows:

- The alongshore rates of change in subaerial beach volume are shown in for three different periods.
- Selected subaerial beach profile plots.
- Timeseries of subaerial beach profile volumes and regression analysis for selected profile locations.

Wategos Beach to Belongil Beach

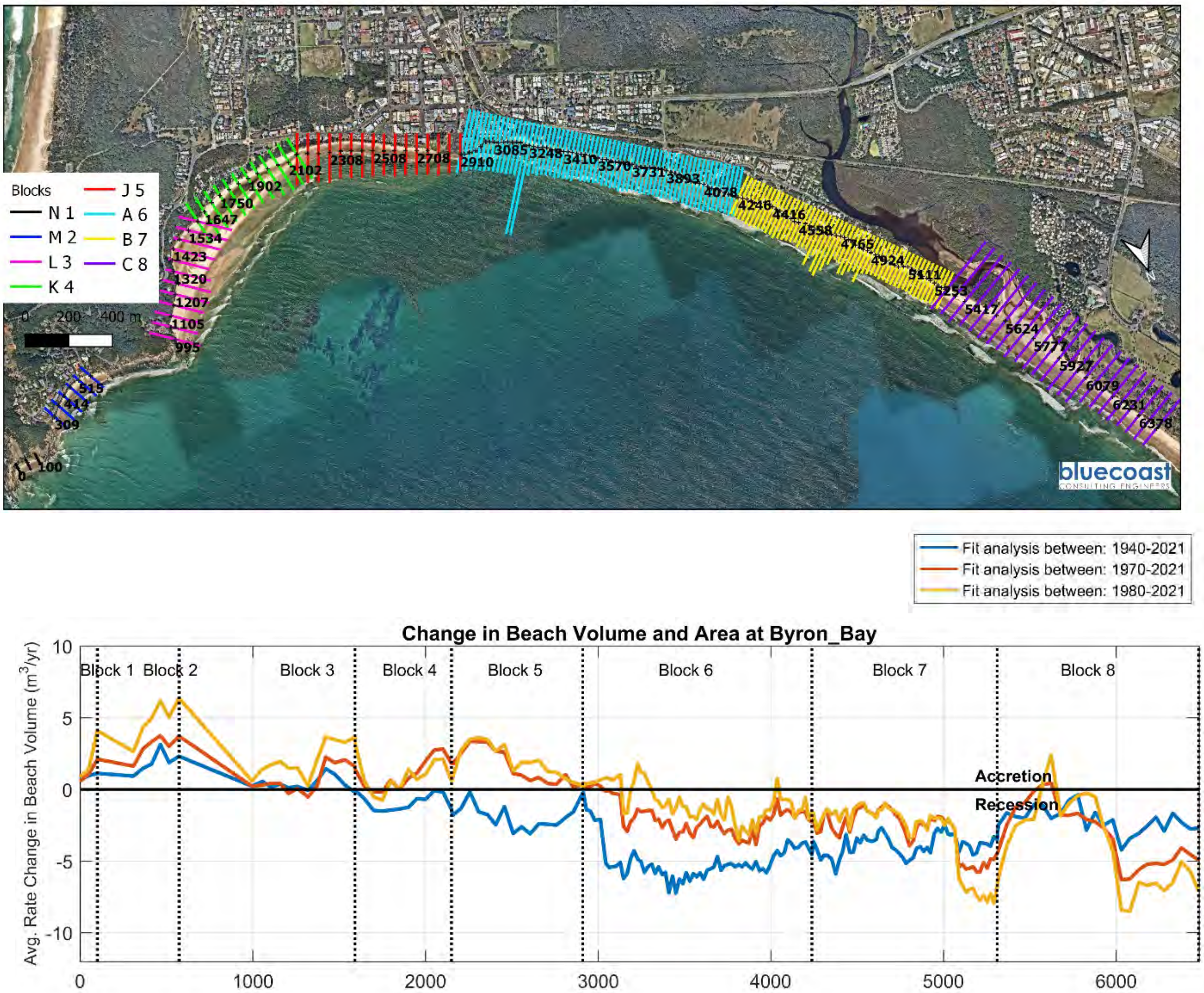


Figure 126: Alongshore rate of subaerial beach volume change at Cape Byron to Belongil Beach.

---

9 Photogrammetry derived beach profiles present snapshots in time. The sparse temporal nature of the data can mask the true timing and magnitude of change in beach behaviour.

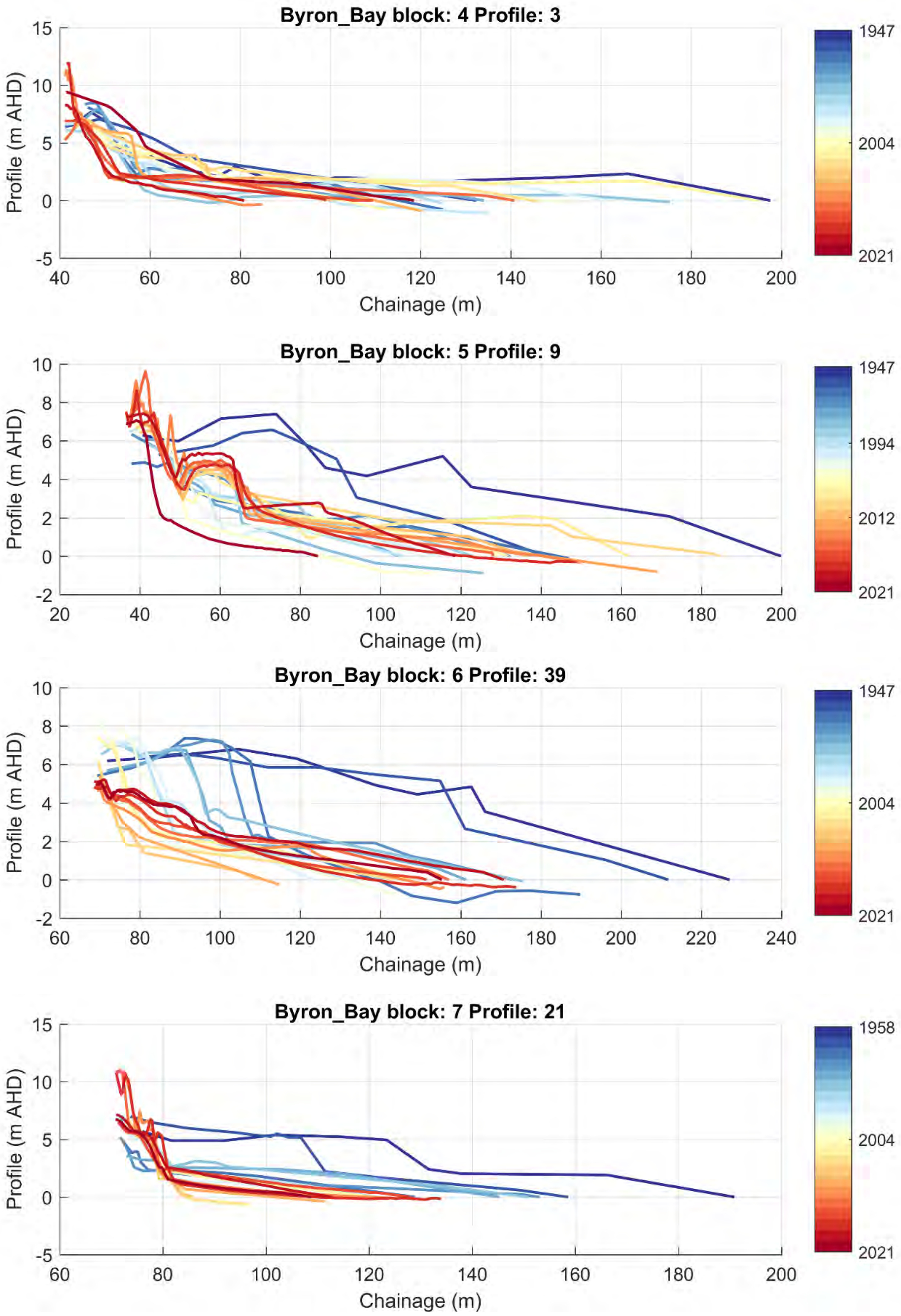


Figure 127: Selected subaerial beach profile plots between Clarkes Beach (Block 4) and Belongil Beach (Block 7).

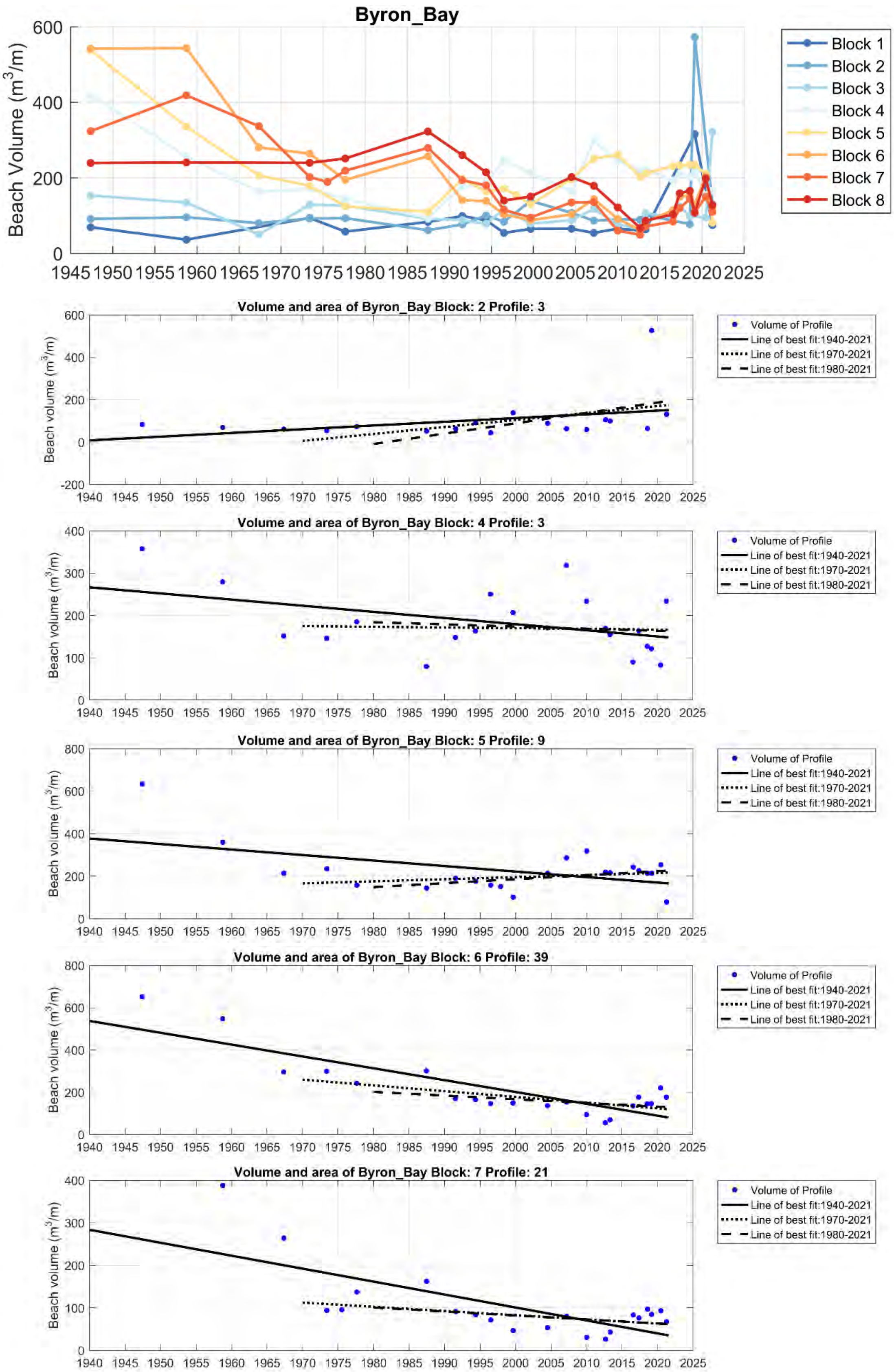


Figure 128: Timeseries of subaerial beach volumes and regression analysis for selected profile locations.

Brunswick Heads to South Golden Beach

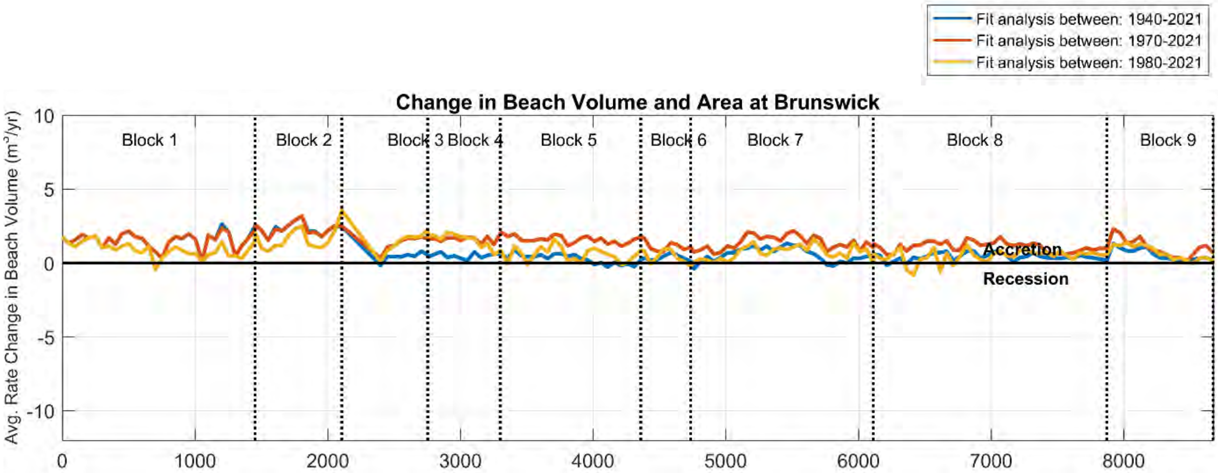


Figure 129: Alongshore rate of subaerial beach volume change at Brunswick Heads to Wooyung.

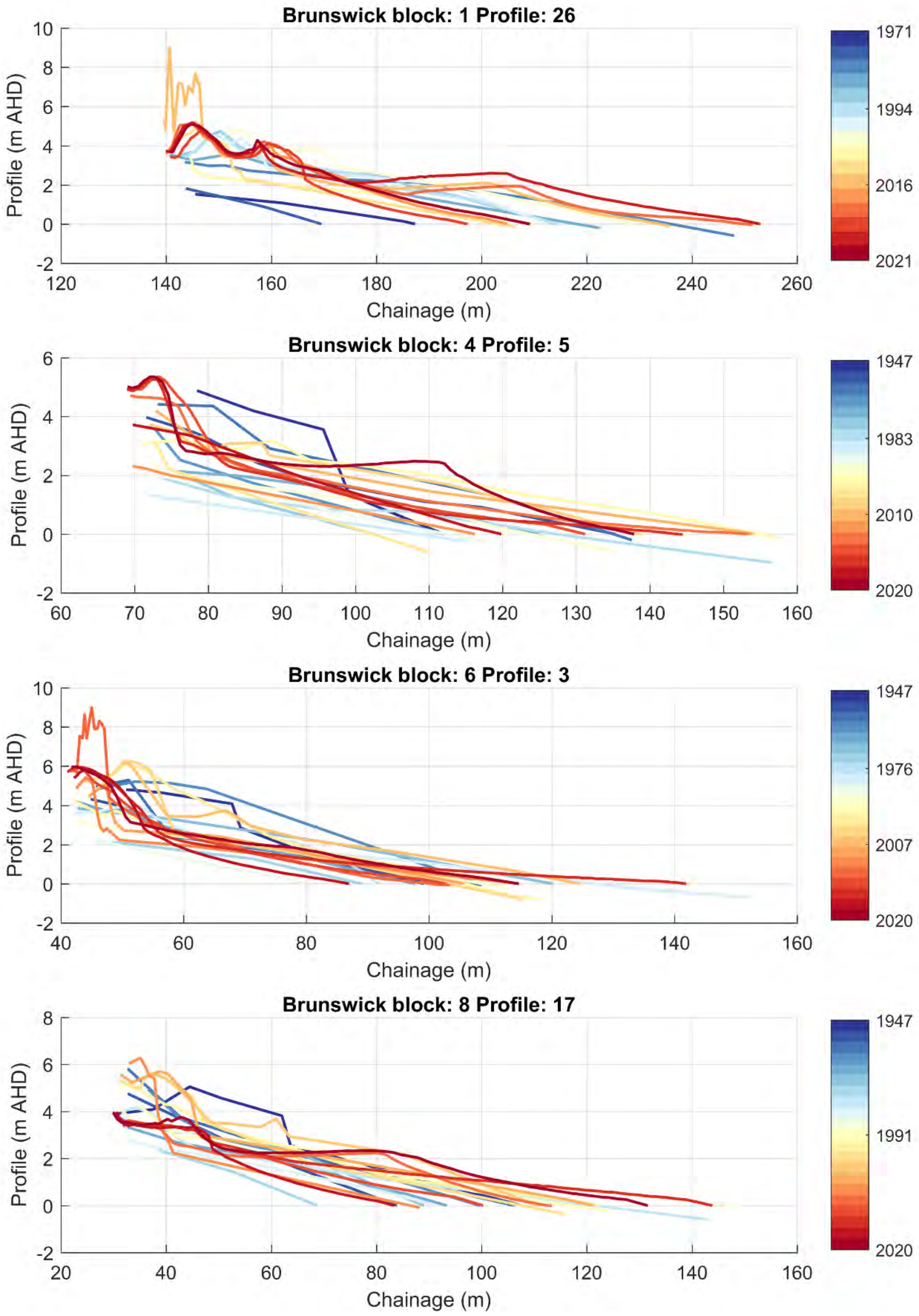


Figure 130: Selected subaerial beach profile plots between south of Brunswick Heads (Block 1) to South Golden Beach (Block 8).

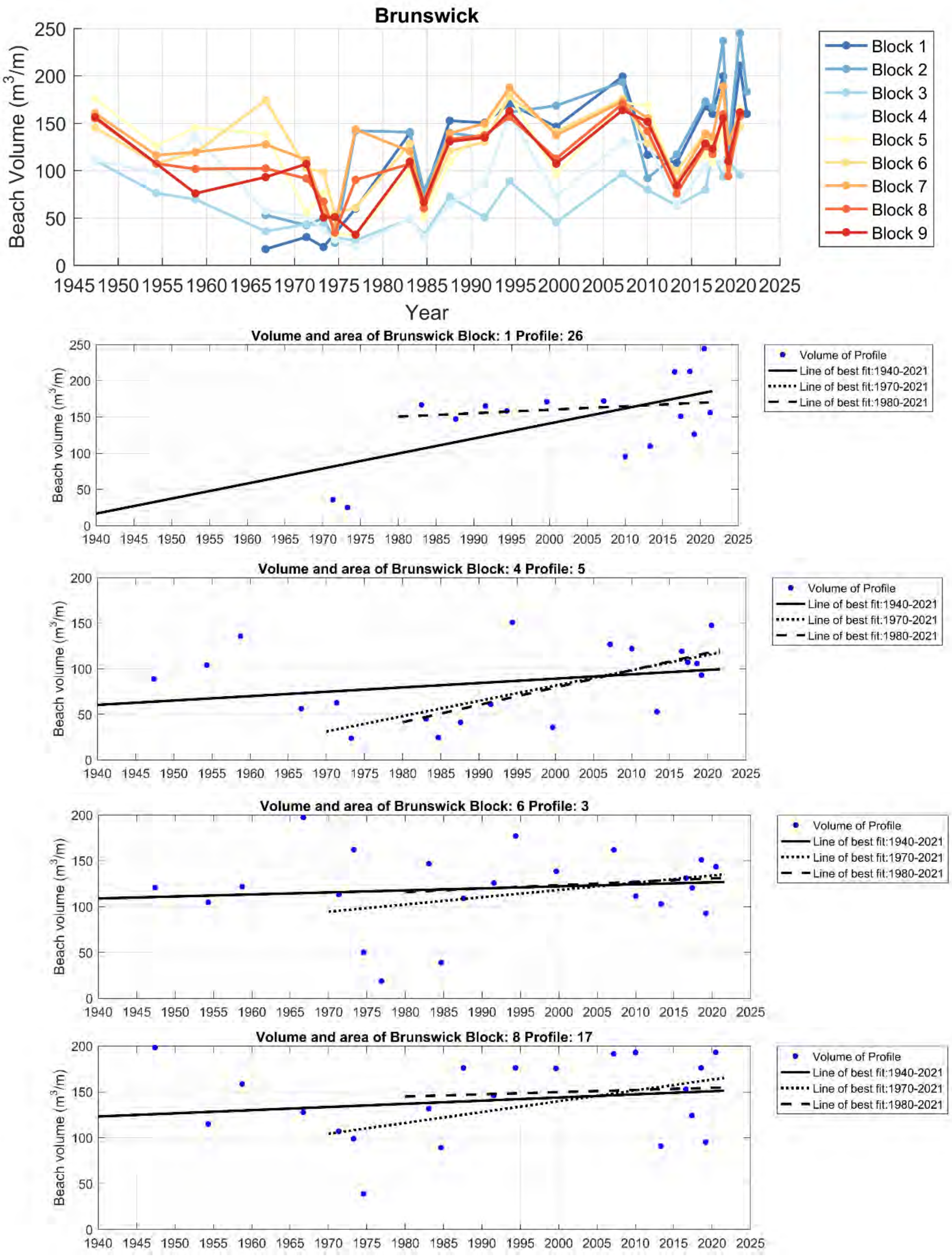


Figure 131: Timeseries of subaerial beach volumes and regression analysis for selected profile locations between Brunswick Heads and Wooyung.

Beach erosion

Storm demand volumes were estimated by analysis of subsequent dates in the NSW Beach Profile Database for a range of storms. The following storm events have been analysed (where data was available):

- Tropical Cyclone Dinah 1967
- Tropical Cyclone Wanda 1974
- East Coast Low in 1996
- East Coast Low in 2009
- Tropical Cyclone Oma 2019

The alongshore distribution of storm demands is presented in Figure 132 and Figure 133. The beach profiles may not be immediately pre- and/or post-storm event and can therefore be influenced by beach recovery and other non-storm profile changes.

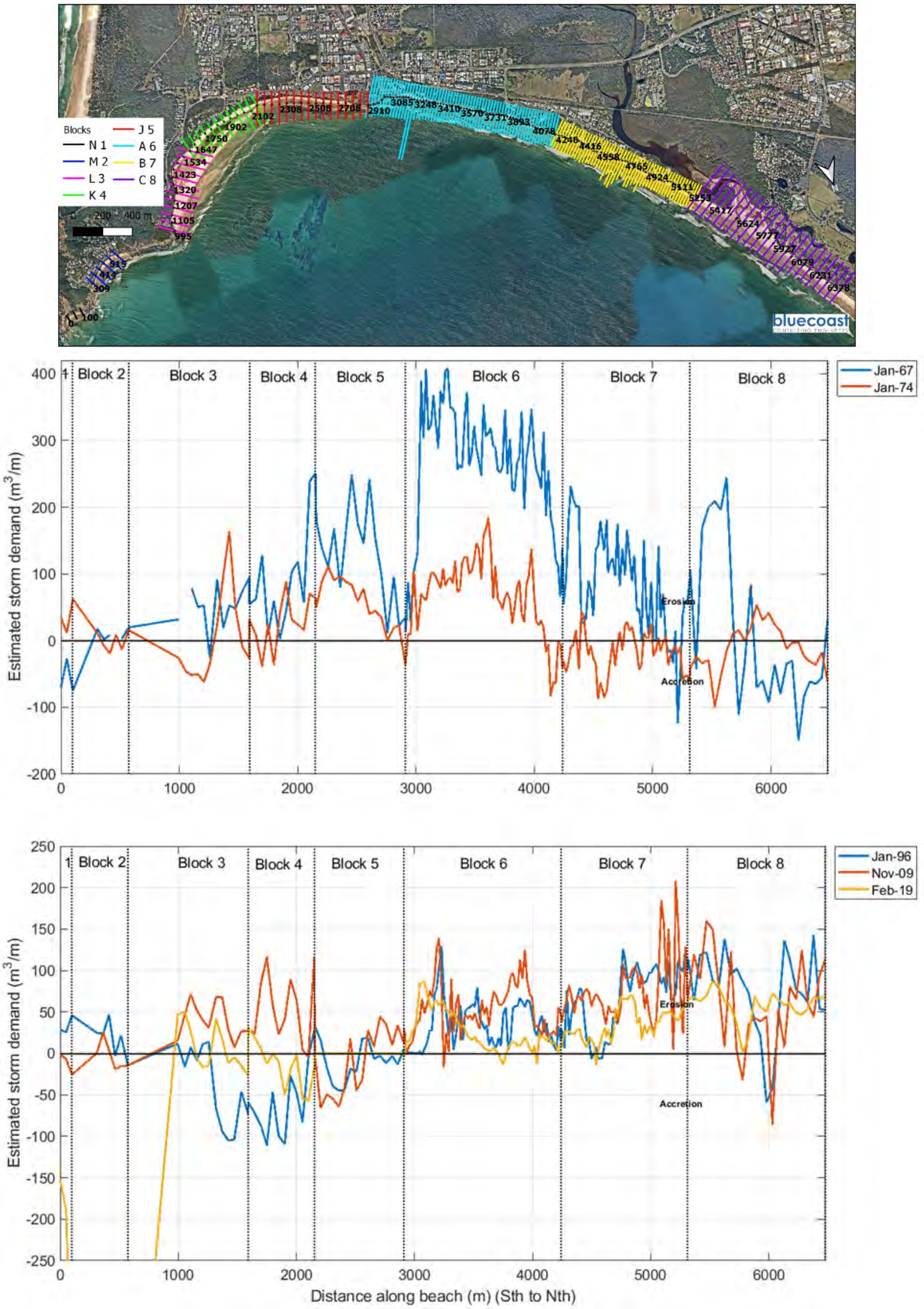


Figure 132: Little Wategos to Belongil Beach - alongshore storm demand estimates derived from NSW Beach Profile Database for storms in 1967, 1974, 1996, 2009 and 2019.

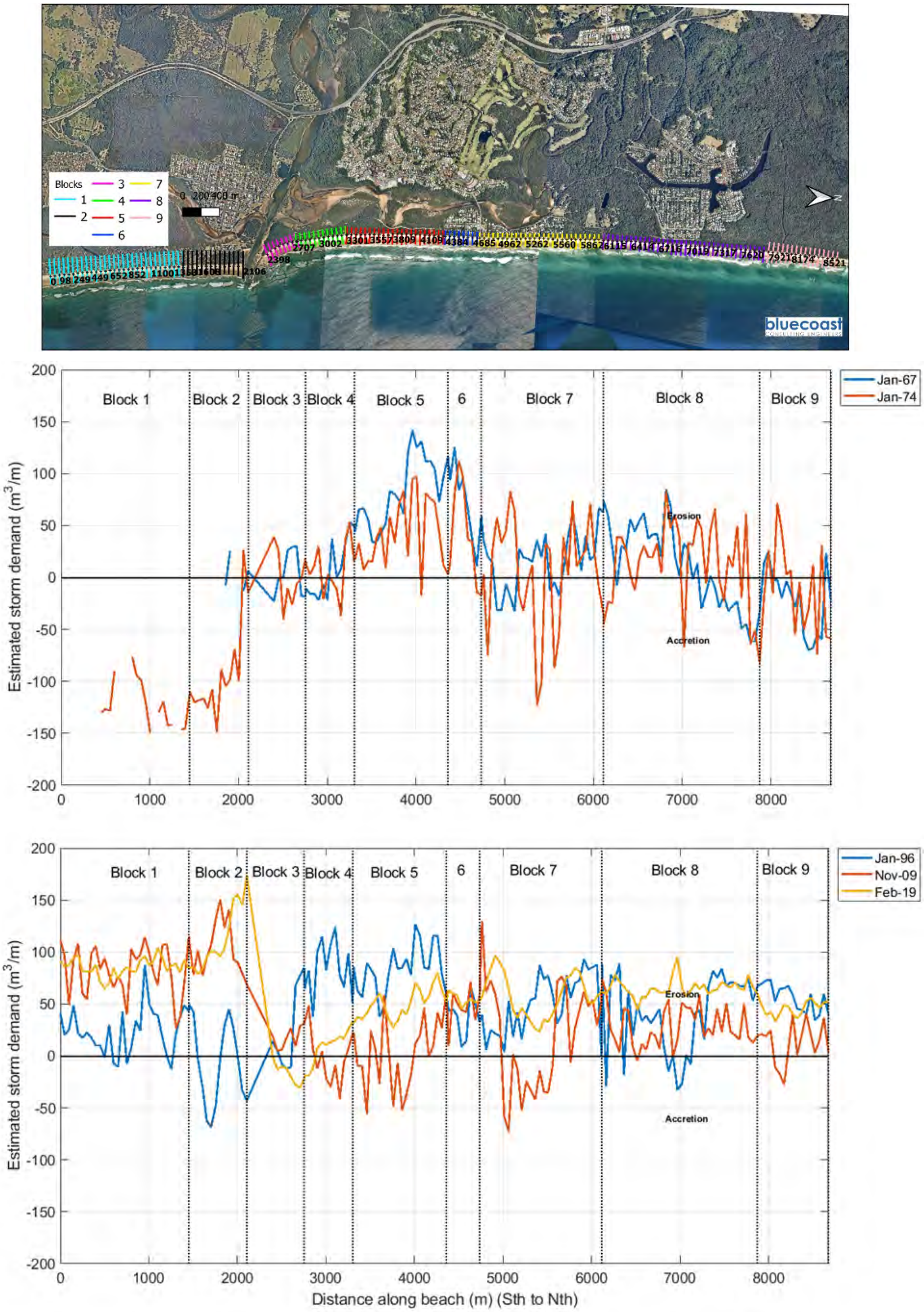


Figure 133: Brunswick Heads to South Golden Beach - alongshore storm demand estimates derived from NSW Beach Profile Database for storms in 1967, 1974, 1996, 2009 and 2019.

bluecoast
CONSULTING ENGINEERS

Byron Shire Council

Appendix C: Analysis of a headland bypassing event using satellite derived bathymetry

Analysis of a headland bypassing event using satellite derived bathymetry

To	NSW Department of Planning and Environment (Zoe Immisch)
From	Bluecoast Consulting Engineers (Evan Watterson and Tasman Van Loon)
Copy	Byron Shire Council (Chloe Dowsett)
Reference	P23297_HeadlandBypassingSDB_R2.00
Date	23 November 2023
Subject	Analysis of a headland bypassing event using satellite-derived bathymetry

Introduction

This document provides an analysis of satellite-derived bathymetry (SDB) datasets for Byron Bay between 2018 and 2022. The analysis is intended to provide further insight into headland bypassing around Cape Byron and its effect on the behaviour of Byron Bay's beaches. Specifically, the analysis seeks to quantify the volume and timing of sand movements through the embayment and outline any implications of this for coastal monitoring and management. Ultimately the outcomes are hoped to underpin sound coastal management decisions.

This work was undertaken for the NSW Department of Planning and Environment (DPE) in support of the Coastal Hazard Assessment (CHA) (Bluecoast, 2023) being undertaken Stage 2 of Byron Shire Council's Coastal Management Programs (CMPs). Section 4.4.3 of the Stage 2 Byron Shire Coastal Hazard Assessment Study report provides an overview of the headland bypassing process at Cape Byron. The SDB analysis was used to add further detail to the understanding of this bypassing process and extend the sand budget for the Byron embayment.

SDB validation against 2018 NSW Coastal LiDAR

The first stage of the analysis involved a validation of the 2018 SDB dataset against the 2018 NSW Coastal LiDAR. The validation was an important first step used to determine if the SDB technique applied to Byron Bay had sufficient accuracy to provide meaningful insights into the 2018 to 2023 headland bypassing event. A slide pack providing additional details on the SDB validation is provided in Attachment 1, with a summary provided below.

The validation task involved:

- The 2018 NSW Coastal LiDAR was supplied to EOMAP for calibration and validation purposes. Within the Byron region the coastal LiDAR was captured on four separate dates between 16 July 2018 and 23 August 2018. The coastal LiDAR covers the full coastal profile down to depths of around 20 to 30m (i.e., it includes the subaerial and subaqueous components).
- EOMAP then used the LiDAR survey to produce more accurate depths for the 2018 SDB. EOMAP's comparison showed a good overall agreement of SDB and LiDAR survey data, with 94% of the SDB data being within EOMAP's Standard 1 of ±0.5m + 10% of survey data depths (refer to Figure 1). The original 2018 SDB dataset covered a 16km^2 area, which was later reduced to a 12km^2 area of interest (AOI). EOMAP's data delivery report on the validated 2018 SDB is provided as Attachment 2.

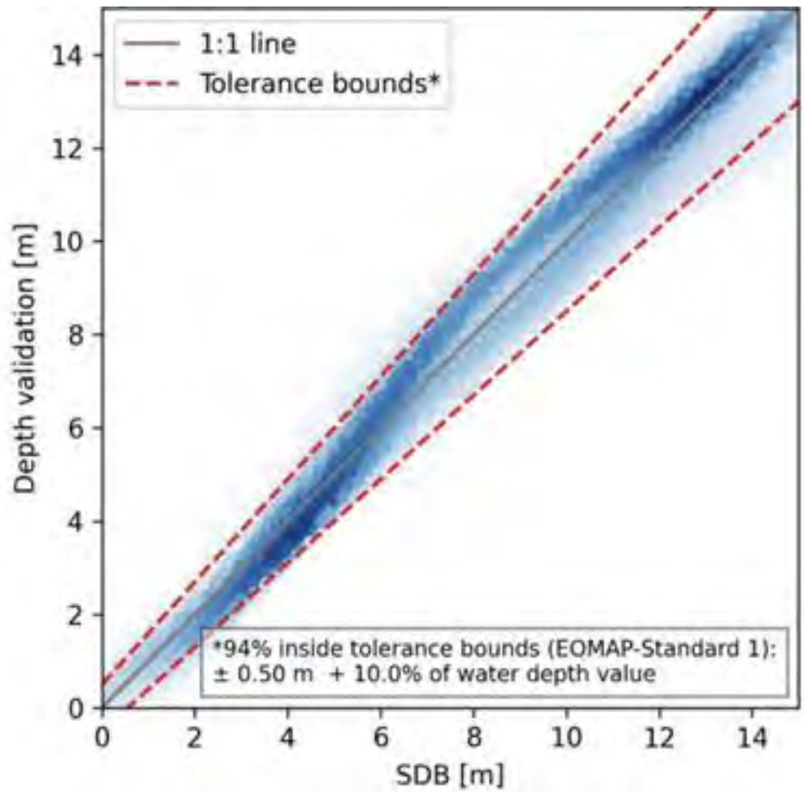


Figure 1: Comparison of 2018 SDB with 2018 Coastal LiDAR survey.

- The SDB errors, expressed as volumes (m^3) were calculated for analysis compartments defined in the CHA report (see Section 4.2.1 of Bluecoast, 2023) within our AOI[1]. The SDB errors were then compared with the observed range of actual sand volume changes in the Byron embayment[2]. To obtain meaningful results (i.e., the volumetric analysis shows mostly morphological change rather than SDB error) it was deemed that the volume error should be within ±30%. This was based on the quoted accuracy range for longshore sand transport rates of ±20-30% (nominally ±20%) in the main Stage 2 report.

Within the AOI, 7 out of 10 compartments showed a volume error less than ±30% of the natural variability with an average error of 28.6%. When coupled with profile comparisons against the high-quality 2018 NSW coastal LiDAR, it was deemed that the SDB datasets would be sufficiently accurate to reasonably show the movement of sand from a large bypassing event around the Cape and through the upper shoreface of the Byron embayment. Based on this outcome it was recommended to proceed with the purchase of additional datasets for 2019 to 2022 over a reduced 12km^2 AOI and proceed with the further analysis as described below.

[1] As the surveys used in the CHA's sand budget analysis were of high accuracy any difference between the 2018 Coastal LiDAR survey and the 2018 SDB was taken as 'volume error' due to the inaccuracies inherent to the SDB technology. Assessment of change in sand volumes in the CHA report was overtaken across the entire Byron LGA, covering 64 analysis cells and being a wider area than that assessed here.
[2] For each analysis compartment the observed range of sand volume change was calculated as the maximum observed difference between successive surveys (2002 to 2018 with coverage > 70%).

Dataset overview

Four additional SDB datasets were obtained from EOMAP for each year from 2019 to 2022. The datasets were based on Sentinel-2 satellite imagery and provided at a 10m resolution across a 12km^2 AOI which is shown in Figure 2. This AOI was chosen based on the outcomes of the 2018 SDB validation exercise as well as the intention of capturing as much as possible of the sand bypassing process at Cape Byron.

Datasets from winter months were selected due to:

- lower water turbidity that typically occurs at this time of year
- lower sun elevations which reduce light reflections resulting in better depth accuracy.

Informed by the 2018 SDB validation exercise the 2018 Coastal LiDAR dataset was also used, in the deeper areas where seabed changes are less, as a validation dataset for the 2019, 2020, 2021 and 2022 SDB datasets.

SDB datasets extend over the subaqueous (underwater) component of the coastal profile only. As described in Table 1, each SDB dataset was matched with the most representative and corresponding subaerial (or terrestrial) survey. These were selected to provide the most coverage across the subaerial analysis compartments as well as closest possible alignment in time. The combined datasets for each year (2018-2022) are shown in Figure 3. Figure 3 does not show the datasets for 2018 since this was taken as the reference year for volumetric calculations.

Table 1: Selected SDB (bathymetric) and subaerial datasets for each year, 2018-2022.

Year	SDB date	Subaerial dataset – date(s) of survey (data source)
2018	25 July 2018	NSW Coastal LiDAR - 16 July 2018 to 29 August 2018 (DPE)
2019	26 May 2019	Drone survey - 29 July 2019 (Bluecoast for Byron Shire Council)
2020	24 June 2020	Interpolated from LiDAR-derived NSW Beach Profiles - 22 June 2020 (DPE)
2021	9 June 2021	Interpolated from LiDAR-derived NSW Beach Profiles - 12 April 2021 (DPE)
2022	8 August 2022	Terrestrial LiDAR – 10 September 2022 (DPE)

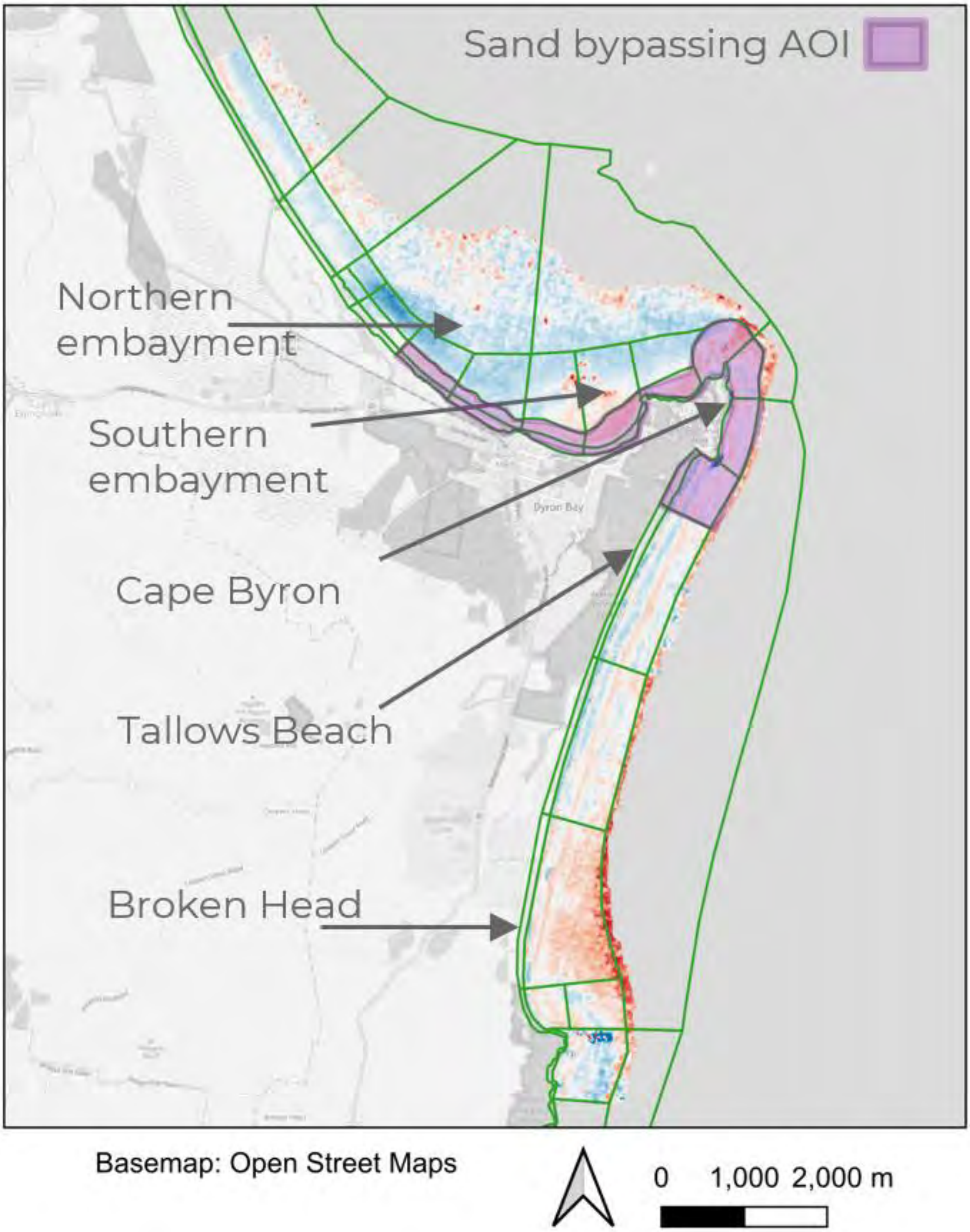


Figure 2: Selected AOI for defining SDB dataset extents.

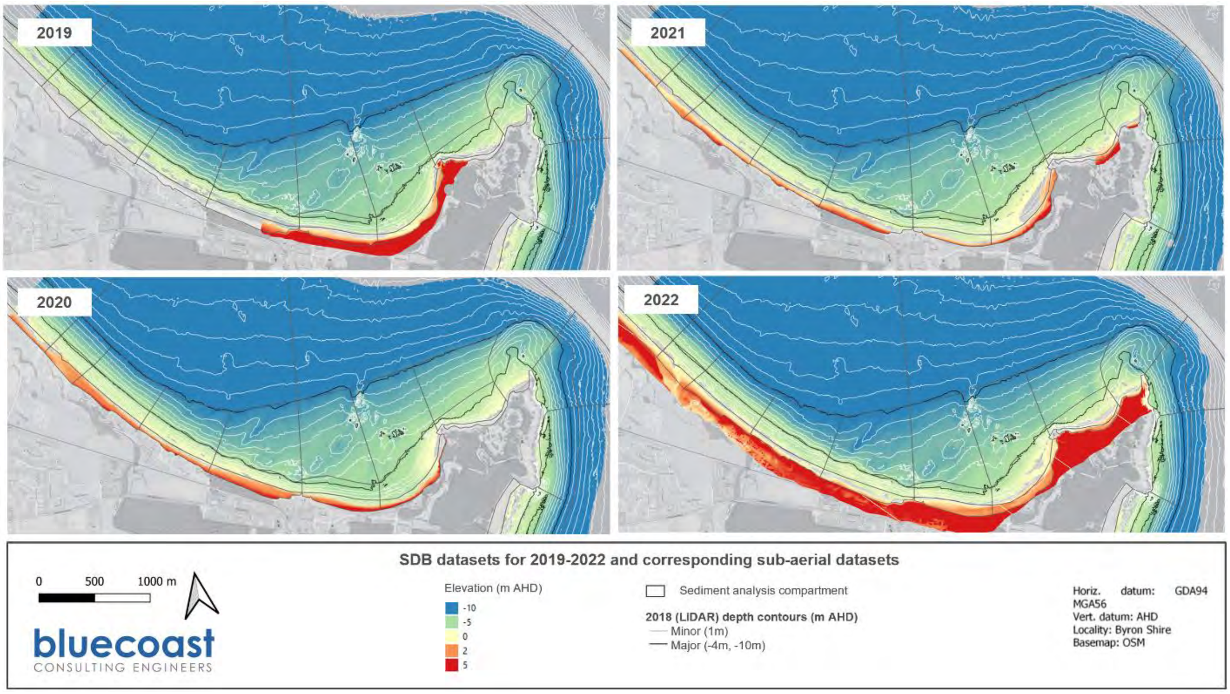


Figure 3: SDB datasets 2019-2022 including corresponding sub-aerial datasets.

Analysis results

Elevation differences were calculated for each year (2019-2022) using 2018 as a reference year. This was done as follows:

- the 25 July 2018 SDB was used as the reference survey for calculating volume differences for the bathymetric datasets (i.e., the SDB datasets)
- the 2018 NSW Coastal LiDAR was used as the reference survey for the subaerial datasets.

Elevation difference maps are provided in Figure 4 along with the corresponding Nearmap aerial images. The difference maps show areas of sand loss/erosion relative to the 2018 seabed coloured red and areas of sand gain/accretion (relative to 2018) coloured blue. The aerial imagery provides a useful visual comparison of the sand movements between surveys compared to the more quantitative SDB. Sequential (year-on-year) difference maps are provided in Figure 5.

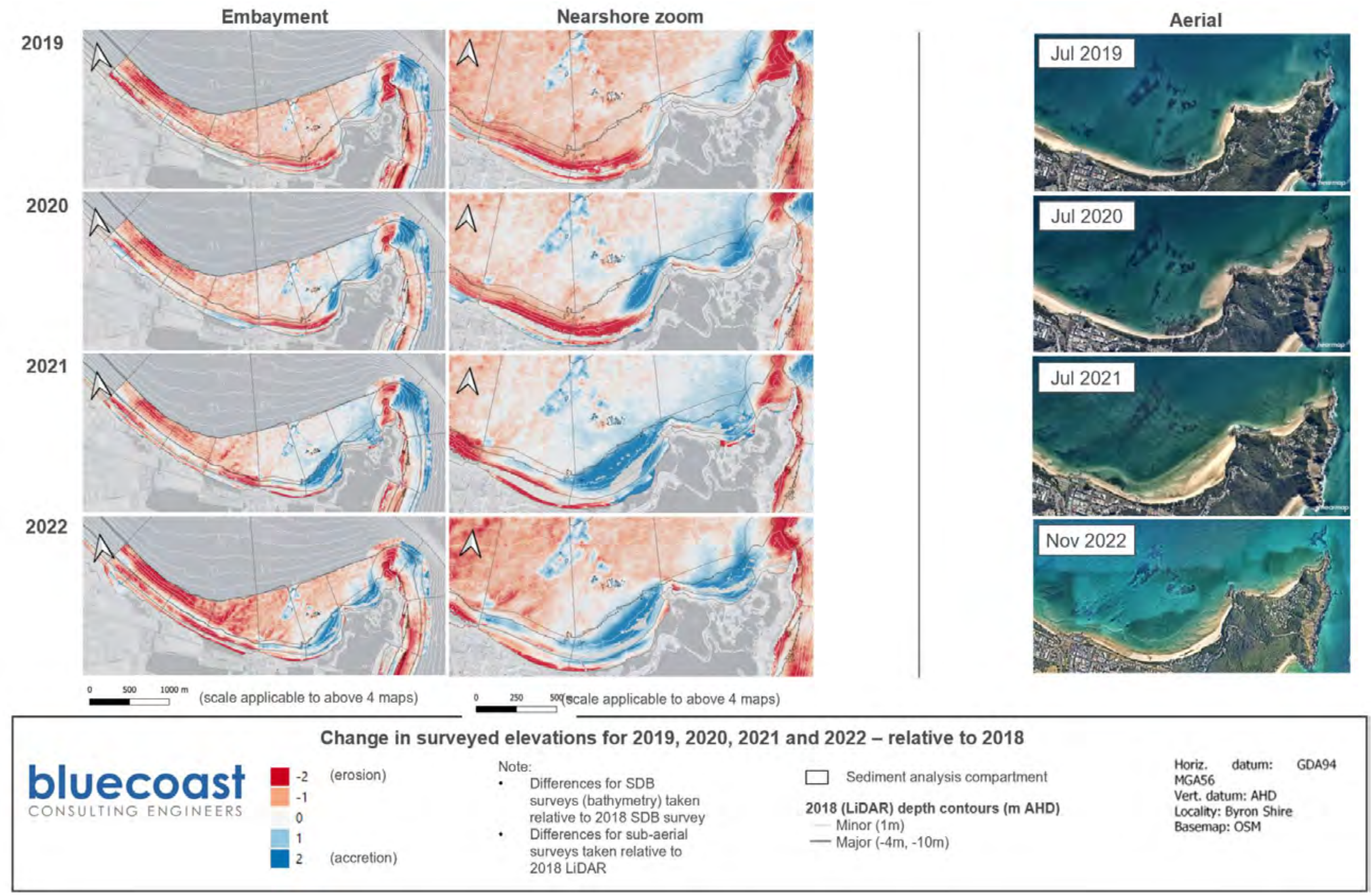
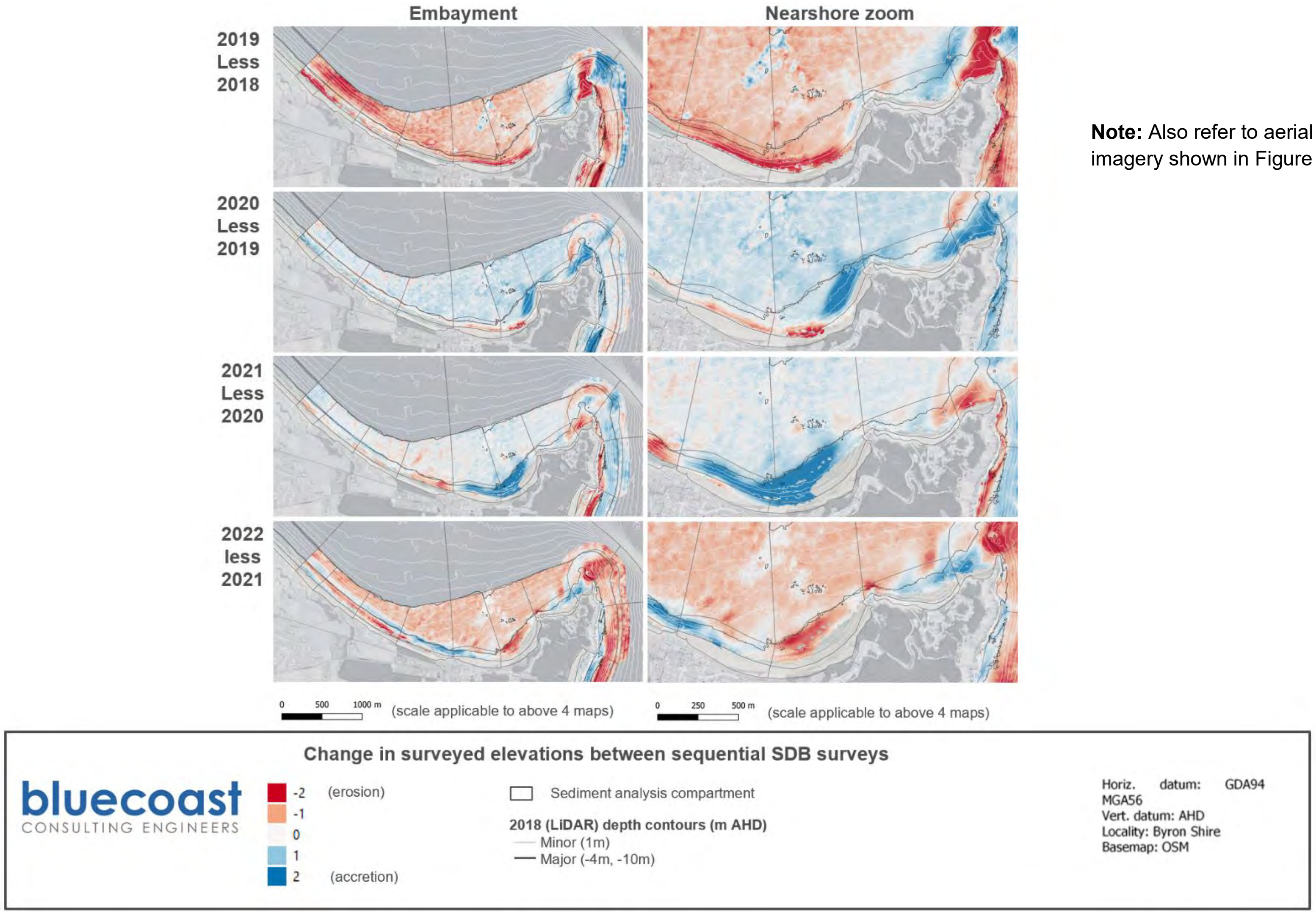


Figure 4: Difference maps for 2019, 2020, 2021 and 2022, relative to 2018.



Note: Also refer to aerial imagery shown in Figure 4.

Figure 5: Sequential SDB difference maps between 2018 and 2022.

Table 2 provides a summary of the sand volume changes between the available SDB datasets for the key areas (which are combinations of the individual analysis compartments). The sand volume changes for individual analysis compartments that are relevant to this SDB analysis are provided in Attachment 3.

Table 2: Summary of surveyed sand volume changes in Byron Bay region.

Zone	Volume (m^3) change relative to 2018 baseline				
	2018 (baseline)	2019	2020	2021	2022
Tallow Beach *(Northern most 2.8km)*					
Subaerial beach (crest of dune to 0m AHD)	0	-8,000	-2,000	-5,000	-2,000
Upper shoreface (0 to -12m AHD)	0	-296,000	-56,000	-149,000	-270,000
Sub-total	**0**	**-304,000**	**-58,000**	**-154,000**	**-272,000**
Cape Byron					
Subaerial beach (crest of dune to 0m AHD)	0	-	-	-	-
Upper shoreface (0 to -12m AHD)	0	-332,000	-25,000	12,000	-458,000
Lower shoreface (to 22m water depth)	0	NA	NA	NA	NA
Sub-total	**0**	**-332,000**	**-25,000**	**12,000**	**-458,000**
Southern embayment					
(Little Wategos to JSPW)					
Subaerial beach (crest of dune to 0m AHD)	0	-17,000	-46,000	7,000	-38,000
Surfzone (0m to -4m AHD)	0	-260,000	-79,000	409,000	431,000
Upper shoreface (-4 to -10m AHD)	0	NA	NA	NA	NA
Lower shoreface (-10 to -15m AHD)	0	NA	NA	NA	NA
Sub-total	**0**	**-277,000**	**-125,000**	**416,000**	**393,000**
Northern embayment					
(JSPW to Belongil Creek)					
Subaerial beach (crest of dune to 0m AHD)	0	-7,000	88,000	-70,000	-177,000
Surfzone (0m to -4m AHD)	0	-266,000	-272,000	-332,000	-437,000
Upper shoreface (-4 to -10m AHD)	0	NA	NA	NA	NA
Lower shoreface (-10 to -15m AHD)	0	NA	NA	NA	NA
Sub-total	**0**	**-273,000**	**-184,000**	**-402,000**	**-614,000**

Note: Volumes changes are only provided for compartments which are expected to have errors within ±30% are provided. Volumes are based on the combined topographic survey (or subaerial) and bathymetric (SDB) datasets, between each of which there is a gap in coverage. To account for gaps volume change is calculated as the average survey height difference multiplied by the compartment area. The 'total volume change' for each compartment is presented in Attachment 2, and summarised in the values presented in the above table.

Discussion

The SDB datasets from 2018 and 2022 capture a significant sand bypassing event. The difference maps in Figure 4 show a distinct sand wave (or slug of sand) that moves around the Cape, from south to north, to infill The Pass (in 2021) and Main Beach (in 2022).

Key discussion points are:

- Prior to the bypassed sand arriving, the embayment was depleted of sand meaning beaches and dune systems experienced erosion. In 2018 surveys showed that Byron's southern embayment contained a below average amount of sand (see Figure 44 and Table 9 in the main report). By 2019, and based on the SDB data, a further 277,000m^3 of sand had been lost. This reduced the southern embayment sand volume to historically low levels. Between the 2018 and 2019 surveys sand lost was most pronounced at Clarkes Beach (187,000m^3) and Main Beach (146,000m^3)[3]. By 2020, Clarkes Beach had begun to recover but Main Beach lost a further 66,000m^3 (i.e., 212,000m^3 loss relative to 2018).

  These depleted sand volumes left the southern embayment's beaches vulnerable to dune erosion. The surf zone was deeper and narrower than normal (e.g., at Main Beach in 2020 the -4m AHD contour was 100m landward of its position in 2018). This allowed wave action (e.g., TC Oma in February 2019) to progressively erode the dune system during high tides. Between 2019 and 2021, around 30m of vegetated and previously stable dune sand was eroded along Clarkes Beach and Main Beach. This equated to around some 72,000m^3 of sand being eroded from the Main Beach dunes, from Byron Café to JSPW (see Figure 5). By supplying sand to the littoral sand movement system, the 72,000m^3 that was eroded from the Main Beach dune system would have supplied sand downdrift and reduced erosive effects.

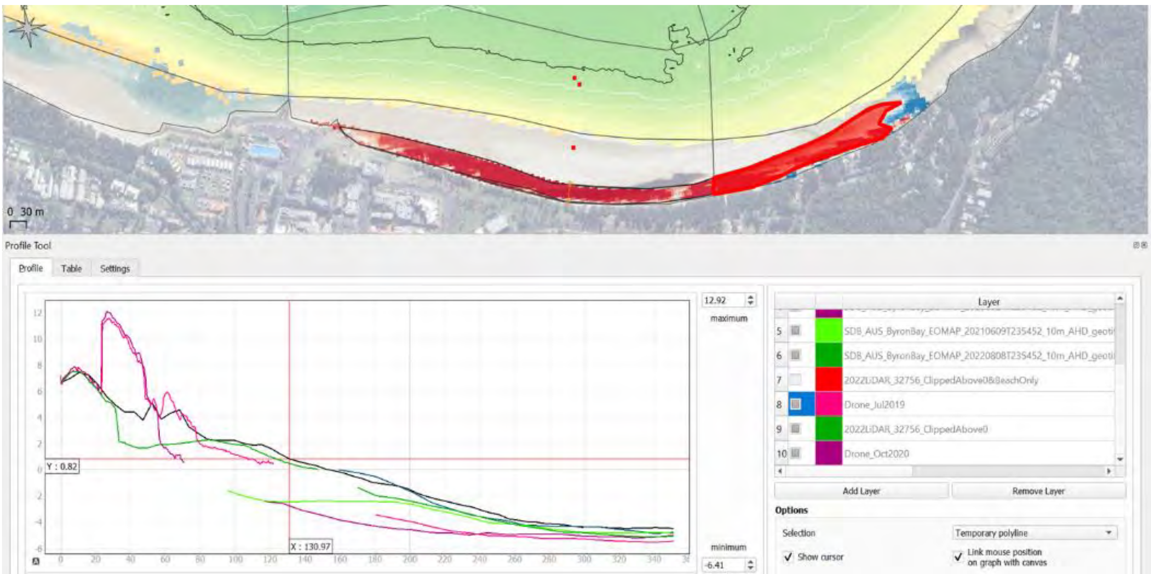


Figure 5: Coastal profiles at Main Beach between 2018 and 2022 showing progressive loss of vegetated dune associated with reduced sand buffer in the surf zone (elevations relative to AHD).

- Figure 6 plots the volume changes for each main alongshore compartment zone in the embayment, taken as the sum of the beach and surf zone compartments (i.e., from the dunes

---

[3] The sub-compartment around Wategos Beach gained sand over the period between 2018 and 2019 as bypassing recommenced (see accretion blue in top middle panel in Figure 4).

down to -4m AHD) in alongshore areas of Wategos Beach (WB), Clarkes Beach (CB), Main Beach (MB) and Belongil Beach (BB). By 2020 the updrift area of the southern embayment had started to recover due to bypassing sand supply. Between 2020 and 2021, the volume of sand in the southern embayment (relative to 2018) increases from -125,000m^3 to +416,000m^3 (541,000m^3 increase in one year). Clarkes Beach (from dune down to -4m AHD) increased from a relative (to 2018) volume of -49,000m^3 in 2020 to 372,000m^3 in 2021 (an increase of 421,000m^3). These compartment sand volume changes are consistent with previous analysis which estimated annual range of sand supply around the Cape from around 150,000 to over 900,000m^3/year (noting that sand transport rates can be higher than the change in sand volume within a compartment).

The naturally restored sand supply led to increased beach widths and refilled the surf zone creating a wider, shallower surf zone to restore the sandy buffer (see Figure 5). To retore the dunes along Clarke Beach and Main Beach dunes, Byron Shire Council undertook beach scraping to move around 12,000m^3 of sand (approximately 14m^3/m over an approximately 850m length of shoreline) from the intertidal area up the profile to create an incipient dune and swale just seaward of the dune's erosion scarp.

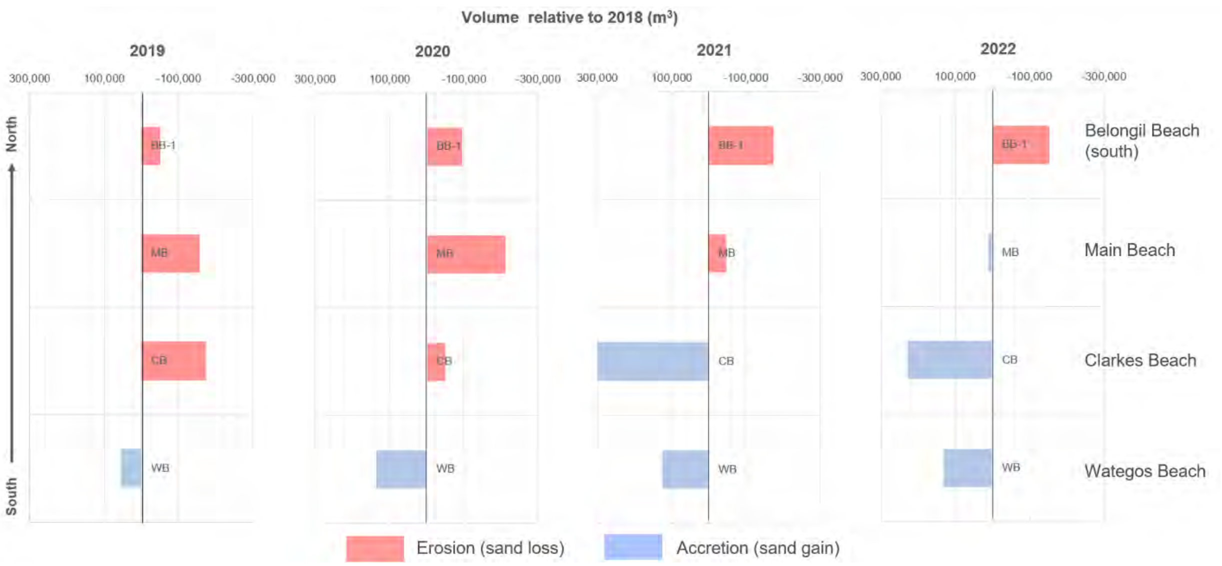


Figure 6: Volume changes between 2019 and 2022 for each alongshore zone from Wategos Beach to Belongil Beach (south).

- The cycle described above can be observed in DEA Coastline data (mean annual shoreline positions), see Figure 7. The figure shows a naturally occurring lack of bypassing and sand supply between 2018 and 2020 leading to headland bypassing induced/enhanced erosion along Clarkes Beach and Main Beach (see most landward annual shoreline observed along 700m of Main Beach in 2021). This was followed by beach recovery as supply was restored to Clarkes Beach in 2021 and to Main Beach in 2022. The pattern and timing of shoreline change observed in the DEA Coastline aligns with the sand volumes changes observed in the SDB.

  The DEA Coastlines extend back to 1988 allowing identification of other similar headland bypassing driven cycles of this nature and possibly to identify correlations to underlying ENSO and wave climate signals. Such analysis is beyond the scope of this work. A preliminary review indicates that:

  - at Main Beach other cycles appear to have occurred in:
    i. 1988 to 1989 (erosion) with recovery from 1989 to 1991
    ii. 1998 to 2000 (erosion) with recovery from 2000 to 2003

iii. 2007 to 2009 (erosion) with recovery from 2009 to 2010

- The erosion phase of cycles i, ii and the most recent (2018 to 2023) occurred 0 to 4 years after a major El Niño event. While the most eroded period generally occurred during La Niña, when longshore transport in the embayment is higher (see main Stage 2 report).
- the erosion phase of the 2018-2022 cycle reached the most landward shoreline position observed at Main Beach and Clarkes Beach, marginally more landward than cycle i. A key reason for the extent of the shoreline recession was that that at the start of the cycle the embayment shorelines were in an average or below average position.

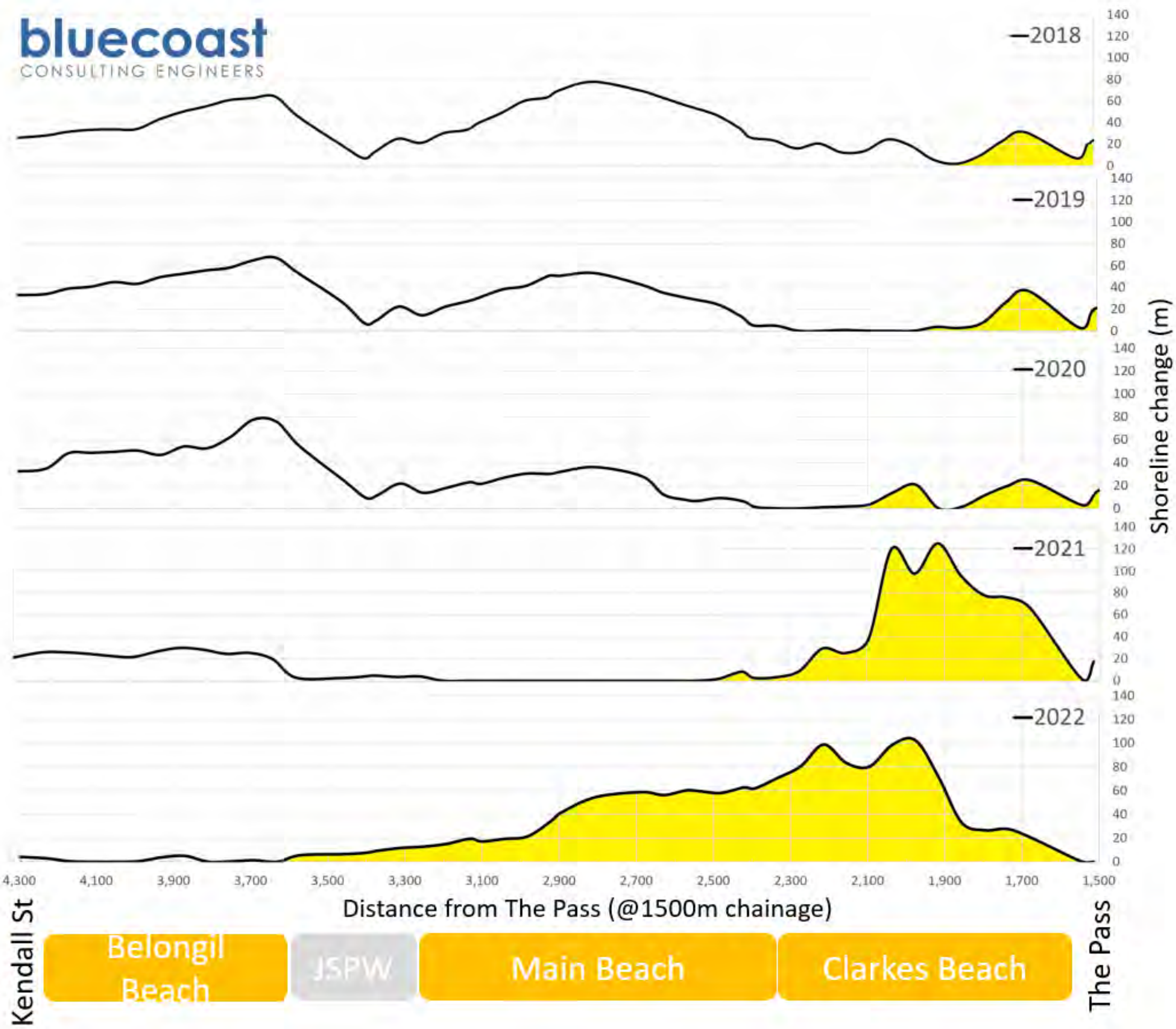


Figure 7: Time history of satellite-derived embayment shorelines from 2018 to 2022.

Note: Data is derived from the annual mean sea level shoreline from the DEA Coastlines product. All data is presented as the differences from the minimum observed position at each shoreline location at approximately 60m alongshore intervals (observation period 1988 to 2022). That is, where the shoreline change plots as zero metres (0m), this is the most landward shoreline position observed. The accretion wave, coloured yellow, is shown for illustrative purposes. Also note (i) minimum observed shoreline along Clarkes Beach in 2019 translating to Main Beach by 2021 and then on to Belongil Beach by 2022 and (ii) the progressive erosion (landward movement of the shoreline) along Main Beach from 2018 to 2021.

- The SDB data and associated elevation difference maps confirm a distinct sand transport pathway inshore of the -4m AHD contour (see labelled major depth contours in Figure 3). This is the approximate cross-shore limit for littoral transport of sand within the embayment and was previously identified and discussed in the Main Beach Shoreline Project's Technical Report (Bluecoast, 2022) and subsequently in the main body of the Stage 2 report. The SDB dataset were not considered accurate enough to provide meaningful sand movement information in the deeper analysis compartment where a secondary cross embayment pathway exists (i.e., the upper shoreface analysis cells (-4 to -10m AHD) defined in the embayment). Estimates in Bluecoast's previous work indicate the relative split between the two pathways to be 70 : 30 (littoral : cross embayment).

Implications for coastal monitoring and management

This analysis provides further insights on the timing and volume of sand associated with sand bypassing events at Cape Byron. Being only a single instance, the results of this analysis cannot be generalised across all future scenarios, however, by comparing to longer time datasets further analysis could reveal greater insight. As noted in the main Stage 2 report, headland bypassing is a highly variable process that depends on numerous factors and the timing and volume of sand involved in an individual bypassing event can vary.

The following implications are considered for coastal management of the Byron embayment:

- The erosive phase of the current cycle is currently centred around the rock and geobag structures along Belongil Beach. This means the sandy buffer in front of these structures is reduced exposing the structures to increased wave action and potential damage, particularly the interim geotextile structures and poorly designed and/or constructed rock/rubble structures. Implications are (i) the need for inspections and maintenance/repairs while the structures remain exposed (ii) this area remains vulnerable to storm erosion and/or wave overtopping while the sand buffer is reduced.
- Over the next 6- to 24-months the erosion phase will move downdrift towards Belongil Creek entrance. This should be monitored for any changes to the entrance stability hazard and for possible effects of the north side of the creek (geobag coastal protection/training works fronting Elements of Byron resort) .
- Clarkes Beach and Main Beach in particularly but also Belongil Beach are vulnerable to erosion and shoreline variability due to headland bypassing. Development along this zone should be considered in the context of these natural processes as they will continue to occur, albeit not every year/decade. For example, Apex Park and the fringing dune system are an asset in accommodating these variations. Little Wategos and Wategos Beach are considered less vulnerable as it is underlaid by bedrock or boulders which provide a landward termination to shoreline movement.
- There are accessible datasets, such as Nearmaps aerial photography, DEA Coastlines and ENSO indexes, that could be used to monitor the likelihood of the commencement of a potentially damaging bypassing cycle. Potentially damaging cycles seem occur when (i) shoreline/sand volumes in the embayment are average or below average at the start of a cycle and (ii) a strong El Niño event precedes a period of reduced sand supply to the embayment by 1 to 4 years.

Other implications include:

- Coastal hazards, as mentioned in the NSW Coastal Management Manual, are defined in the *Coastal Management Act 2016*. The CM Act 2016 lists seven hazards, none of which specific related to variable longshore sand supply and headland bypassing or other other forms of bypassing on longshore drift coastlines (e.g., bypassing of river entrance, bypassing of coastal structures). From Newcastle north the NSW coast has a longshore sand transport system with rate varying from under 100,000m^3 to around 550,000m^3. Recognition of the importance of longshore transport may be expected to lead to better coastal management outcomes.

- In defining coastal erosion hazard lines in NSW, it is common practice to define a storm demand (e.g., using Gordon, 1987) (in m^3/m of subaerial beach volume over a shoreline length) and use the Neilsen et al (1992) dune erosion profile to define the erosion extents. This gives no consideration to the volume of sand in the subaqueous part of the coastal profile at the time of a storm erosion event. As is clear in Figure 5, a lack of sand in the surfzone (as well as on the beach berm) lead to the dune being far more vulnerable to dune erosion than would otherwise have been the case.

References

Bluecoast 2023 *Byron Shire Coastal Hazard Assessment Study – Byron Shire CMP Stage 2.* Report prepared for Byron Shire Council.

Attachment 1: SDB validation slide pack

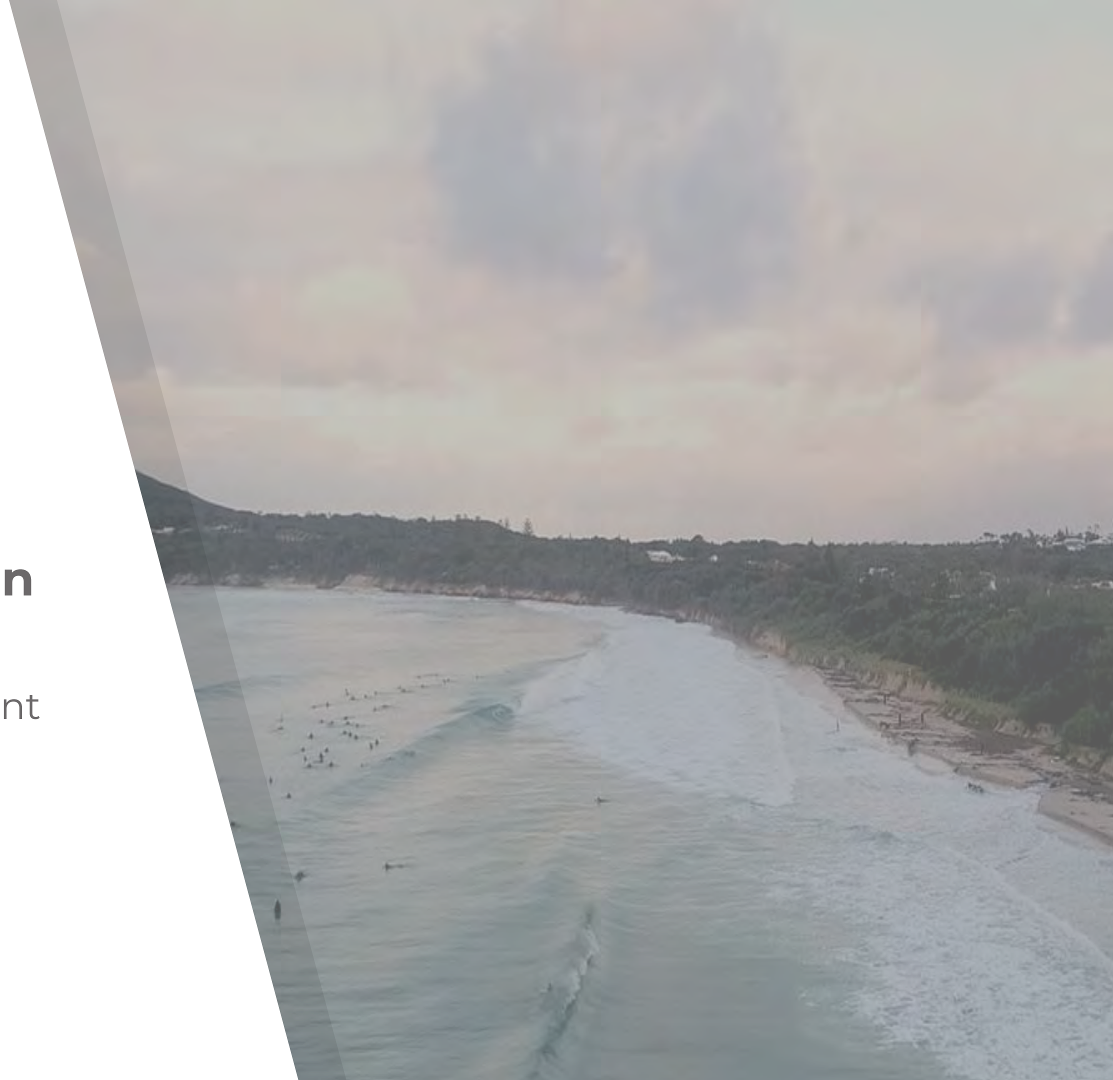
bluecoast
CONSULTING ENGINEERS

2018 – 2023 Satellite Derived Bathymetry (SDB) analysis and coastal processes update

Stage 1: SDB Dataset Validation

Department of Planning and Environment

April 2023



Overview

bluecoast
CONSULTING ENGINEERS

Purpose

- Assess whether Satellite-derived Bathymetry accurately represents known Byron embayment depths closely enough to extend the sand budget analysis by describing the 2018 to 2023 sand bypassing event

How

- SDB dataset was supplied by EOMAP. The date was selected for image quality and to align with 2018 LiDAR bathymetry
- The LiDAR bathymetry used as a calibration and validation dataset to produce more accurate depths
- Compare sand volume changes based on the observed seabed differences to the SDB error volumes
- Inspection of areas of interest and analysis of suitability

Outcome

- Decision to proceed with Stage 2.
- Data correlation is good in the shallow areas to the south of the Cape and in the southern part of the embayment. Additional SDB datasets will likely be able to capture the movement of sand through these areas.

Datasets

2018 LiDAR Dataset

Elevation (m)
0
-30

Calibrated SDB Dataset

Basemap: Open Street Maps

0 1,000 2,000 m

The SDB bathymetric dataset was calibrated by the provider using the 2018 LiDAR dataset (shown left).

The LiDAR survey data helped to increase the accuracy of the SDB data especially in the deeper waters south of Cape Byron, which most exposed to waves. This can lead to resuspension of sediments and slightly increased turbidity even under the suitable conditions. Water depths shallower than 5m are less impacted, as the light reflection from the seafloor is higher and SDB retrieval therefore less prone to residual turbidity. EOMAP expect that the LiDAR survey will also help to stabilise results in deeper waters for further timestamps, as the seabed dynamics are highest in the shallow water above 5m (moving sand banks) and more stable in deeper waters.

The calibrated dataset was trimmed by the provider to remove some of the areas with higher uncertainty in the deeper sections of the analysed area.

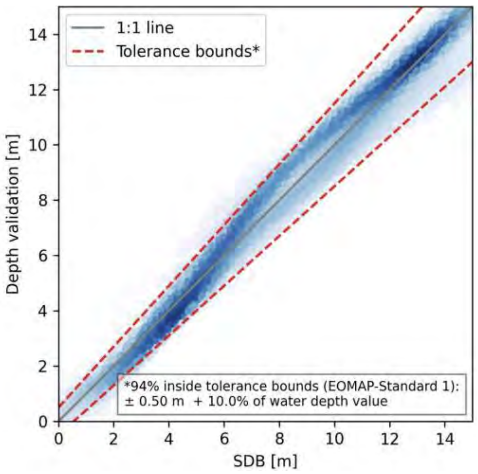
Parameter	LiDAR	SDB
Captured	01-07-2018 to 31-12-2018	25-07-2018 23:52:59 UTC
Resolution	5m	10m
Datum	AHD	AHD

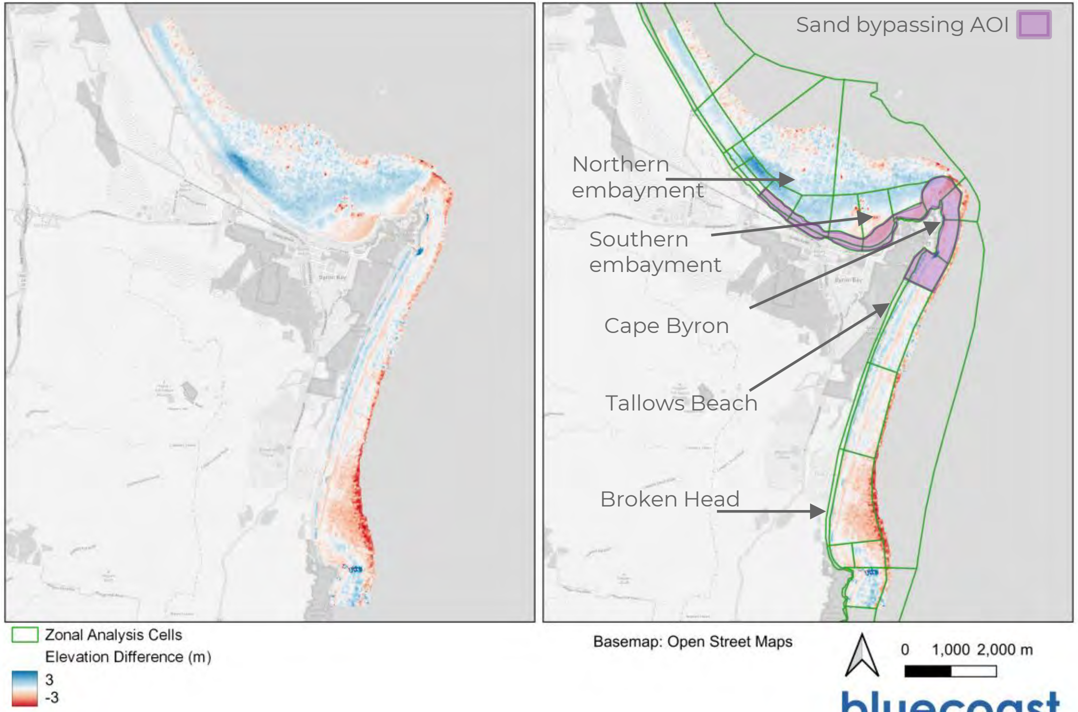
Difference maps

The difference plots, which compare the seabed elevations across the LiDAR and SDB, highlight areas where there is the greatest differences.

Overall (refer to correlation plot below), the SDB:

- Is typically (94% of data) within EOMAP's stated tolerance bounds
- compares well for the shallow (~0-6m) parts of the coastal profile as well as the deeper (<12m) parts
- between ~6-12m water depths these is a systematic bias, whereby the SBD is shallow than the known depths this is likely due to wave action and turbidity which is greatest on the exposed open coast (e.g., southern Tallows Beach and Broken Head)
- the SDB dataset correlates well along the northern end of Tallows Beach, Cape Byron and the shallower parts of the southern embayment



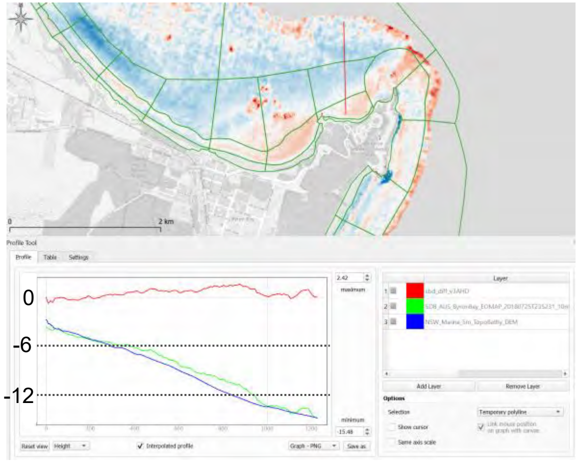


The area of interest for the sand bypassing event to be investigated in Stage 2 is analysed in profile plots on the following page. It shows good correlation in this region of depths up to ~6m before the datasets start to vary.

Areas of interest

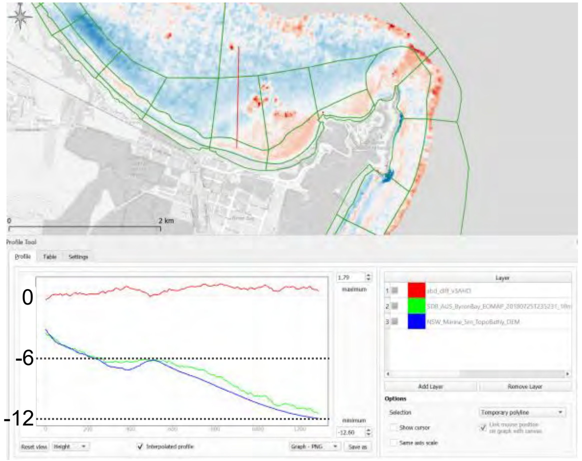
Southern embayment (Wategos)

Good correlation in shallower water up to 6m, varying in region between 6-12m depth (identified on previous slide)



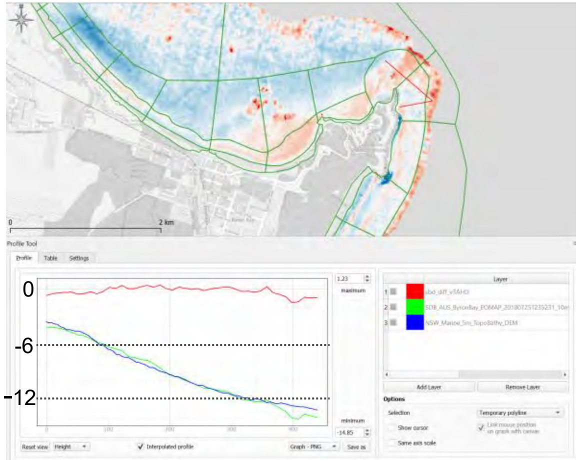
Southern embayment (Main Beach)

Good correlation in shallower water. Identifies the bar feature shown in the LiDAR but with a less pronounced trough.



Cape Byron

Good correlation through the whole depth up to the depth cut-off of 12-14m.



Results

bluecoast
CONSULTING ENGINEERS

Longshore zone	ID	Approx. cell contour boundary	Max. observed diff. between successive surveys (m^3)	Coverage	Mean depth diff. (m)	Volume error (m^3)	Volume Error %
Beaches of Broken Head Nature Reserve	BH-3-2		222,285	96%	0.346	230,332	104%
Beaches of Broken Head Nature Reserve	TB-1-2a		111,284	98%	-0.112	- 25,816	-23%
Beaches of Broken Head Nature Reserve	TB-1-2b	<12m	355,799	100%	-0.297	- 117,185	-33%
Tallows Beach	TB-2-2		966,121	98%	-0.575	- 989,430	-102%
Tallows Beach	TB-3-2		691,965	98%	0.047	61,852	9%
Tallows Beach	TB-4-2		231,031	98%	0.155	183,414	79%
Tallows Beach	TB-5-2		403,998	99%	0.274	118,541	29%
Cape Byron	CaB-1-1		414,107	100%	0.006	1,871	0%
Cape Byron	CaB-2-1	<12m	112,635	99%	-0.074	- 17,579	-16%
Cape Byron	CB-BYPASS		451,643	97%	-0.226	- 76,469	-17%
Southern Byron embayment	WB-1-2		145,271	99%	-0.286	- 46,590	-32%
Southern Byron embayment	CB-1-2	<4m	145,892	100%	-0.513	- 110,563	-76%
Southern Byron embayment	MB-1-2		178,608	100%	-0.146	- 18,697	-10%
Southern Byron embayment	WB-1-3		144,432	100%	0.662	253,103	175%
Southern Byron embayment	CB-1-3	4-10m	14,681	100%	0.216	119,628	815%
Southern Byron embayment	MB-1-3		35,711	100%	0.311	171,672	481%
Southern Byron embayment	BB-LS-1	>10m	120,828	99%	0.312	551,093	456%
Northern Byron embayment	BB-1-2		152,047	98%	0.294	34,269	23%
Northern Byron embayment	BB-2-2	<4m	138,520	99%	-0.040	- 4,851	-4%
Northern Byron embayment	BB-3-2		49,266	95%	0.375	41,973	85%
Northern Byron embayment	BC-1-2		31,281	94%	0.648	43,962	141%
Northern Byron embayment	BB-1-3		31,066	100%	0.823	391,919	1262%
Northern Byron embayment	BB-2-3	4-10m	33,464	100%	1.004	244,643	731%
Northern Byron embayment	BB-3-3		62,985	100%	1.678	314,734	500%
Northern Byron embayment	BB-LS-2		101,385	101%	0.305	726,185	716%
Tyagarah Beach	TY-1-2	>10m	46,351	99%	0.367	194,160	419%

Sand bypassing AOI

The ‘Maximum observed difference between successive surveys’ (2002 to 2018 with coverage > 70%) was taken from MBSP & CMP volumetric analysis and used to represent the range of observed ‘natural’ change for each of the analysis compartments shown on Slide 4. The surveys used in the MBSP & CMP were either LiDAR or traditional single beam hydrographic surveys and are of high accuracy. The ‘Volume error’ is a comparison between the SDB and the high-accuracy LiDAR survey and this therefore taken to be an error due to inaccuracy inherent to the SDB technology.

The volume error was compared to the maximum observed difference between successive surveys to determine is the SDB dataset has sufficient accuracy to provide a meaningful outcomes during the 2018 to 2023 bypassing event. The draft CMP (Stage 2) quotes an accuracy range for longshore sediment transport rates of ±20-30% (nominally ±20%). It is considered the volume error should be within ±30% to obtain meaningful results (i.e., the volumetric analysis shows mostly morphological change rather than survey error).

Results are shown from south to north and the area of interest (AOI), with the highest sand movement (shown in purple). Within the AOI, 7 out of 10 compartments show volume error less than ± 30% of the natural variability with an average error of 28.6%. When coupled with the profile comparisons for the AOI on the previous slide and high-quality terrestrial LiDAR, the indications are that the SDB datasets will be sufficiently accurate to reasonably show the movement of sand around the Cape and through the southern embayment.

Outcome: Based on these results it is our recommendation that Stage 2 of this project proceed. DPE should review the information herein to make that decision. Given the accuracy reduces for southern and northern extents, future SBD datasets could be purchased for the 12km^2 extents, which would save 8% of the.

Attachment 2: EOMAP's data delivery report

Delivery Report

Satellite-Derived Bathymetry, Byron Bay, Australia

Date: 2023-03-15
Version: 1

Clients: Bluecoast Engineers
Reference: 20221212.1306

EOMAP GmbH & Co.KG,
Schlosshof 4, 82229 Seefeld
Germany

Authors:	e-mail	Phone
Andreas Müller	mueller@eomap.de	+49 8152 99861 10
Philip Klinger	klinger@eomap.de	+49 8152 99861 10

1 Objective

EOMAP was contracted by Bluecoast Engineers to provide Satellite-Derived Bathymetry (SDB) for the first of potentially several timestamps for the area of interest (AOI) of Byron Bay, Australia (Figure 1).

Figure 1: Area of Interest (AOI) at Byron Bay, NSW

2 Satellite Data

For this project, we have used a high resolution (10m) multispectral satellite dataset from ESA's Sentinel-2 satellites.

Satellite data selection

Out of all archived satellite data, we have selected datasets based on the following criteria:

(1) atmosphere free of clouds, haze or dust
(2) no floating substances or objects (oil films, floating vegetation, ice)
(3) as clear water as possible
(4) most favourable illumination and recording geometries to ensure radiometric stability and avoid water surface effects (sunglint)
(5) minor or no impact of waves and wave-breaking.

The satellite datasets used are listed in Table 1.

Table 1: List of satellite image data used.

Tile ID / Catalogue ID	Sensor name	Number of spectral bands	Spatial resolution in m	Date of image recording UTC
56JNP	Sentinel-2	13	10	2018-07-25TZ23:52:59

3 Methods

This section describes the method to derive shallow water depth, habitat classification and shoreline information from optical satellite imagery.

3.1 Satellite-Derived Bathymetry, Method

For this project, we used optical satellite image data to derive bathymetric information for shallow waters. EOMAP applied its proprietary, physics-based inversion method to derive quantitative information of the shallow water bathymetry using the reflected light energy in different wavelengths of the visible and near infrared region. The core algorithm of this retrieval is independent on on-site survey data and is embedded in a standardized workflow (Figure 2) which includes the following steps:

- correct the satellite data for effects of adjacency of the land,
- correct for atmospheric impacts using a coupled retrieval of in-water optical properties (IOP's) and atmosphere (Heege et al. 2014),
- minimize effects of sunglint on the water surface,
- retrieve spatial information on spectral absorption and scattering (in physical units) of water constituents in the water column,
- retrieve spatially resolved information on water depth and seafloor albedo,
- comparison of Satellite-Derived Bathymetry product against USGS ICESat-2 satellite lidar data,
- referencing the bathymetric data to a defined vertical reference (e.g. MSL, LAT) using predicted tidal information of the most nearby station.

The calculation of bathymetric uncertainties is part of the data analysis and involves the uncertainties of the model performance, considering seafloor reflectance intensities, sensor and environmental noise and the decrease of the reflectance intensities with depth.

The method and its workflow are described in more detail in scientific articles and publications and is known as Modular Inversion Program (MIP, Siermann et al. 2014, Wettle et al. 2014, Heege et al. 2014, Hartmann et al. 2019). It allows for mapping bathymetry and benthic habitats up to approx. 1.2 times Secchi Disk depth at time of satellite image recording. The current version includes cutting-edge processes with improved corrections of atmospheric, adjacency and sunglitter impacts (e.g. Kiselev et al. 2015). The system is able to process multiple satellite records if available, taking advantage of a patented approach (US Patent 2017) to reduce the uncertainties and indeterminacies of the various environmental variables through simultaneous retrievals.

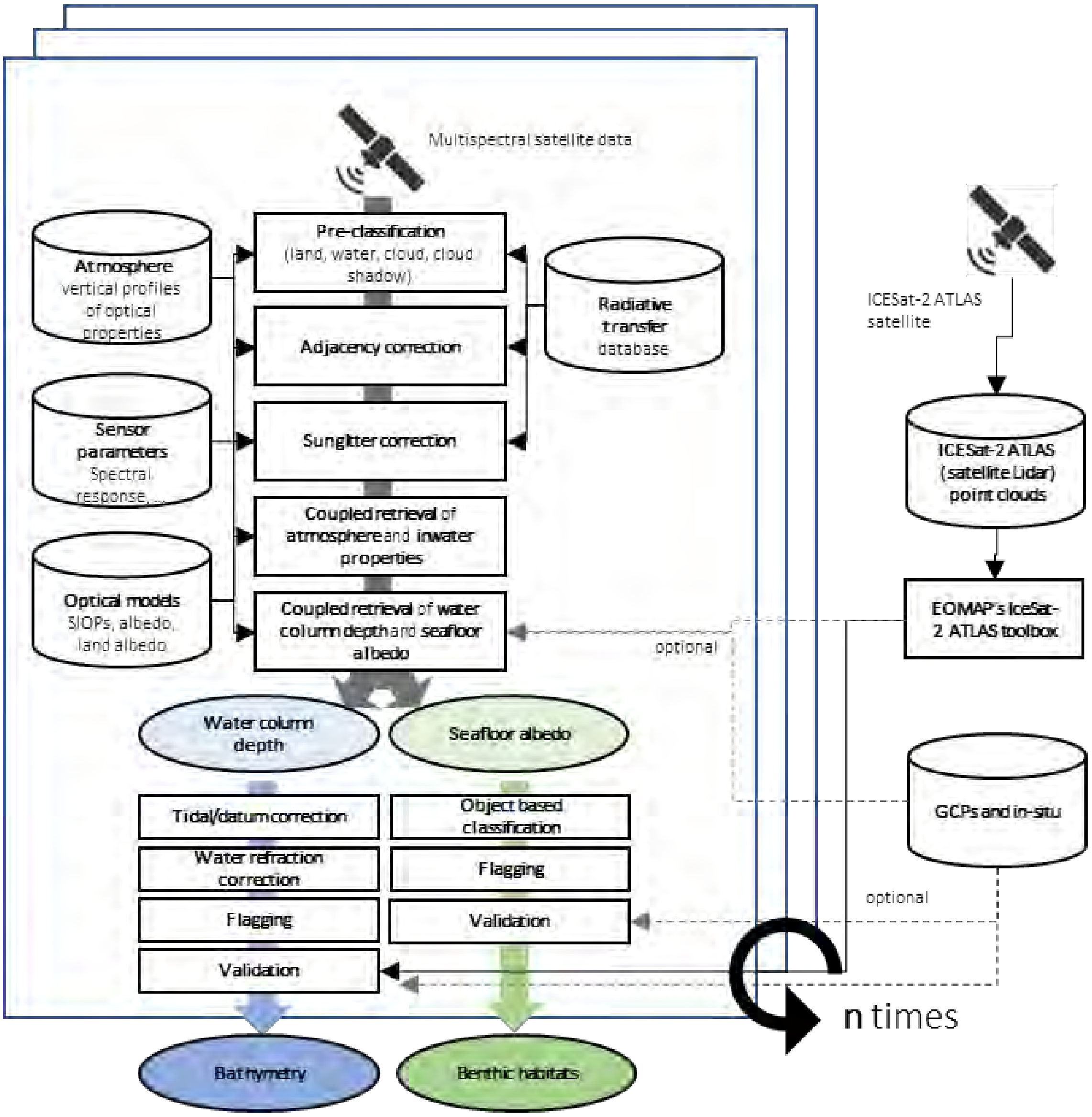


Figure 2: EOMAP's workflow for creating satellite-derived bathymetry and benthic information using optical satellite image data. A set of modules is applied to satellite image radiance data which includes several steps to minimize environmental impacts on the measured spectra. These modules are known as MIP (Modular Inversion Program), which is embedded into EOMAP's Earth Observation Workflow System (EWS), which organizes the modules and processing.

We applied the following tidal values (Table 2) to reference the SDB data to Lowest Astronomical Tide (LAT).

Table 2: List of tidal data applied to the SDB.

Date and time (UTC time) of satellite image recording	Tidal station	Water level at image recording above LAT
2018-07-25TZ23:52:59	Brunswick Heads (6008)	0.7m

3.2 Satellite-Derived Bathymetry, Vertical Uncertainties (VUC)

An error model was applied which allows the extraction of vertical uncertainties for every location. The error model includes the following parameters:

- Uncertainties of the predicted tidal station. This is defined as an absolute offset of +/- 0.2m which can be caused by surge and weather effects. This uncertainty is an external source of error.
- Uncertainties with increasing depth because of
  - Reduced light reflectance intensity with increasing depth which causes higher Signal to Noise ratio. Furthermore, with increasing water depth the spectral range which penetrates the water column is reduced (typically blue and green penetrate deepest, whereas yellow, red and NIR light is limited to shallow waters only).
  - Sea state. With increasing water depth long and high ocean waves can occur which can cause impacts on the SDB grid.
- Uncertainties caused by differences of seafloor reflectance properties. Typically, darker seabed causes higher uncertainties because of the reduced light reflectance whereas brighter seabed performs better.

3.3 Satellite-Derived Bathymetry, QA/QC Procedures

The following QA/QC procedures were applied which included the following items:

- Assessment of the SDB results and check for morphological inconsistencies. This process is a cross check of the generated SDB by comparing the depth penetration of the single wavelengths against spectral analysis and analyst’s knowledge.
- Masking and flagging of biased values or extreme outliers, e.g. in areas without sufficient reflectance form seafloor (optically deep water) or interfering objects and environmental phenomena (e.g. ships, cloud shadows).
- Definition of a spatially varying cut-off depth. Below the cut-off depth, there is no more measurable contribution of the seafloor to the net reflected light signal (optically deep water) and thus, SDB cannot be provided anymore. The cut-off depth is dependent on water clarity and seabed coverage and therefore locally variable. For example, areas with an increased water turbidity or darker seafloor coverage, such as kelp or dark rocks, are like to have a shallower cut-off depth. The cut-off depth is defined by the data analyst typically based on the penetration depth of blue to green light.
- The creation of the standardised geodata delivery to generate relevant and specific ISO conform metadata and geodata.

4 Results

4.1 Bathymetric Data

Bathymetric data were calculated down to a maximum water depth of ~15m (LAT) (Figure 3) at a spatial resolution of 10m. The maximum water depth is dependent on water clarity, especially turbidity, or seafloor type and can vary locally.

Figure 3 illustrates the results of the Satellite-derived Bathymetry processing and Figure 4 illustrates the associated Vertical Uncertainties layer, for the 2018 dataset.

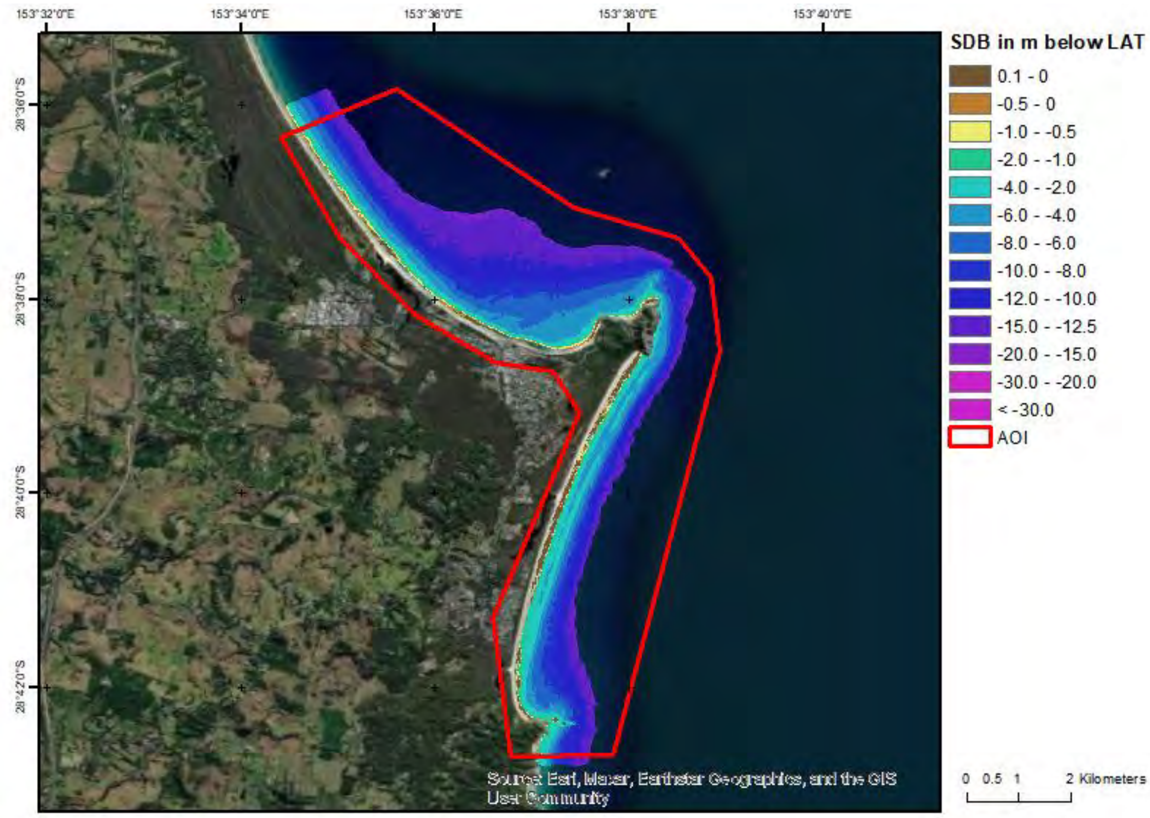


Figure 3: Quicklook of the Satellite-Derived Bathymetry product.

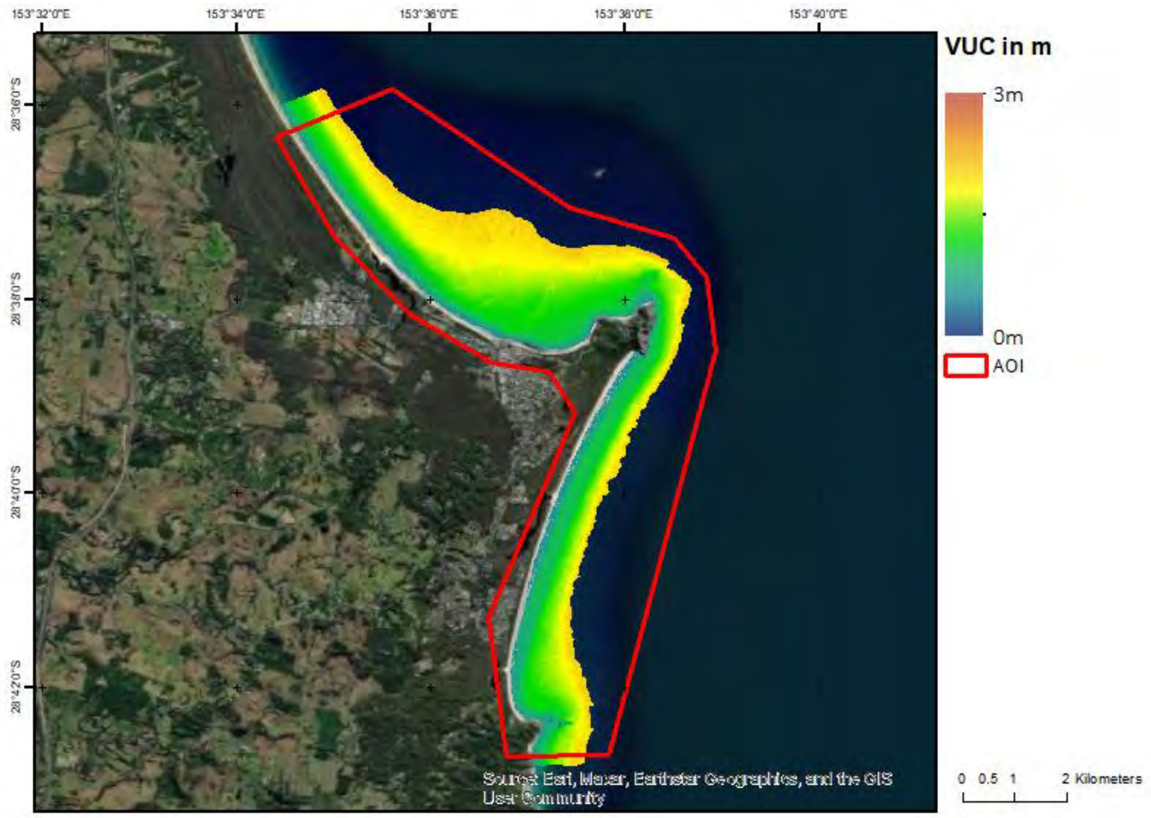


Figure 4: Quicklook of the Vertical Uncertainties product.

The results of the SDB processing have been compared against on-site Lidar data provided by the client (Figure 5). The comparison shows a good overall agreement of SDB and survey data, with 94% of the SDB data being within EOMAP's Standard 1 of +-0.5m +10% of survey data depths. The survey data helped to increase the accuracy of the SDB data especially in the deeper waters along the shore south of Cape Byron, which is often impacted by strong waves. This can lead to resuspension of sediments and slightly increased turbidity even under the best conditions. Water depths shallower than 5m are less impacted, as the light reflection from the seafloor is higher and SDB retrieval therefore less prone to residual turbidity. It is expected that the survey data will also help to stabilise results in deeper waters for potentially upcoming further timestamps, as the seabed dynamics are highest in the shallow water above 5m (moving sand banks) and more stable in deeper waters.

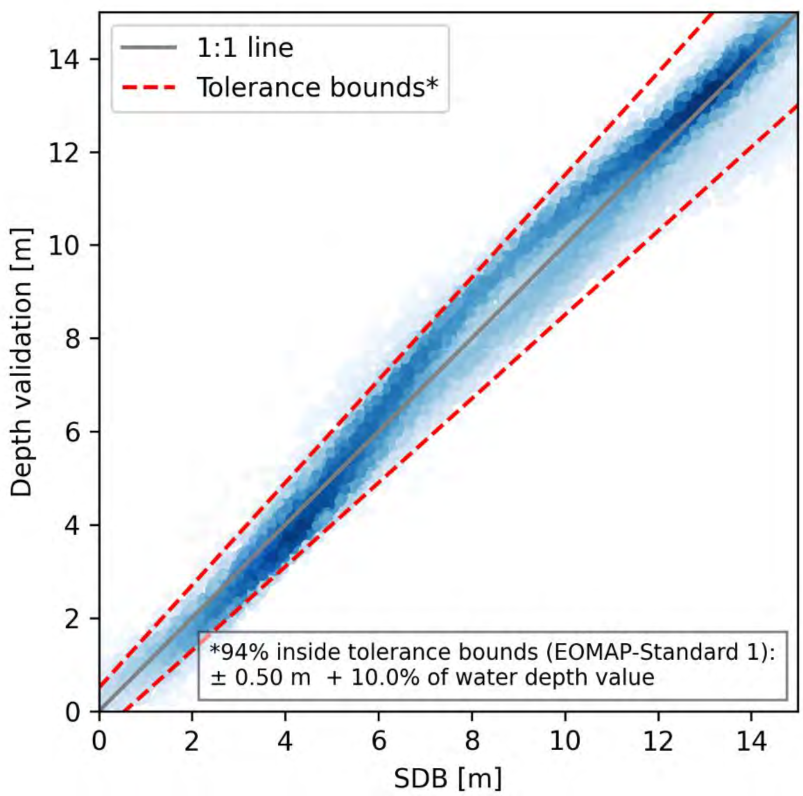


Figure 5: Comparison of SDB vs. client-provided Lidar data

5 Summary

5.1 Satellite-Derived Bathymetry Survey

Table 3: General summary on Satellite-Derived Bathymetry survey

Date of survey (satellite image recording)	2018-07-25
Date of analysis	2023-03-15
Method of analysis	EOMAP's Satellite-Derived Bathymetry method
Spatial resolution of bathymetric surface	10m
SDB Vertical datum	Lowest Astronomical Tide (LAT)
Datum/Projection name	WGS84/UTM56S
Datum/Projection EPSG code	32756
Depth units	Depth in negative meters
Horizontal uncertainties	The horizontal/geolocation uncertainty of the Satellite-Derived Bathymetry data is 10 m CE90.

6 Delivered Files

The delivered files are listed in Table 4 below.

Table 4: List of delivered files

File name	File format	Content
Naming_convention.txt	Text file	Naming convention
DeliveryReport_20221212.1306_BluecoastEngineers_AUS_ByronBay_vs1_20230315.pdf	PDF	Report
\SatelliteDerivedBathymetry		**Satellite-Derived Bathymetry data**
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT.kmz	KMZ	Bathymetry data stored as GoogleEarth Overlay
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_geotiff.tif	GeoTIFF	Bathymetry grid, 32bit floating, depth in neg. m
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_map.pdf	PDF	Bathymetry map
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_metadata.xml	XML	Bathymetry metadata
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_validation.png	PNG	Validation plot
SDB_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_xyz.txt	Text file	ASCII XYZ bathymetry file
\VerticalUncertainties		**Vertical uncertainties**
VUC_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_geotiff.tif	PDF	Vertical uncertainty map
VUC_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_map.pdf	XML	Vertical uncertainty metadata
VUC_AUS_ByronBay_EOMAP_20180725T235259_10m_LAT_metadata.xml	GeoTIFF	Vertical uncertainty grid, 32bit floating

7 References and Further Readings

Athmaram J, Srinivasan S (2017) Acquisition of Satellite Derived Bathymetry Data for Offshore Engineering Projects - Island Case Study. ZADCO SPE-188714-MS (paper can be provided on request)

Cerdeira-Estrada S., Heege, T., Kolb M., Ohlendorf S., Uribe A., Müller A., Garza R., Ressl R., Aguirre R., Marino I., Silva R., Martell, R. (2012): Benthic habitat and bathymetrry mapping of shallow waters in Puerto Morelos reefs using remote sensing with a physics based data processing, Proc. IGARSS, p. 1-4

Dörnhöfer, K., Klinger, P., Heege, T., Oppelt, N. (2017): Multi-sensor satellite and in situ monitoring of phytoplankton development in a eutrophic-mesotrophic lake. Science of the Total Environment 612C (2018) pp. 1200-1214 DOI information: 10.1016/j.scitotenv.2017.08.219

Hartmann K, Heege T, Wettle M, Bindel M (2017) Satellite-derived bathymetry. An effective surveying tool for shallow-water bathymetry mapping. Hydrographische Nachrichten HN108-10. DOI:10.23784/HN108-10Heege, T., Kiselev, V., Wettle, M, Hung, N.N. (2014): Operational multi-sensor monitoring of turbidity for the entire Mekong Delta, International Journal of Remote Sensing, Vol. 35, Issue 8, 2014, p. 2910-2926

Hirschmüller, H. (2008). Stereo processing by semiglobal matching and mutual information. IEEE Transactions on Pattern Analysis and Machine Intelligence, 30(2), 328–341. https://doi.org/10.1109/TPAMI.2007.1166

Hutchinson, M.F., Xu, T. and Stein, J.A. 2011. Recent Progress in the ANUDEM Elevation Gridding Procedure. In: Geomorphometry 2011, edited by T. Hengel, I.S. Evans, J.P. Wilson and M. Gould, S. 19–22. Redlands, California, USA

Jaehoon Jeong, Chansu Yang and Taejung Kim (2015) Geo-Positioning Accuracy Using Multiple-Satellite Images: IKONOS, QuickBird, and KOMPSAT-2 Stereo Images Remote Sens. 2015, 7(4), 4549-4564; doi:10.3390/rs70404549

Kiselev, V., Bulgarelli, B. and Heege, T., 2015. Sensor independent adjacency correction algorithm for coastal and inland water systems. Remote Sensing of Environment, 157: 85-95., ISSN 0034-4257, http://dx.doi.org/10.1016/j.rse.2014.07.025.

Parrish et al 2019. Validation of ICESat-2 ATLAS Bathymetry and Analysis of ATLAS's Bathymetric Mapping Performance. Remote Sens. 2019, 11(14), 1634; https://doi.org/10.3390/rs11141634

Siermann, J., Harvey, C., Morgan, G., & Heege, T. (2014, January 19). Satellite derived Bathymetry and Digital Elevation Models (DEM). International Petroleum Technology Conference. doi:10.2523/17346-MS

US Patent No 9613422 (2017): Using multispectral satellite data to determine littoral water depths despite varying water turbidity. Patent Publication Number 20150310618. Assignee: EOMAP GmbH & Co.KG. Inventor: Thomas Heege

8 Appendix

8.1 File Naming

[Product abbreviation]_[Country code]_[Area]_EOMAP_[Date of satellite image recording]T[Time of satellite image recording]_[Spatial resolution]_[Vertical reference datum]_[Optional]

[Product abbreviation] DSM = Digital Surface Model, DTM = Digital Terrain Model, IMG = Imagery, INT = Intertidal Bathymetry, SDB = Satellite-Derived Bathymetry, SFC = Seafloor Classification, SFR = Seafloor Reflectance, SLB = Satellite Lidar Bathymetry, SSR = Subsurface Reflectance, RGB = True Color Composite Image, VUC = Vertical Uncertainty
[Country code] Country abbreviation following ISO 3166 ALPHA-3 standards
[Area] Area of interest
[Date of satellite image recording] Satellite image date used for the analysis in YYMMDD (YY= Year, MM = Month, DD = Date) in UTC
[Time of satellite image recording] Satellite image time used for the analysis in HHMMSS (HH= Hours, MM = Minute, SS = Seconds) in UTC
[Spatial resolution] in meters; does not apply for SLB.
[Vertical reference datum] Vertical reference datum such as Mean Sea Level (MSL) or Lowest Astronomical Tide (LAT)
[Optional] An optional parameter which is used to support the intuitive use of the data, such as 'metadata' or 'xyz' for metadata files and ASCII XYZ files

Or in case multiple recordings were used for the analysis:

[Product abbreviation]_[Country code]_[Area]_EOMAP_[Start recording date]_[End recording date]_[Spatial resolution]_[Vertical reference datum]_[Optional]

[Product abbreviation] DSM = Digital Surface Model, DTM = Digital Terrain Model, IMG = Imagery, INT = Intertidal Bathymetry, SDB = Satellite-Derived Bathymetry, SFC = Seafloor Classification, SFR = Seafloor Reflectance, SLB = Satellite Lidar Bathymetry, SSR = Subsurface Reflectance, RGB = True Color Composite Image, VUC = Vertical Uncertainty
[Country code] Country abbreviation following ISO 3166 ALPHA-3 standards
[Area] Area of interest
[Start recording date] First satellite image date used for the analysis in YYMMDD (YY= Year, MM = Month, DD = Date) in UTC
[End recording date] Last satellite image date used for the analysis in YYMMDD (YY= Year, MM = Month, DD = Date) in UTC
[Spatial resolution] in meters; does not apply for SLB.
[Vertical reference datum] Vertical reference datum such as Mean Sea Level (MSL) or Lowest Astronomical Tide (LAT)
[Optional] An optional parameter which is used to support the intuitive use of the data, such as 'metadata' or 'xyz' for metadata files and ASCII XYZ files.

Attachment 3: Survey analysis results

(refer to main Stage 2 report for analysis cell extents)

Longshore zone	ID	AREA (m^2)	Volume (m^3) change 2018	2019	2020	2021	2022
Tallows Beach	TB-5-1	81,470	-	8,021	2,220	5,384	2,066
	TB-5-2	432,181	-	296,406	55,634	149,375	270,121
	TB_LS	8,549,119	-	NA	NA	NA	NA
Cape Byron	CaB-1-1	324,169	-	247,864	162,954	40,997	273,601
	CaB-2-1	236,256	-	-4,169	-60,963	-185,913	-14,988
	CB-BYPASS	337,923	-	88,178	-76,668	32,954	199,304
	CB-LS	334,319	-	NA	NA	NA	NA
Southern Byron embayment	WB-1-1	26,753	-	302	-2,477	11,954	17,461
	WB-1-2	162,695	-	56,152	138,378	126,188	154,124
	WB-1-3	382,316	-	NA	NA	NA	NA
	CB-1-1	78,613	-	26,925	27,276	-54,348	-1,787
	CB-1-2	215,344	-	159,674	21,612	-317,960	-265,383
	CB-1-3	553,955	-	NA	NA	NA	NA
	MB-1-1	79,953	-	-10,141	16,097	58,936	57,315
	MB-1-2	128,193	-	156,838	195,739	35,112	-11,699
	MB-1-3	552,848	-	NA	NA	NA	NA
Nouthern Byron embayment	BB-1-1	91,903	-	5,306	-54,697	5,492	88,760
	BB-1-2	116,600	-	51,009	94,669	168,905	128,063
	BB-1-3	476,481	-	NA	NA	NA	NA
	BB-2-1	52,954	-	339	1,527	25,743	41,614
	BB-2-2	122,725	-	41,351	45,848	34,383	125,111
	BB-2-3	243,663	-	NA	NA	NA	NA
	BB-3-1	70,600	-	971	-14,842	29,415	35,265
	BB-3-2	112,075	-	83,103	78,033	65,563	115,782
	BB-3-3	187,576	-	NA	NA	NA	NA
	BC-1-1	45,685	-	763	-20,111	9,146	11,538
	BC-1-2	67,891	-	90,675	53,890	63,586	68,445
	BC-1-3	121,461	-	NA	NA	NA	NA

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

Beach profiles for each beach section

Figure 134 to Figure 137 map the cross-shore (shore-normal) beach profile lines used in the probabilistic erosion and recession hazard model for the Byron Shire.

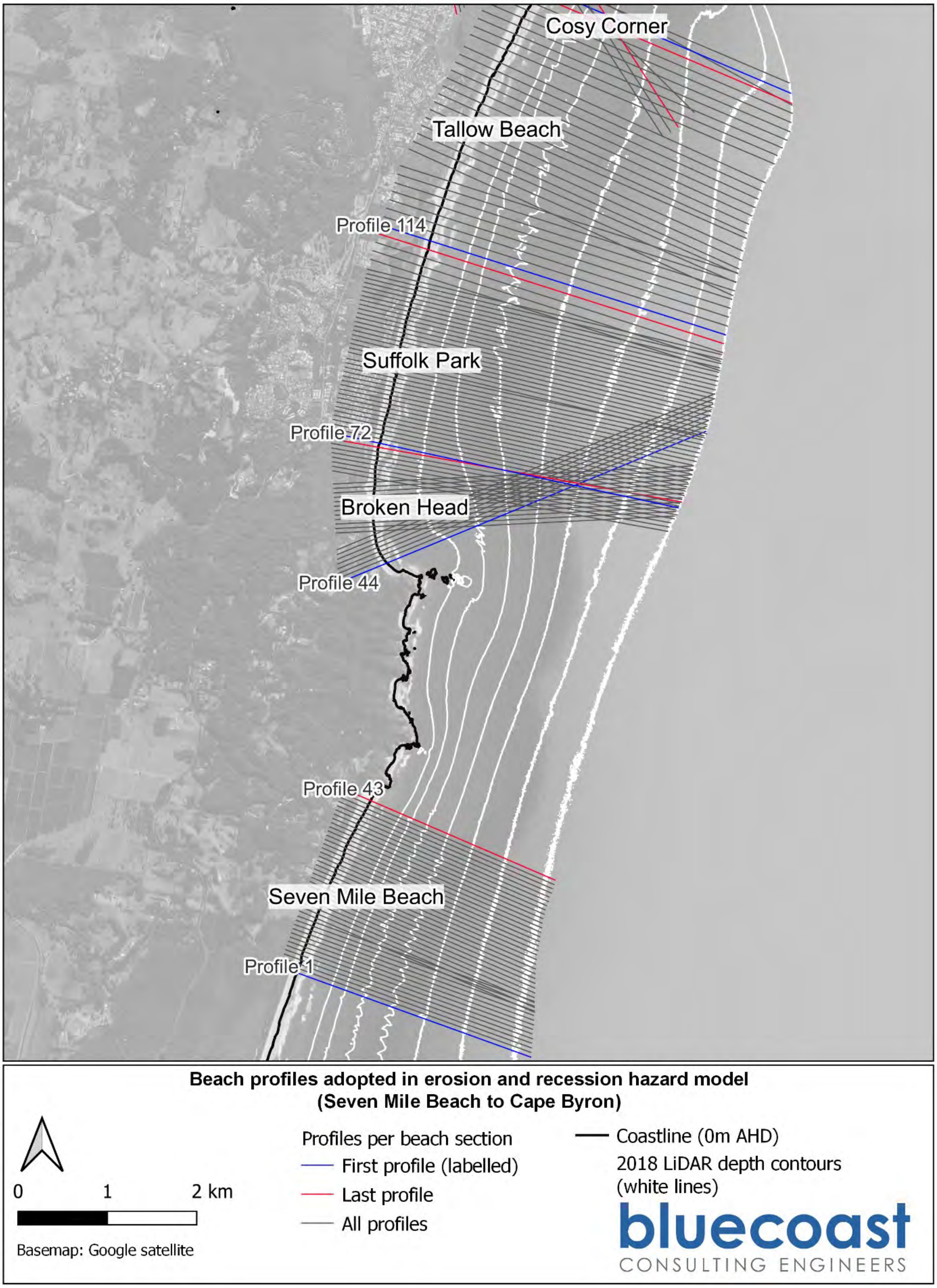


Figure 134: Hazard model profiles for Seven Mile Beach to Cape Byron.

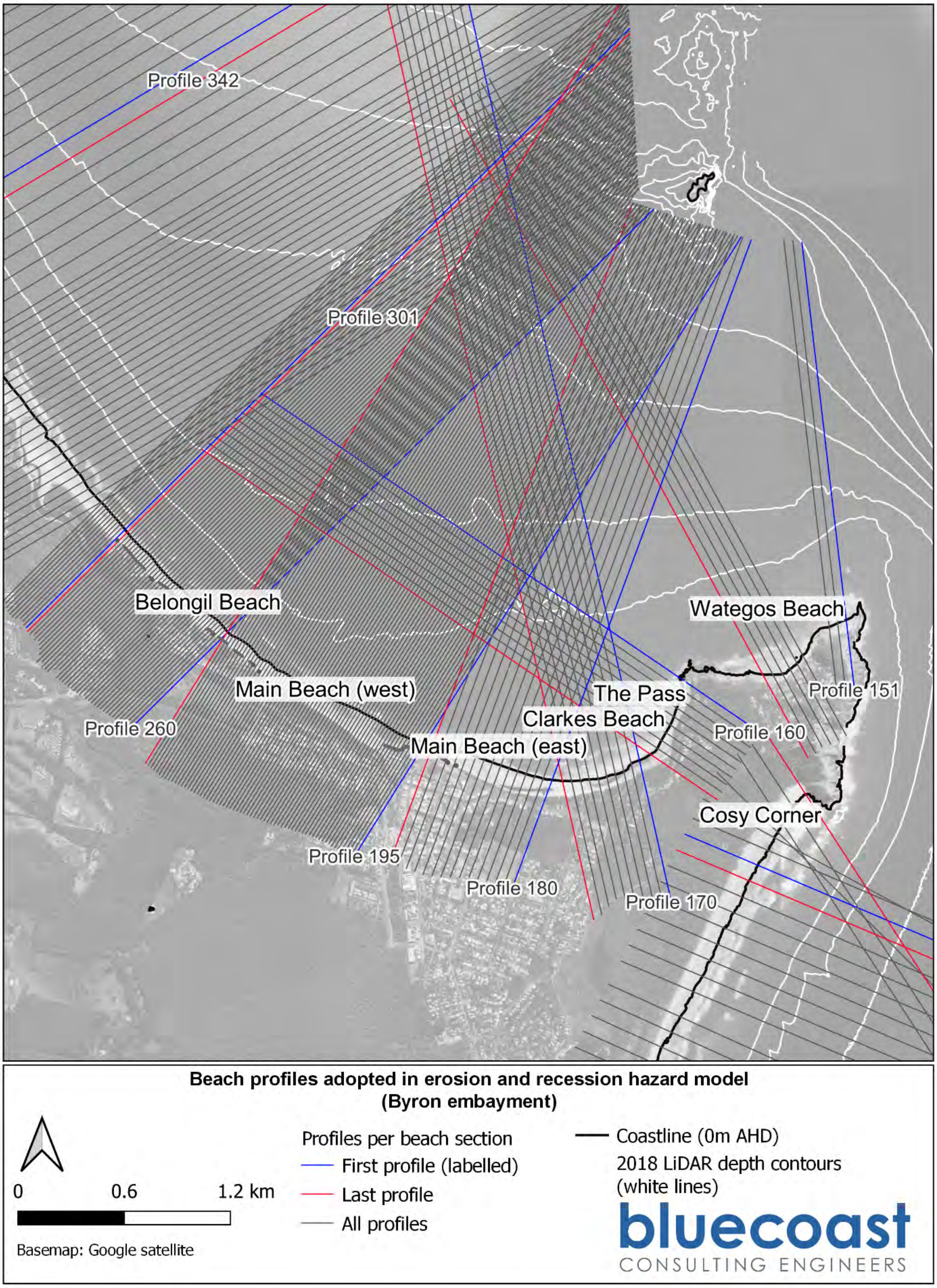


Figure 135: Hazard model profiles for the Byron embayment.

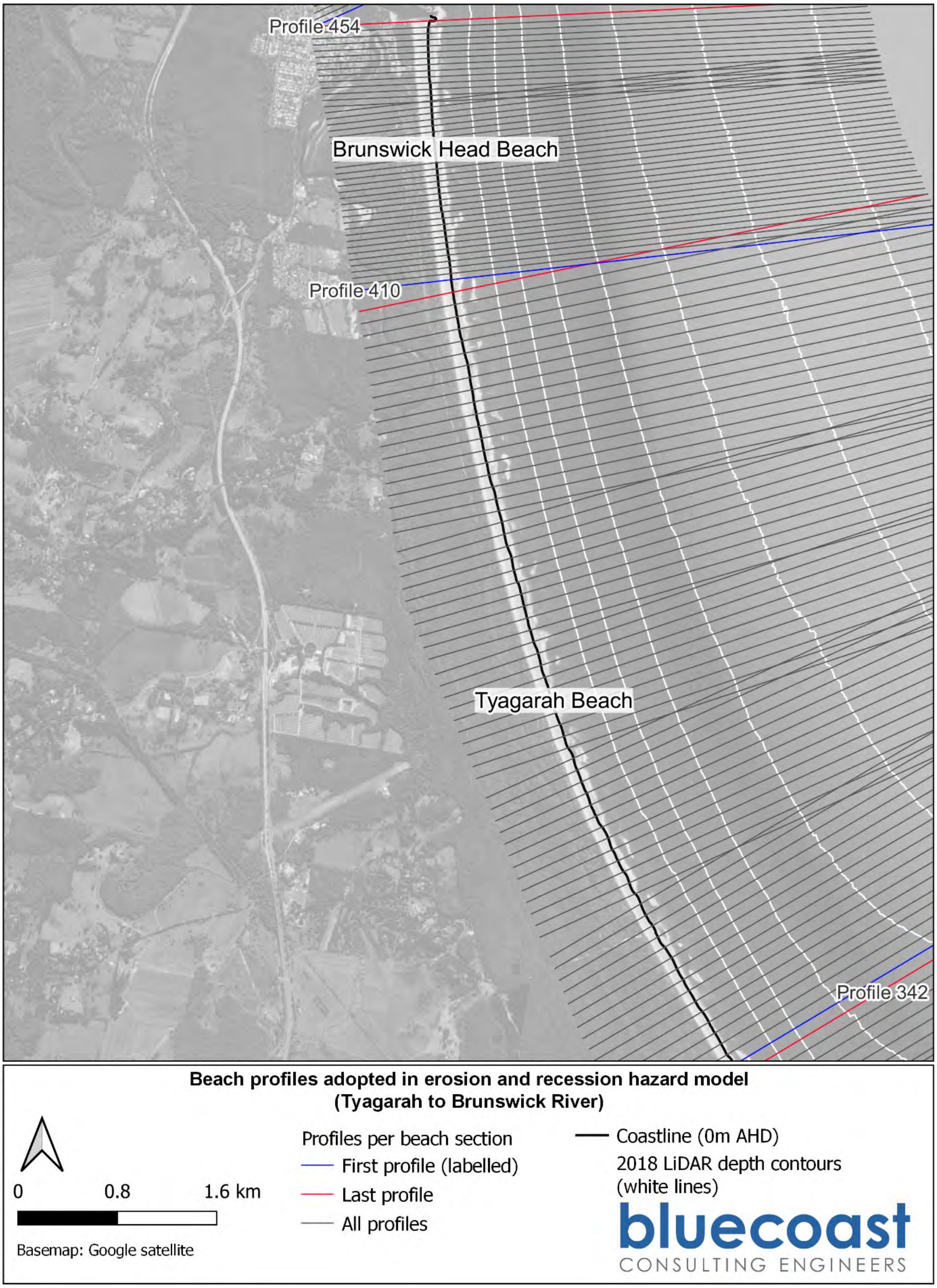


Figure 136: Hazard model profiles for Tyagarah to Brunswick River.

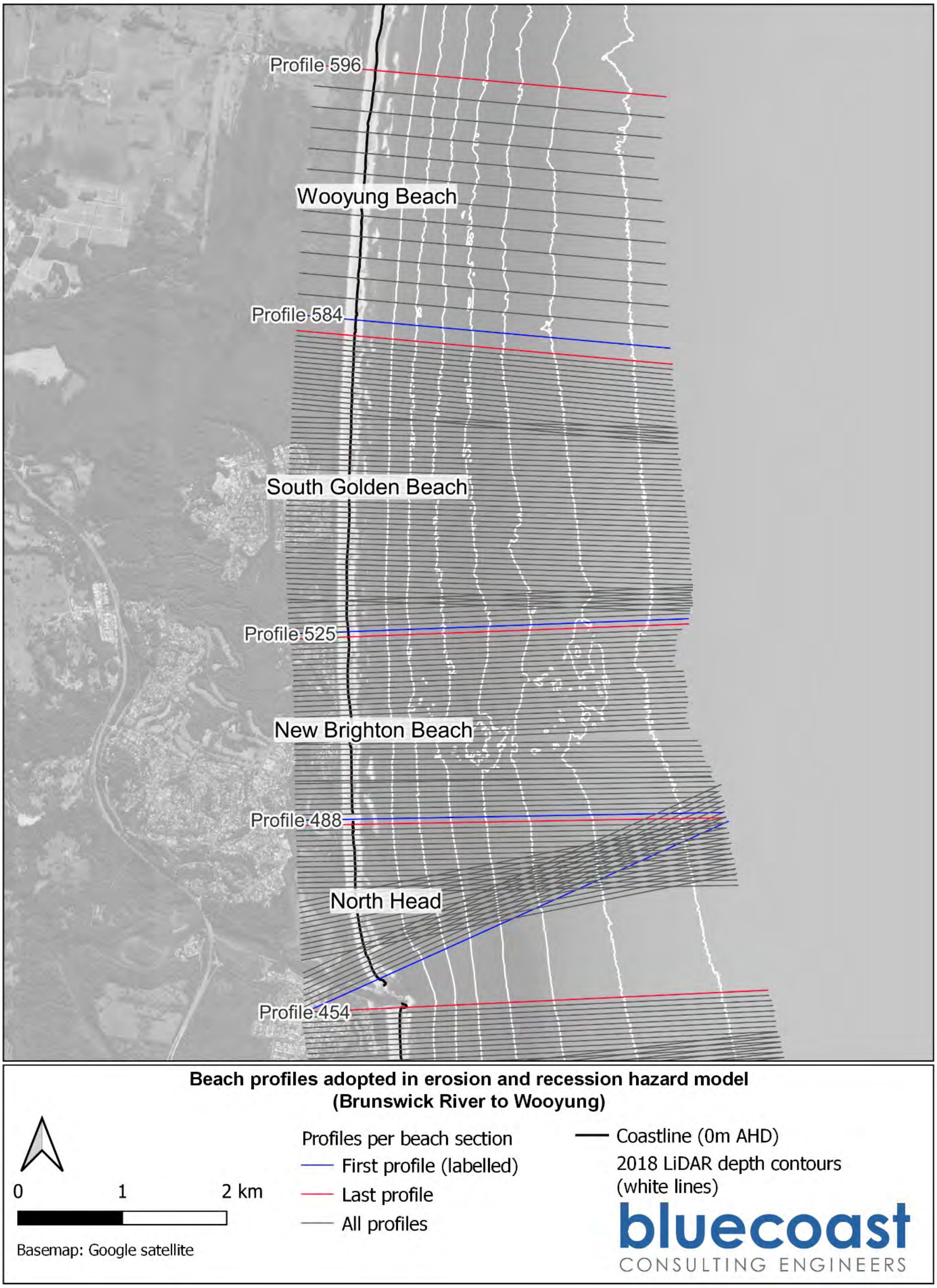


Figure 137: Hazard model profiles for Brunswick River to Wooyung.

Model results for each beach section

The probability of exceedance curves of the landward position of the ZRFC for each beach section across the five planning timeframes (immediate, 2040, 2050, 2070 and 2120) are presented below. The distance (m) from 0m AHD (2018 baseline) is used to define the landward position of the ZRFC and was calculated for each profile. Figure 138 to Figure 155 show representative results for each of the 18 beach sections (refer to limitations discussed in Section 5.4). By exception, the Wategos Beach results (Figure 143) shows the ZSA landward position (instead of ZRFC) due to the steep bedrock topography as discussed in Section 5.4.

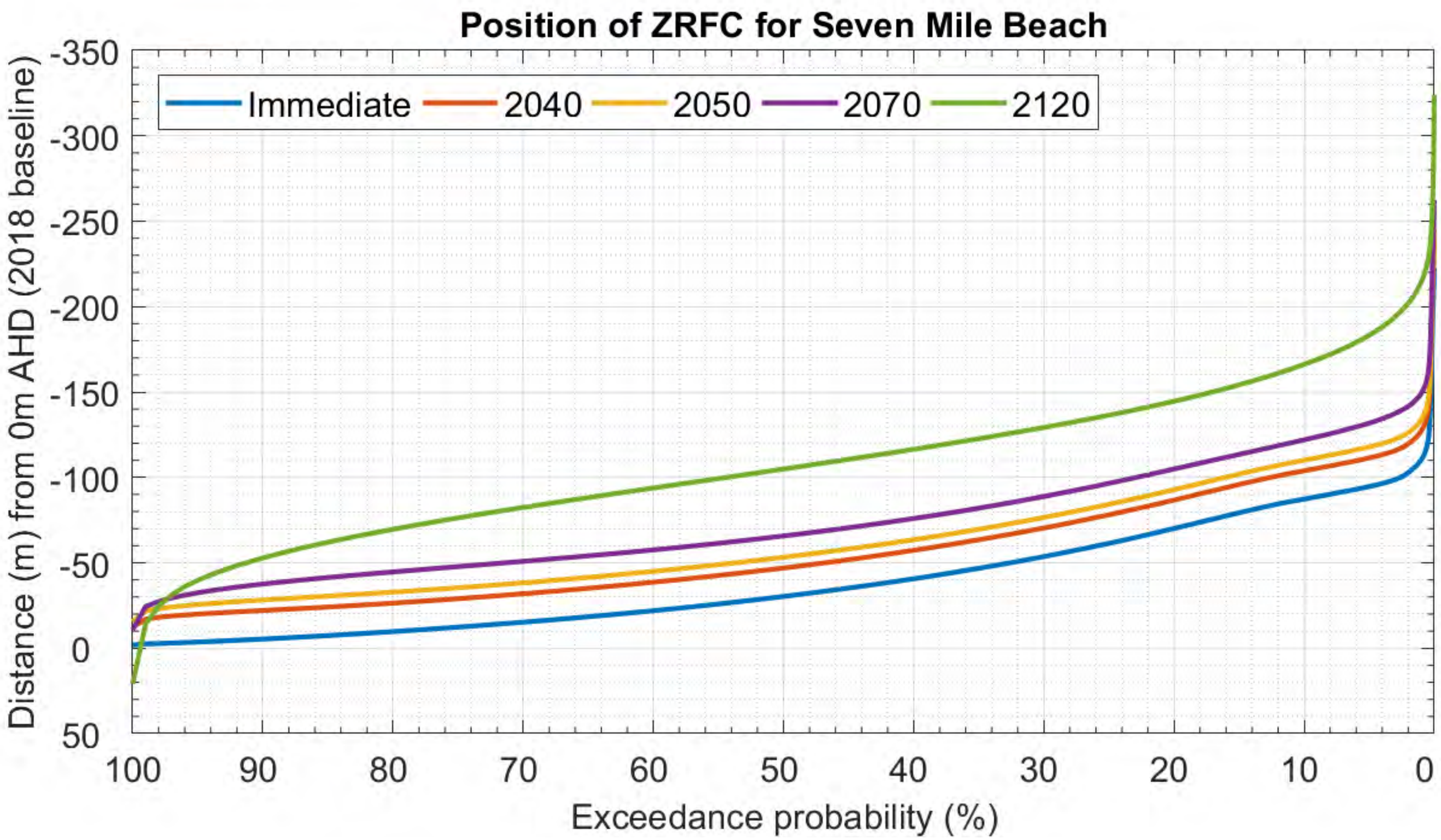


Figure 138: ZRFC probability exceedance curves for Seven Mile Beach (profile 22).

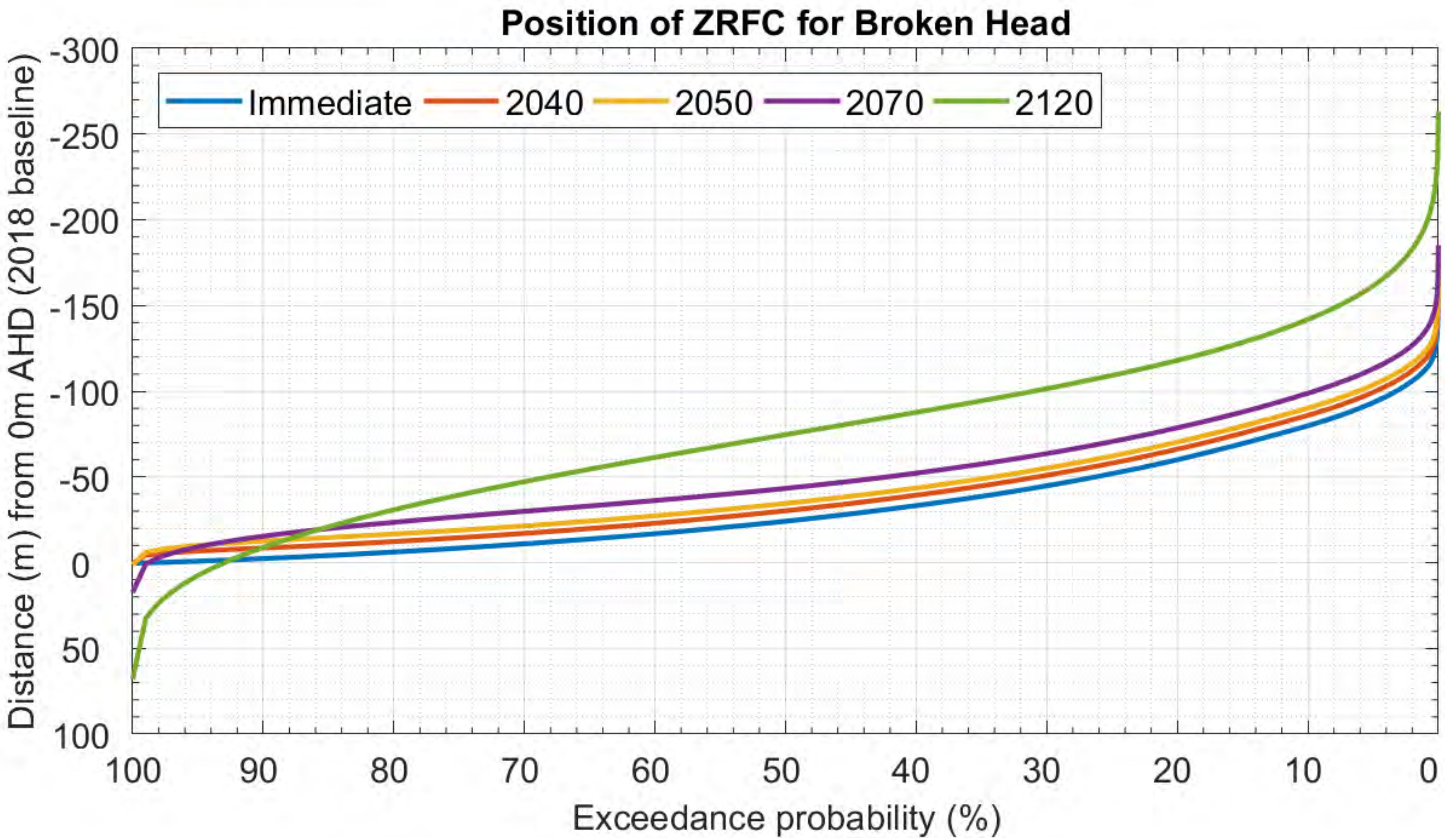


Figure 139: ZRFC probability exceedance curves for Broken Head (profile 57).

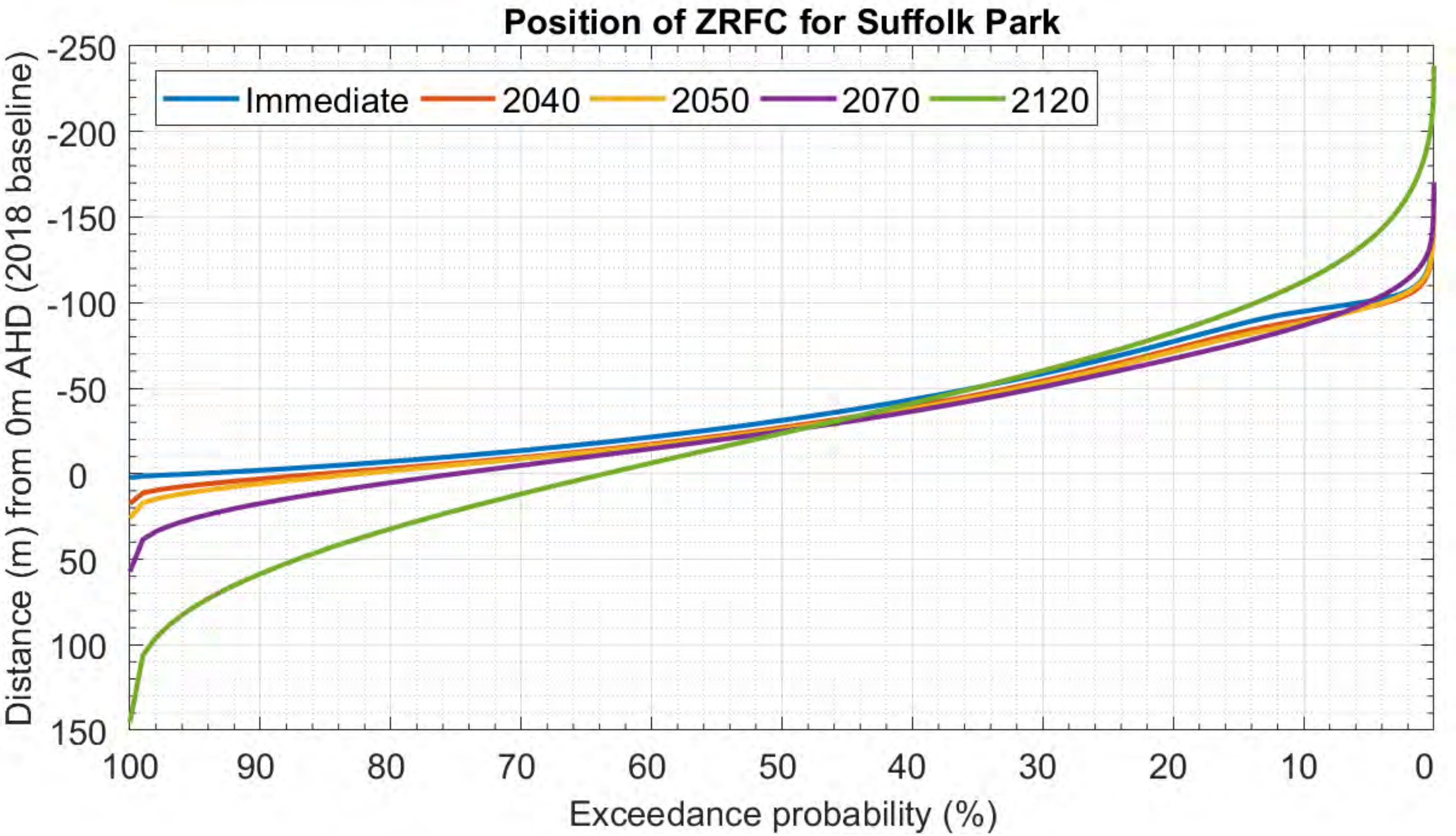


Figure 140: ZRFC probability exceedance curves for Suffolk Park (profile 92).

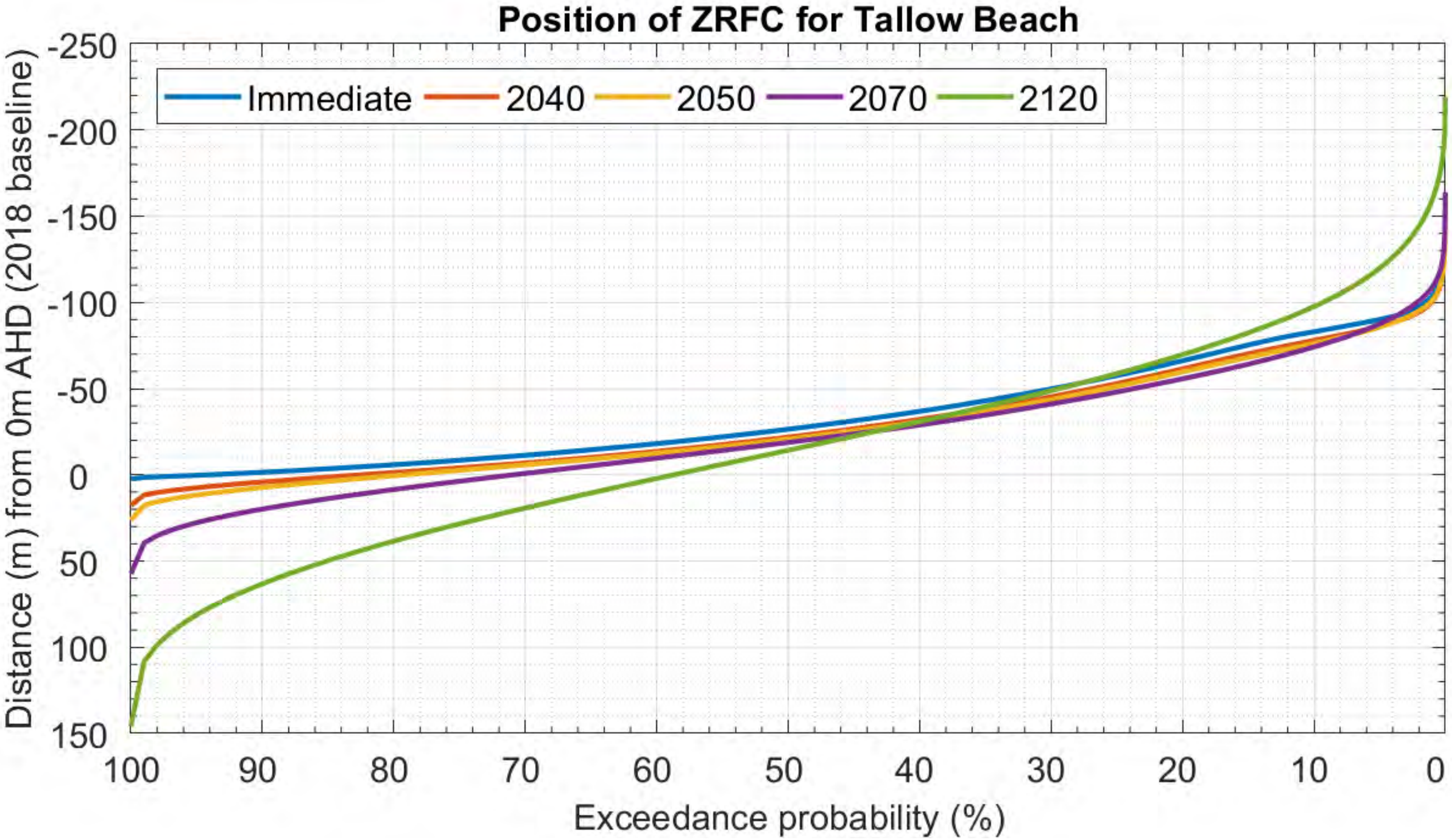


Figure 141: ZRFC probability exceedance curves for Tallow Beach (profile 128).

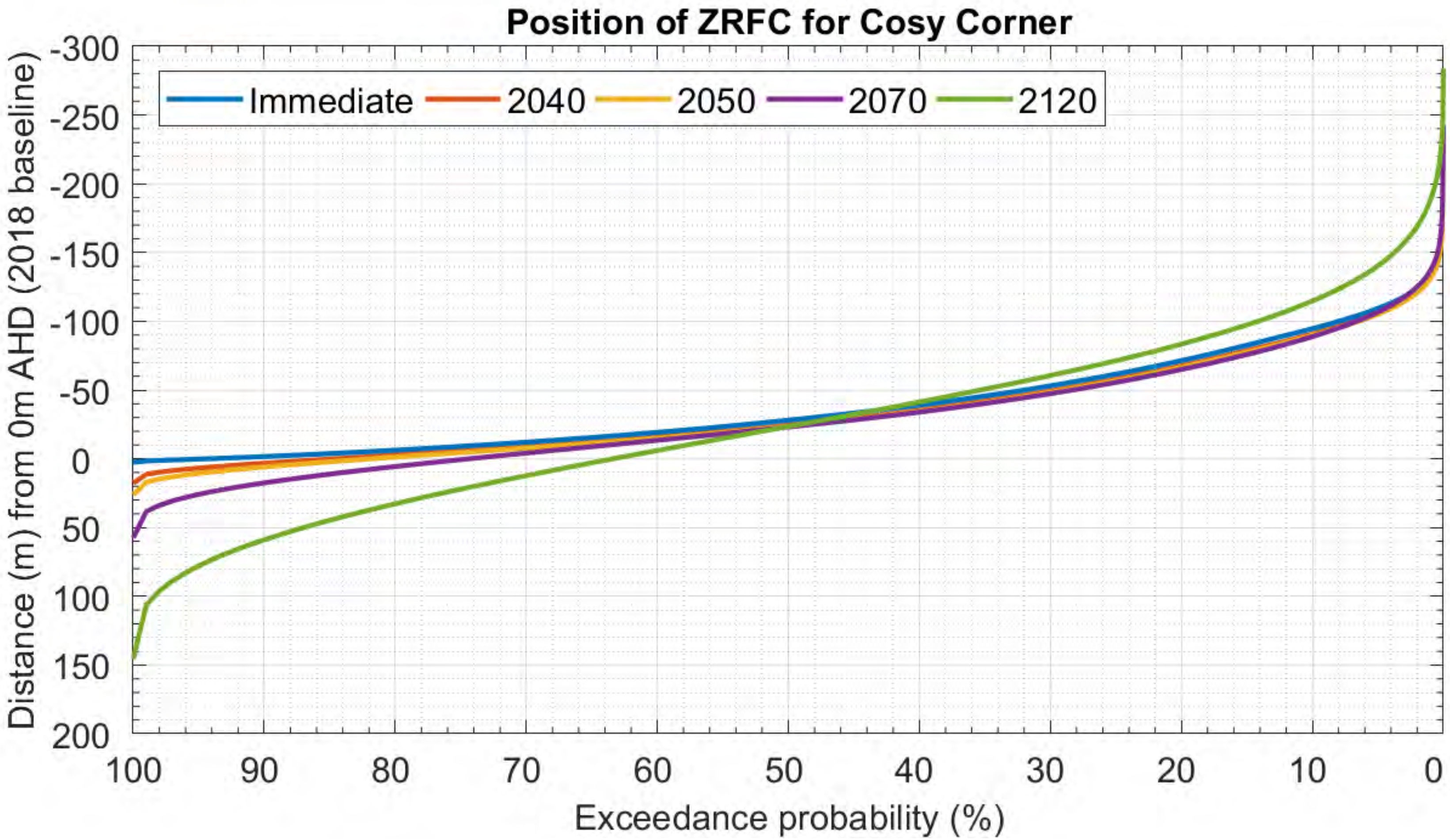


Figure 142: ZRFC probability exceedance curves for Cosy Corner (profile 147).

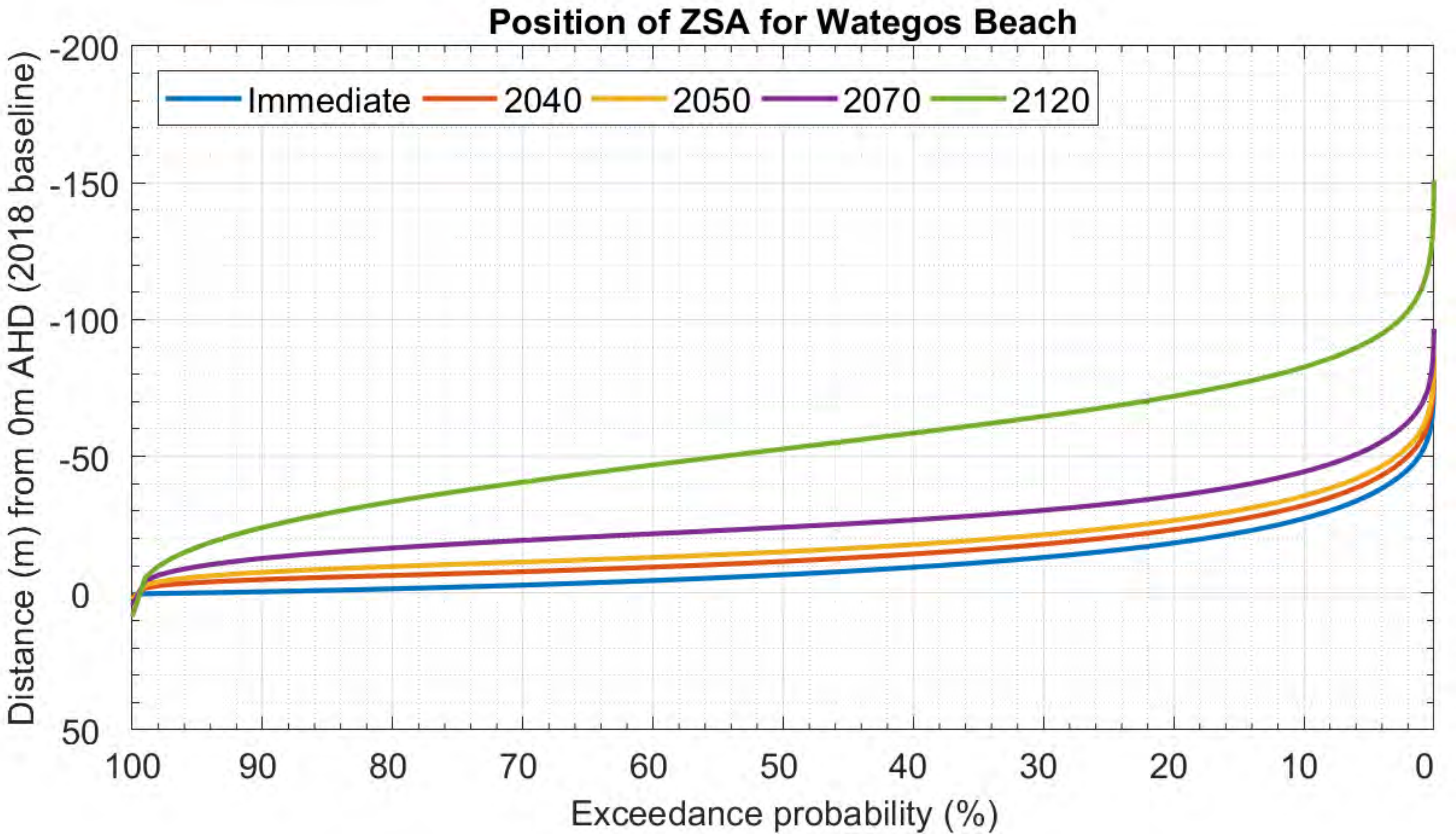


Figure 143: ZSA probability exceedance curves for Wategos Beach (profile 155).

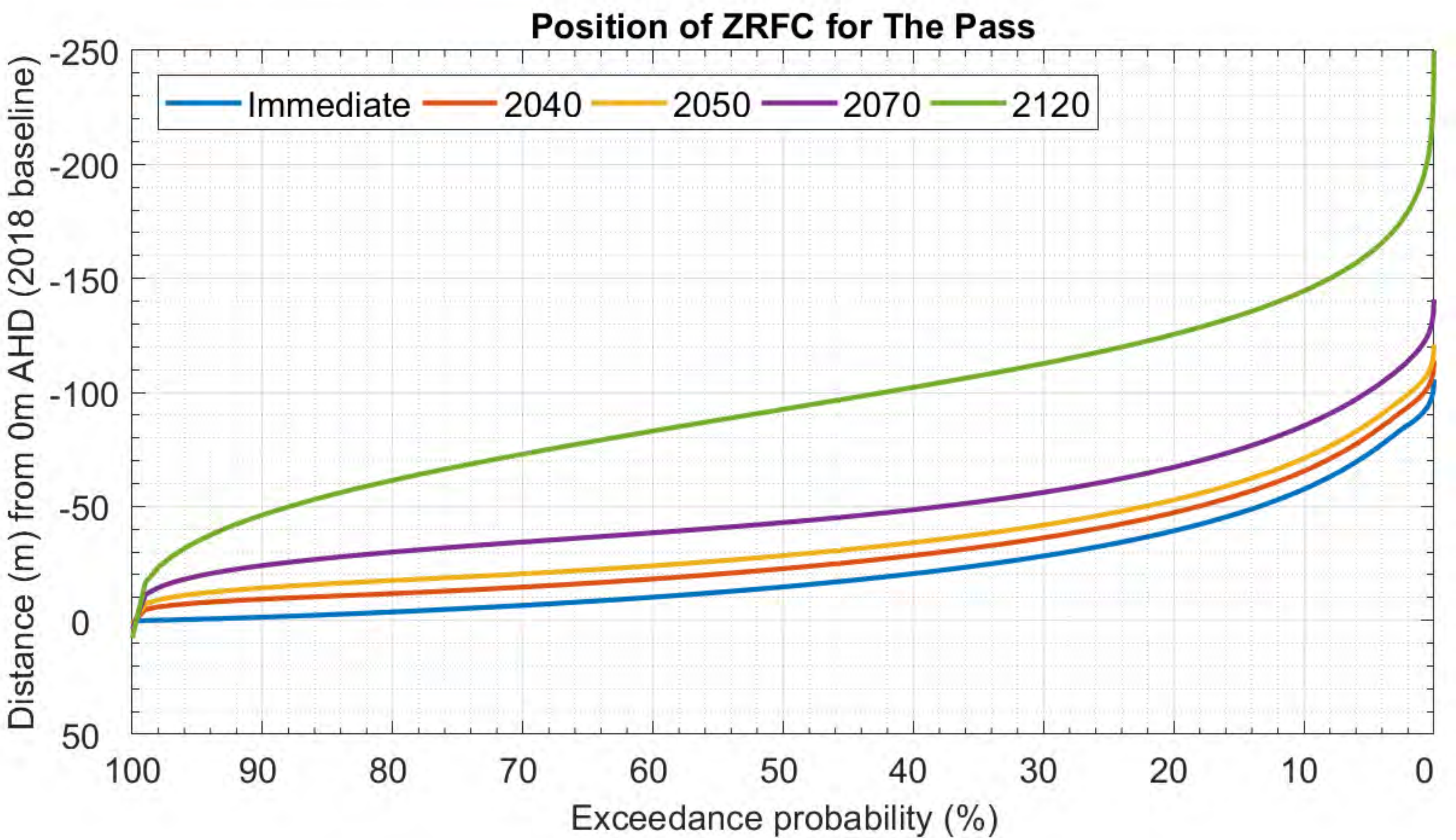


Figure 144: ZRFC probability exceedance curves for The Pass (profile 164).

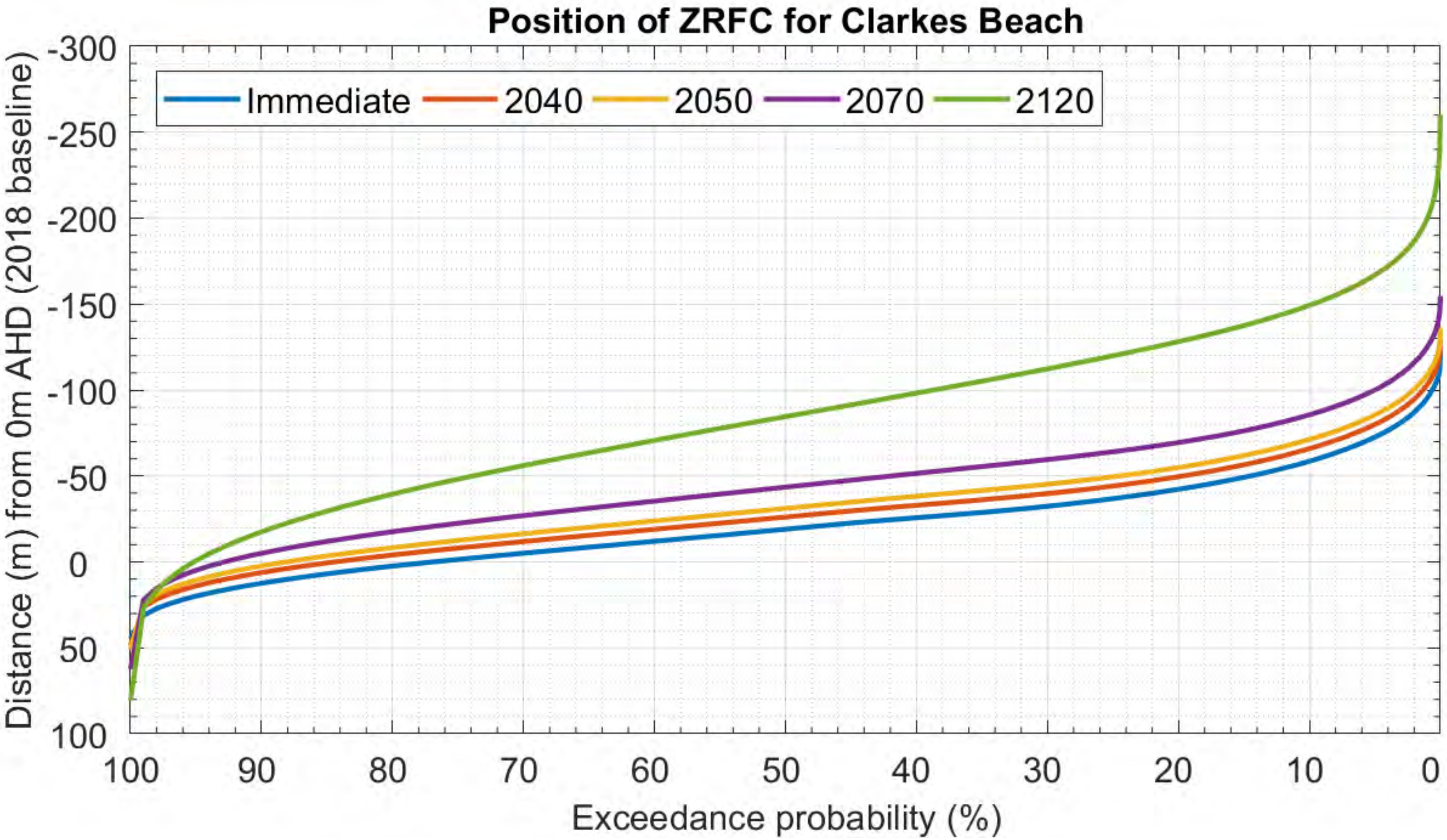


Figure 145: ZRFC probability exceedance curves for Clarkes Beach (profile 174).

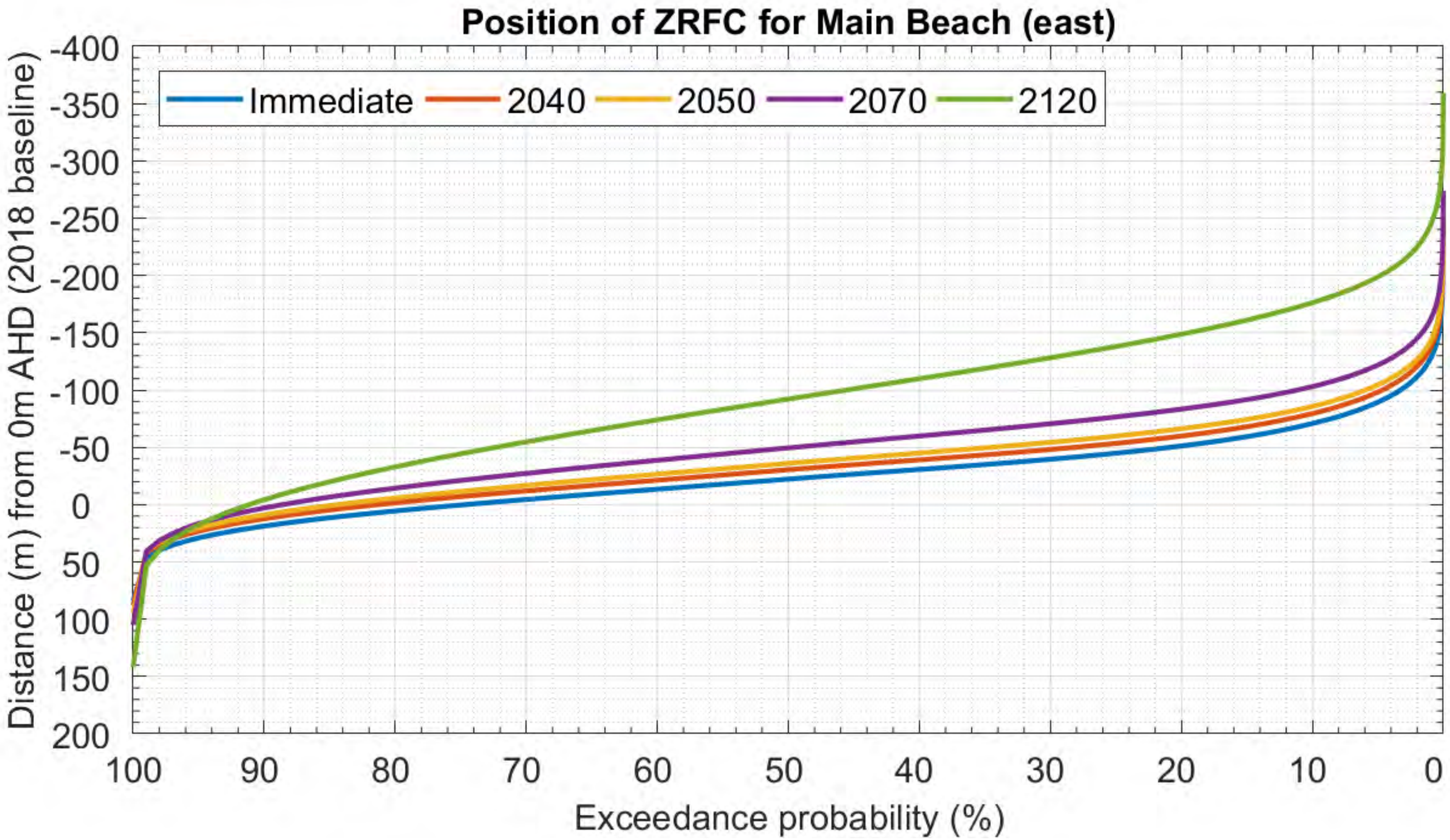


Figure 146: ZRFC probability exceedance curves for Main Beach (east) (profile 187).

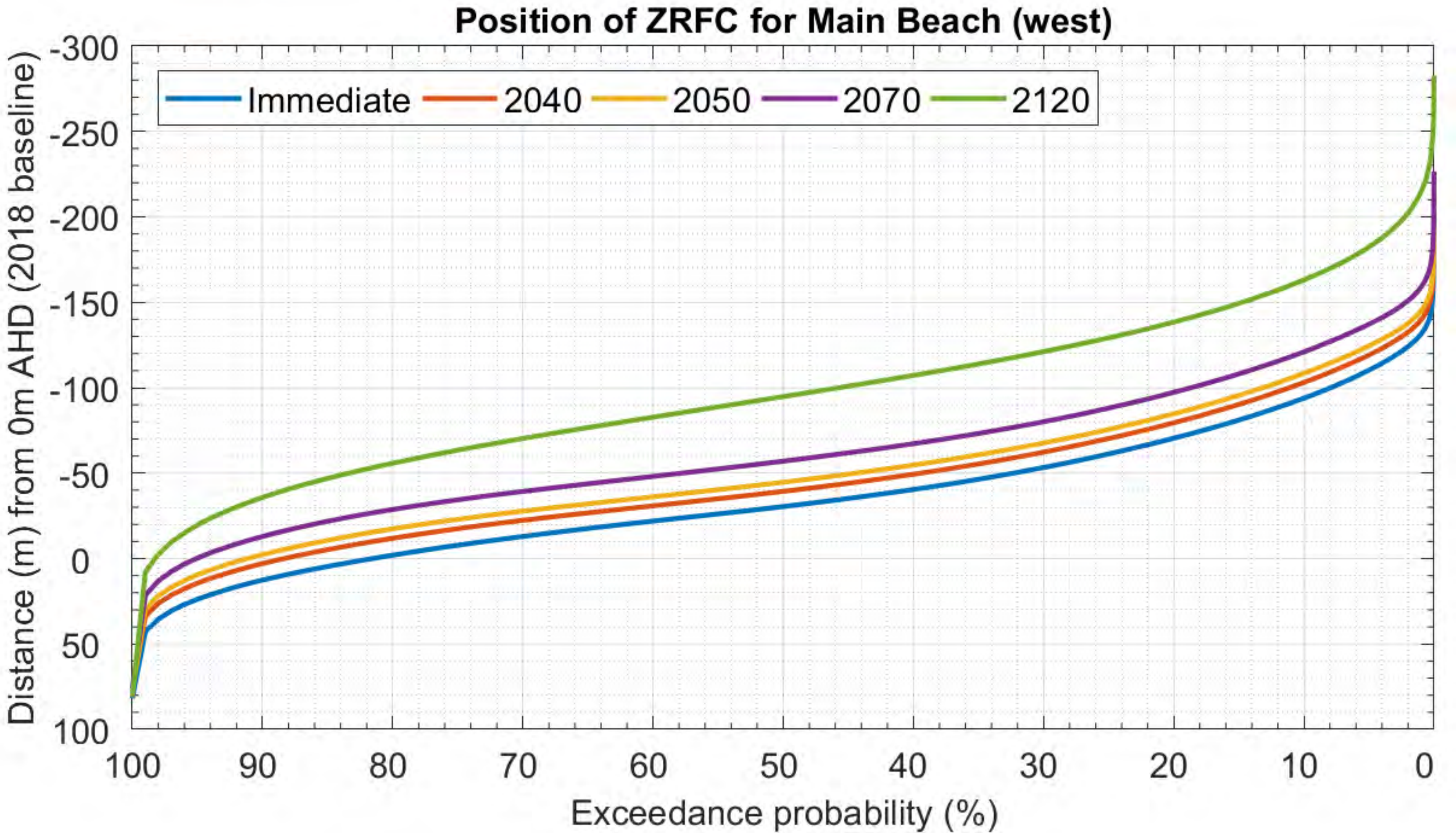


Figure 147: ZRFC probability exceedance curves for Main Beach (west) (profile 227).

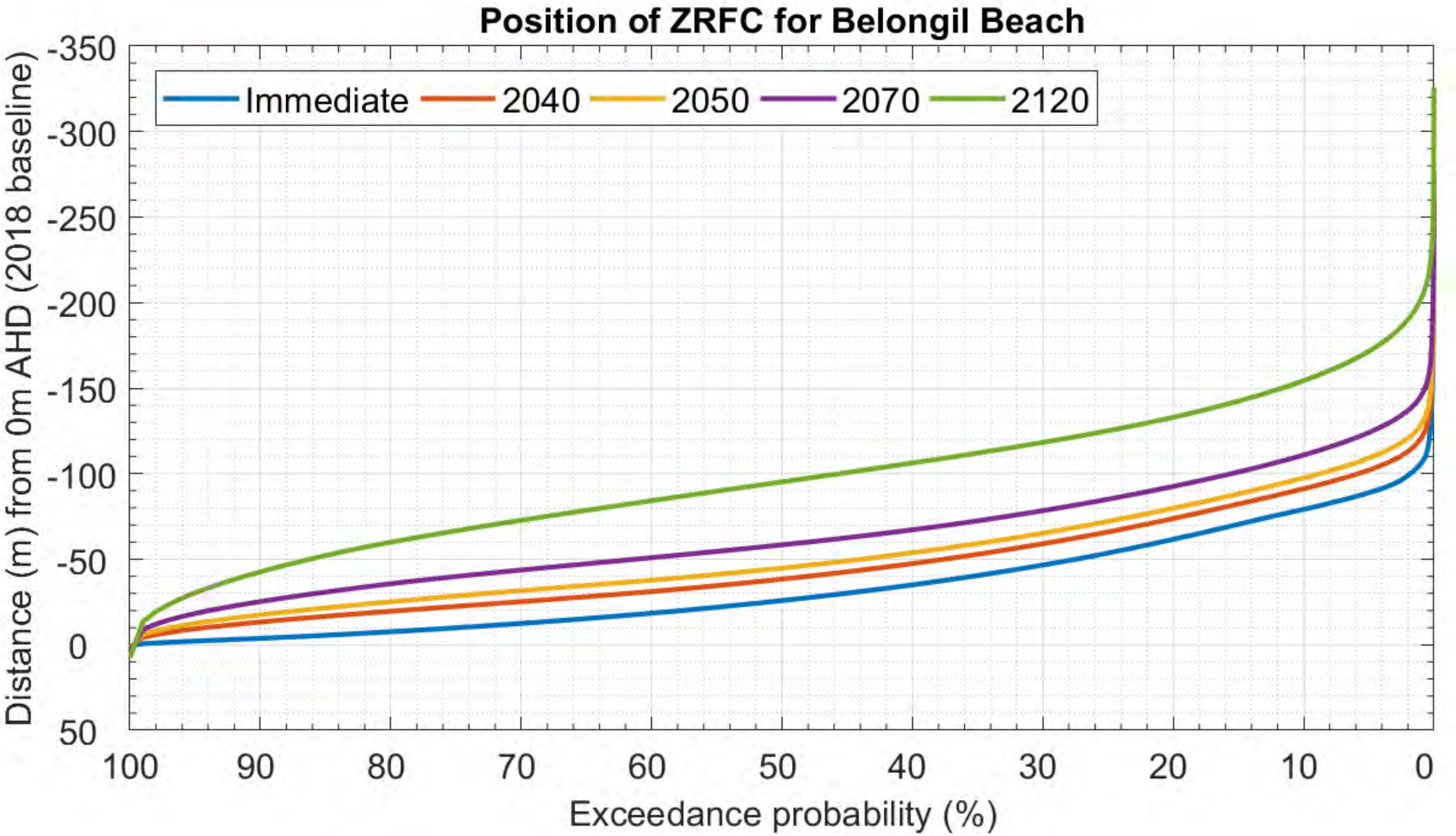


Figure 148: ZRFC probability exceedance curves for Belongil Beach (profile 270).

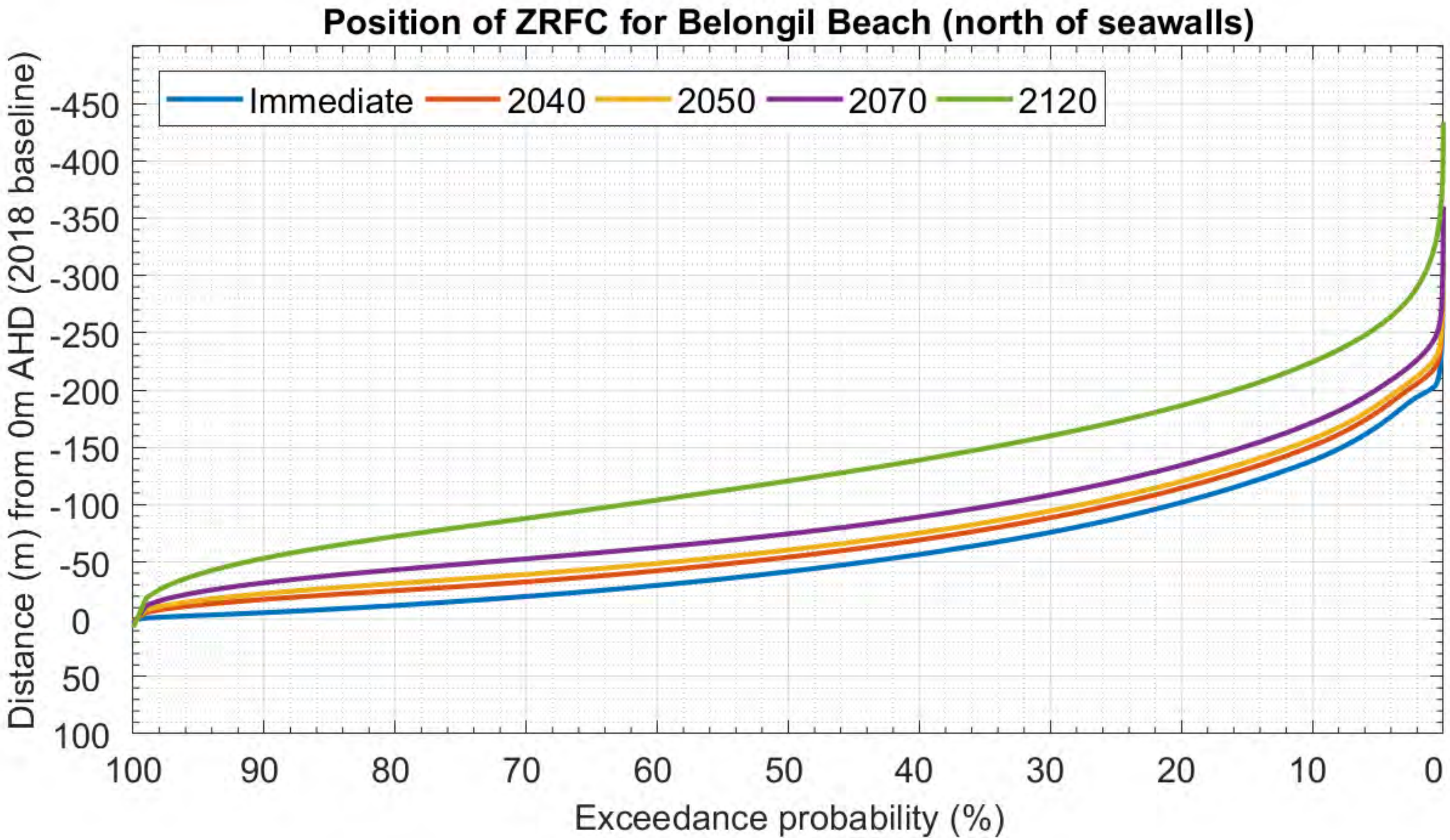


Figure 149: ZRFC probability exceedance curves for Belongil Beach (north of seawalls) (profile 321).

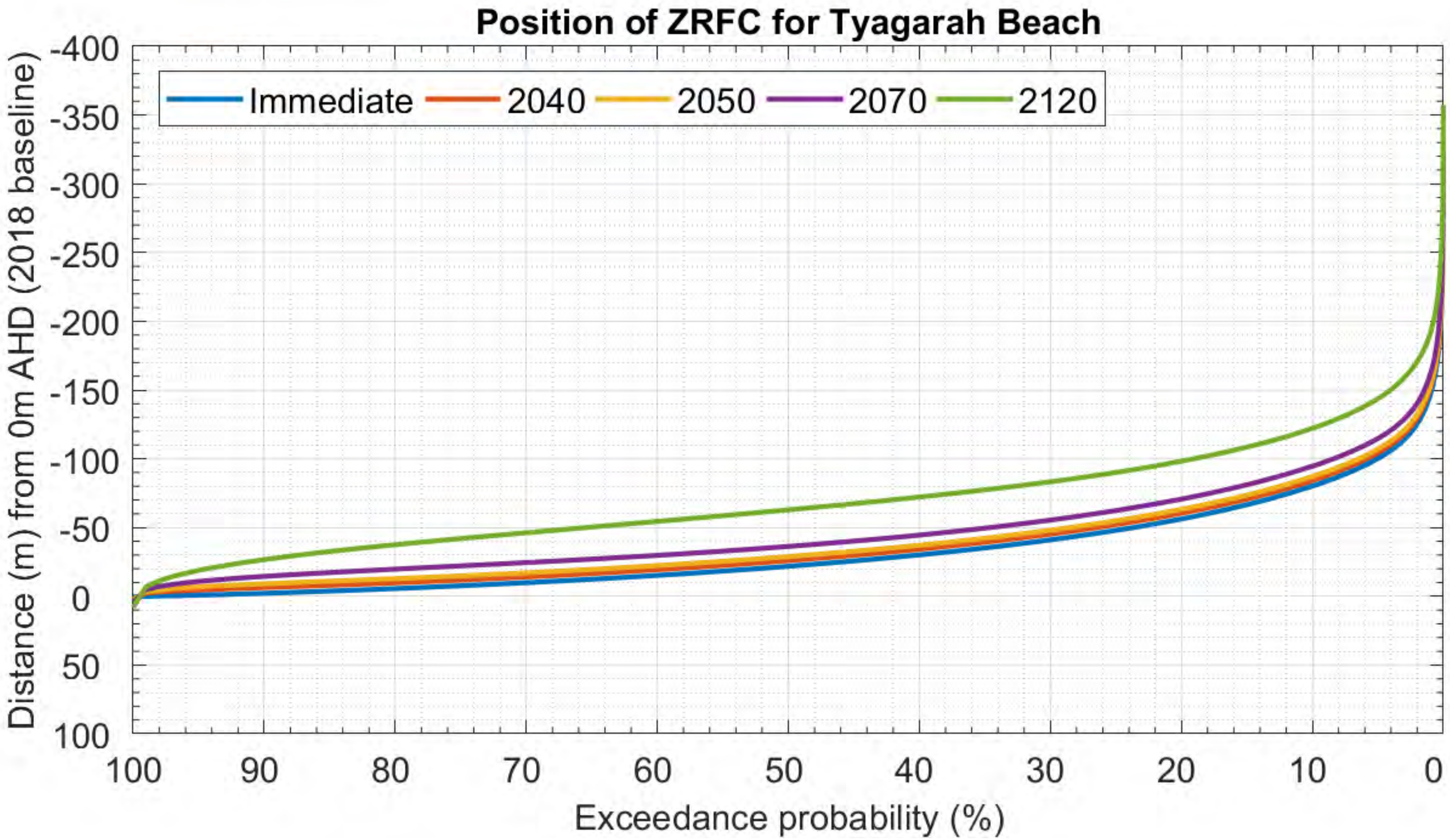


Figure 150: ZRFC probability exceedance curves for Tyagarah Beach (profile 375).

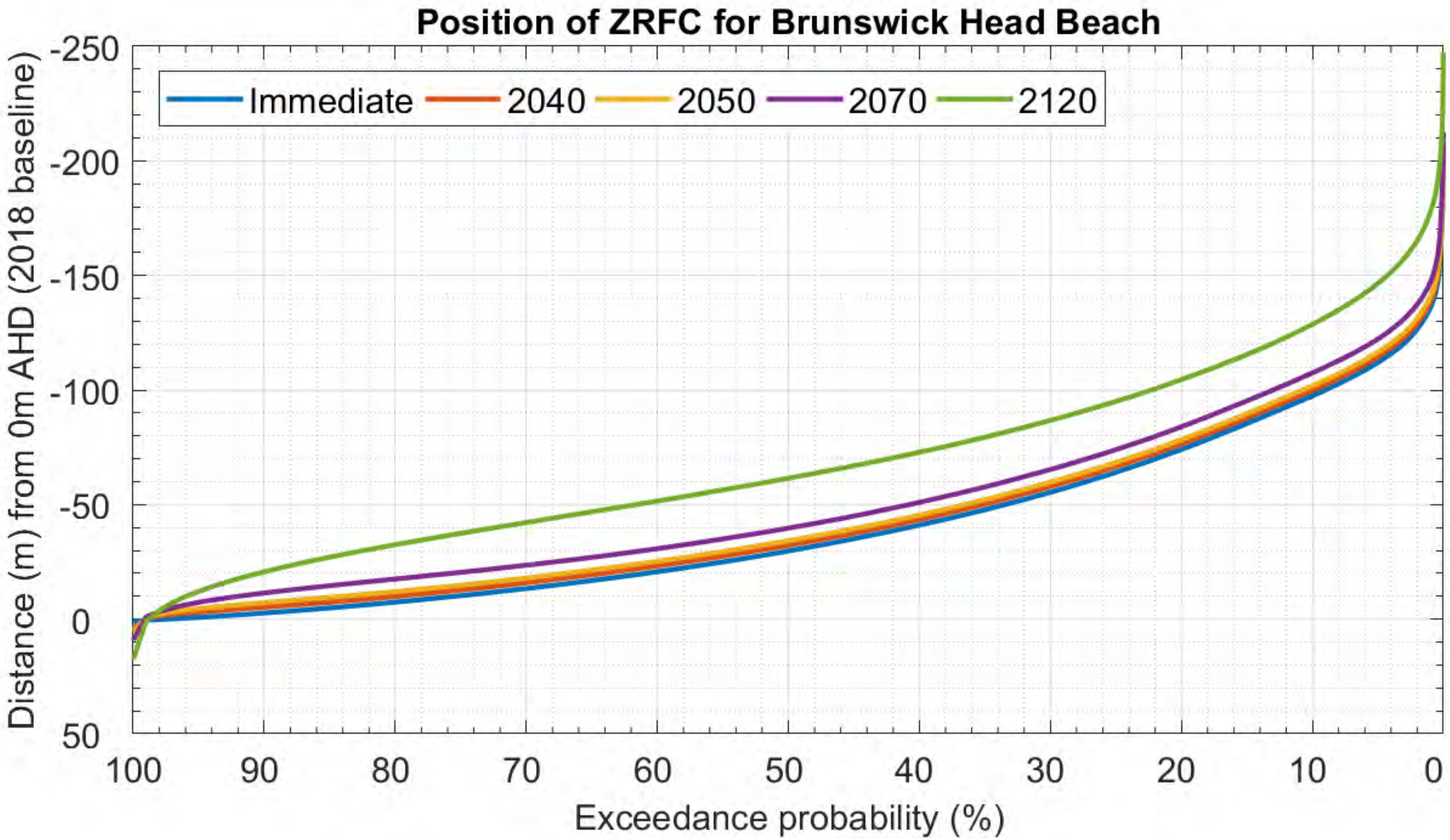


Figure 151: ZRFC probability exceedance curves for Brunswick Head Beach (profile 431).

bluecoast
CONSULTING ENGINEERS

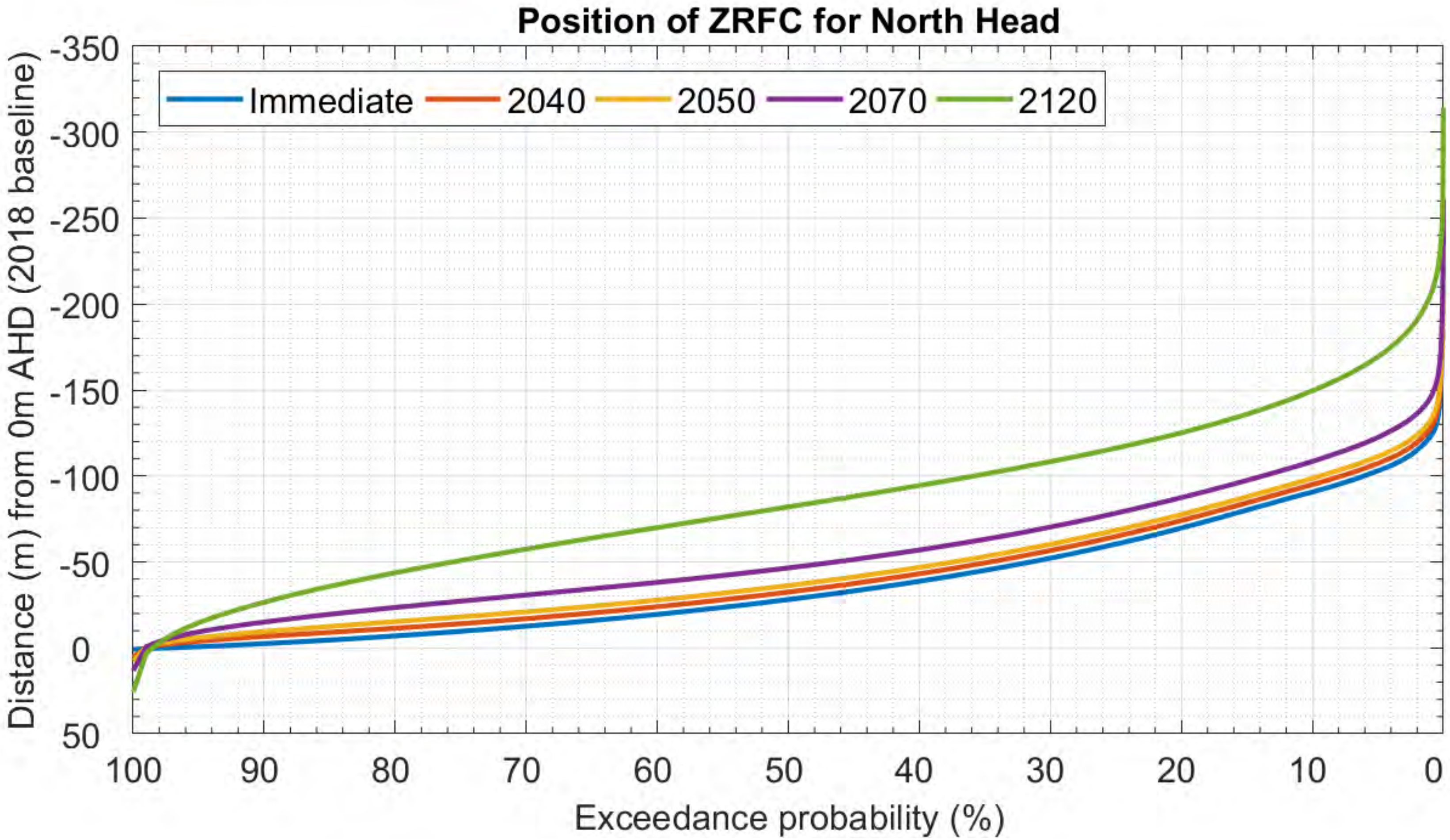


Figure 152: ZRFC probability exceedance curves for North Head (profile 470).

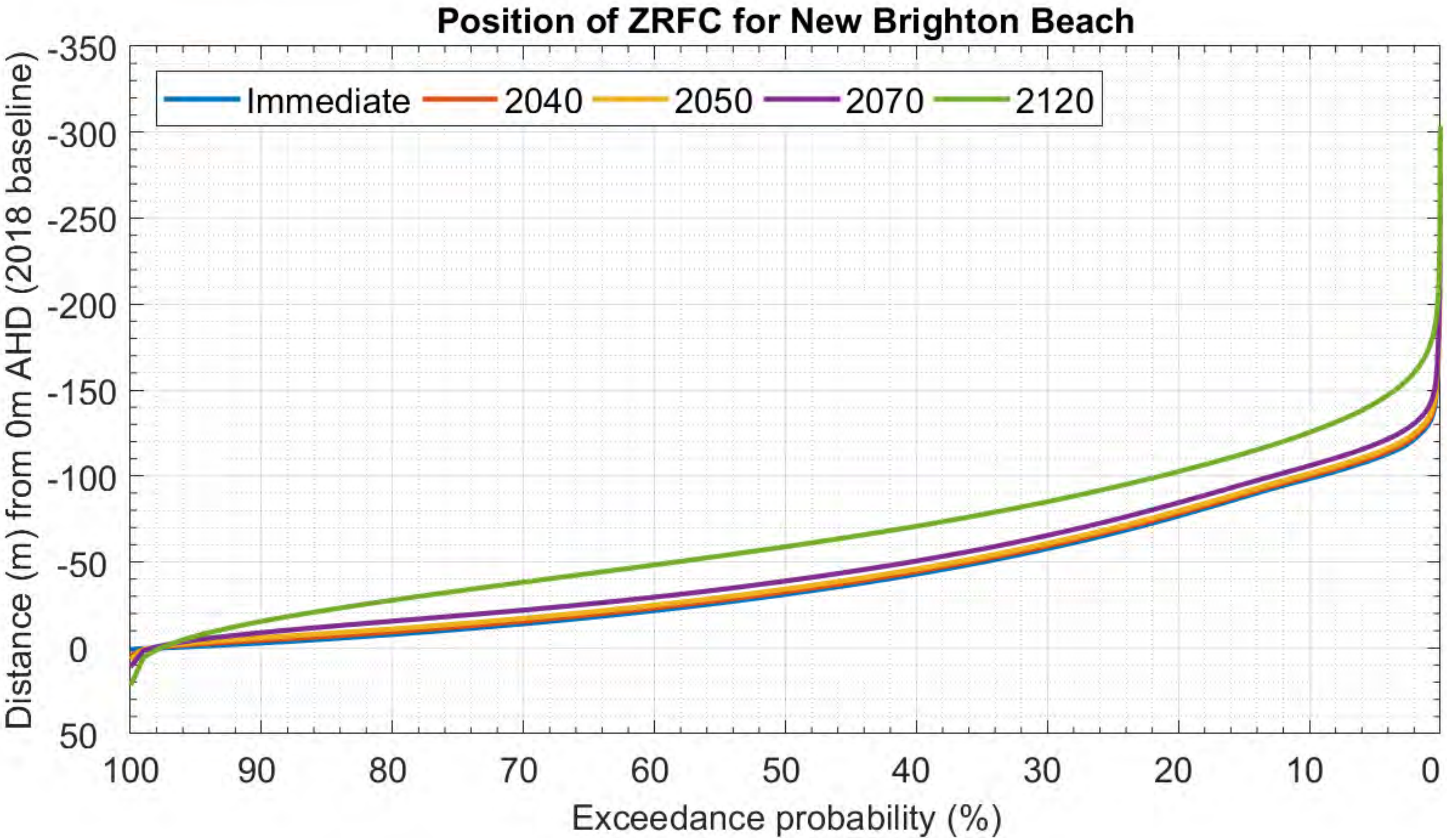


Figure 153: ZRFC probability exceedance curves for New Brighton Beach (profile 506).

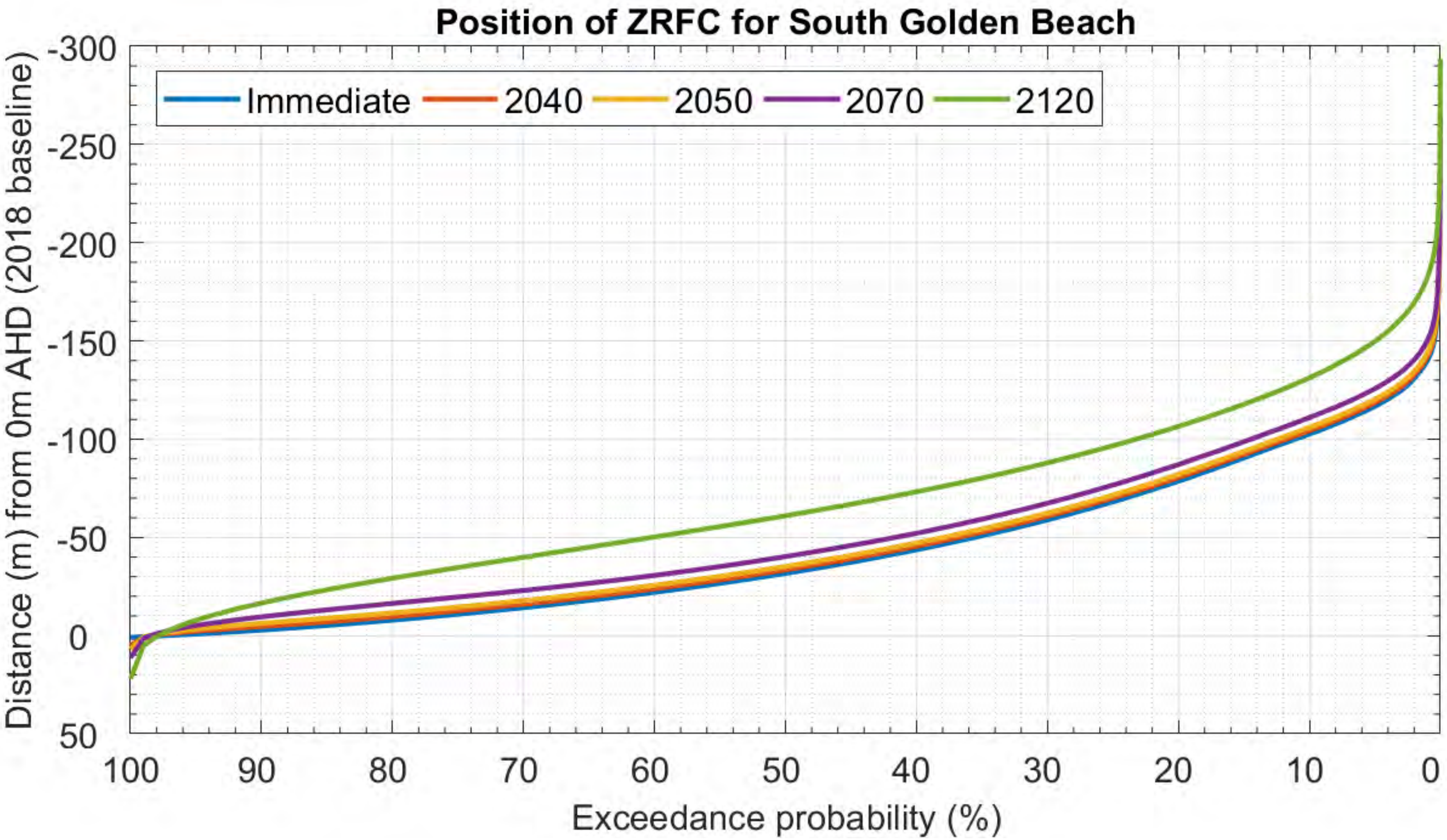


Figure 154: ZRFC probability exceedance curves for South Golden Beach (profile 554).

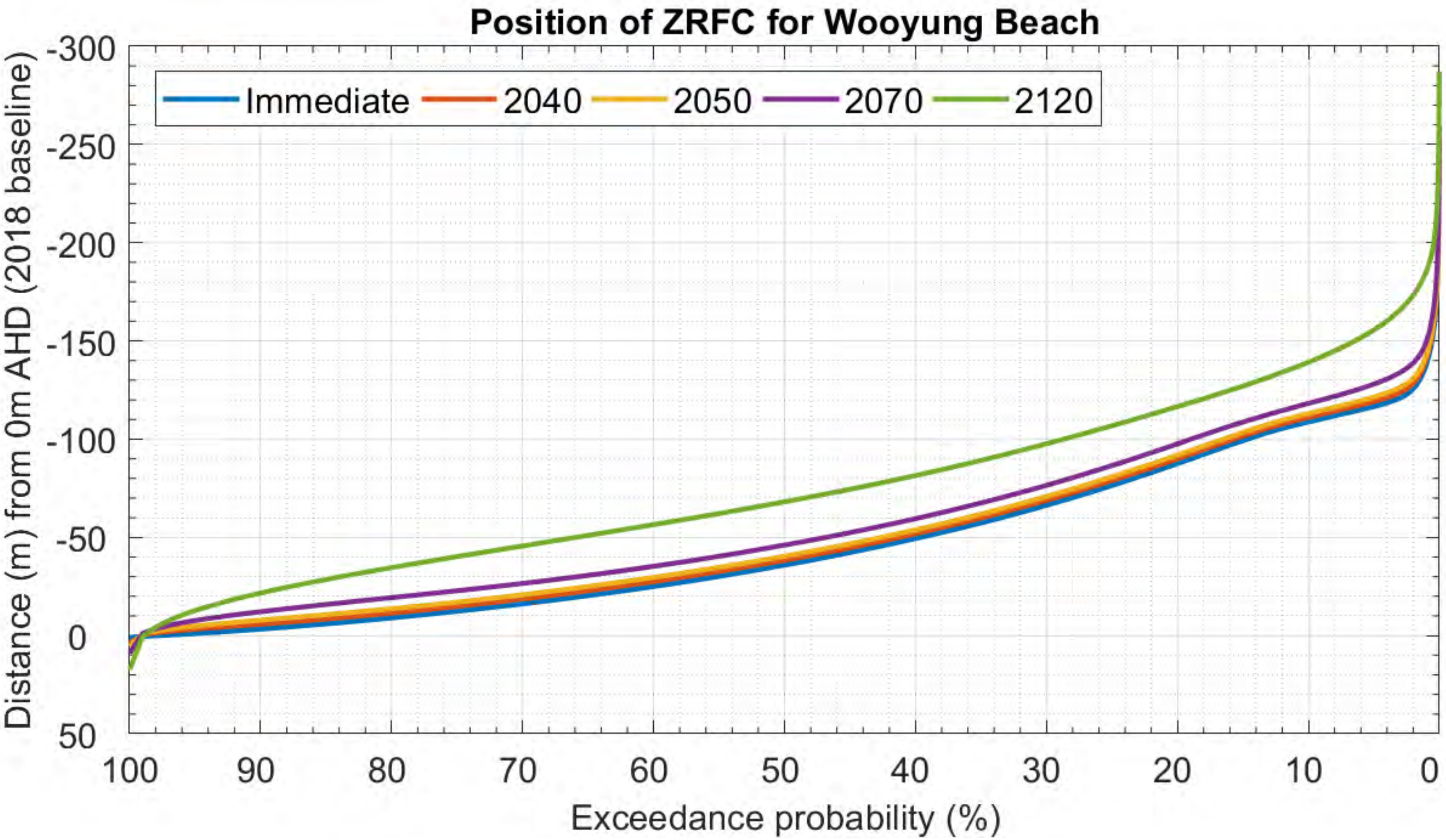


Figure 155: ZRFC probability exceedance curves for Wooyung Beach (profile 590).

Appendix E: Geotechnical hazard assessment (Douglas Partners)

Douglas Partners

Geotechnics / Environment / Groundwater

Integrated Practical Solutions

Report on
Coastal Hazard Assessment Study Preliminary
Landslip Hazard Risk Assessment

Coastal Headlands, Byron Bay and Broken Head

Prepared for
Bluecoast Consulting Engineers Pty Ltd

Project 205203.00
May 2022

Document History

Document details

Project No.	205203.00	Document No.	R.001.doc
Document title	Report on Coastal Hazard Assessment Study Preliminary Landslip Hazard Risk Assessment		
Site address	Coastal Headlands, Byron Bay and Broken Head		
Report prepared for	Bluecoast Consulting Engineers Pty Ltd		
File name	205203.00.R.001.doc		

Document status and review

Status	Prepared by	Reviewed by	Date issued
Revision 0	Gary Samuels	Chris Bell	25 May 2022

Distribution of copies

Status	Electronic	Paper	Issued to
Revision 0	1	0	Heiko Loehr, Bluecoast Consulting Engineers Pty Ltd

The undersigned, on behalf of Douglas Partners Pty Ltd, confirm that this document and all attached drawings, logs and test results have been checked and reviewed for errors, omissions and inaccuracies.

	Signature	Date
Author		25 May 2022
Reviewer		25 May 2022

FS 604853

Douglas Partners Pty Ltd
ABN 75 053 980 117
www.douglaspartners.com.au
Unit 2, 3 Distribution Avenue
Molendinar QLD 4214
Phone (07) 5568 8900

Table of Contents

Page

Report on Coastal Hazard Assessment Study Preliminary Landslip Hazard Risk Assessment

Coastal Headlands, Byron Bay and Broken Head

1. Introduction

This report presents the results of a preliminary landslip hazard risk assessment for the coastal headlands at Byron Bay and Broken Head. The work was carried out at the request of Bluecoast Consulting Engineers Pty Ltd in accordance with Douglas Partners Pty Ltd (DP) proposal 205203.00 dated 21 May 2021, DP's '*Conditions of Engagement'* and acceptance from Heiko Loehr representing Bluecoast Consulting Engineers Pty Ltd on 11 March 2022.

It is understood that the Byron Shire Council (BSC) is requesting a coastal hazard assessment be carried out along the northern Seven Mile Beach to South Golden Beach/Wooyung. The requirements for the study are detailed in the BSC brief '*Byron Shire 2021 Coastal Hazard Assessment Study – 2020 -0076'*. Part of this briefing document includes Task F 'Cliff or Slope Stability' . However, at this stage the following is required as part of the Task 'F' works:

- Identify potential areas where further investigation may be warranted; and
- A preliminary risk assessment for slope stability commenting on initial thoughts with regards to 'risk of life'.

The areas investigated as part of this preliminary assessment included:

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

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

It must be stressed that this assessment is limited to areas that were accessible during the site walkover.

This report must be read in conjunction with the notes '*About this Report'* in Appendix A.

2. Site Description

The assessed sites included the headlands at: The Pass; Wategos Beach; Cape Byron and Broken Head, as indicated in Drawings 1 and 2 in Appendix B.

All locations comprised exposed weathered rock and areas of both sporadic and thick vegetation.

Figures 1 to 6 indicates typical site conditions encountered during the investigation.

Figure 1: Looking north towards The Pass headland from the northern most edge of the beach.

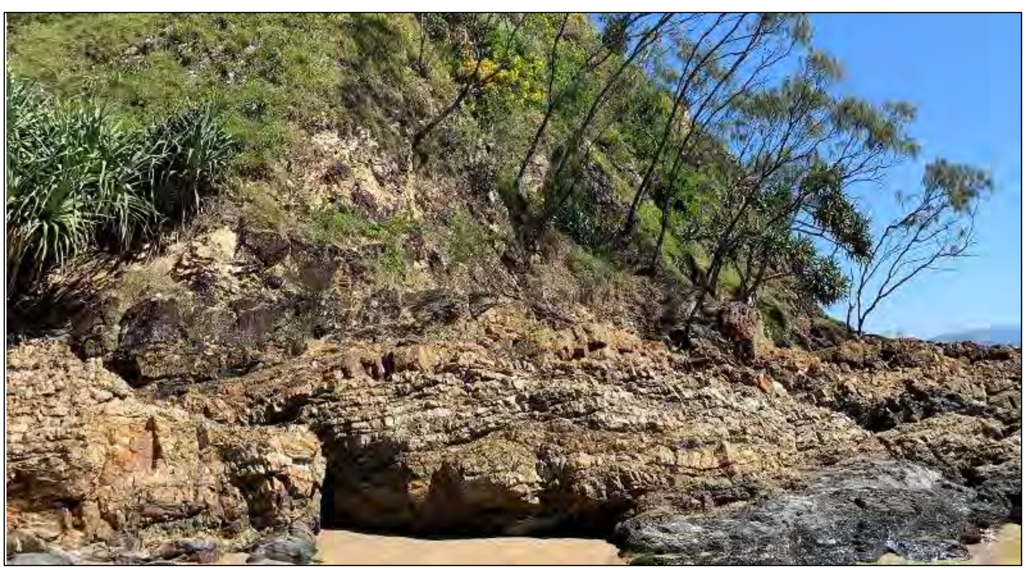


Figure 2: Looking west towards the western headland of Wategos Beach from the western most edge of the beach.

Figure 3: Looking northeast towards the eastern headland of Wategos Beach from the eastern most edge of the beach.

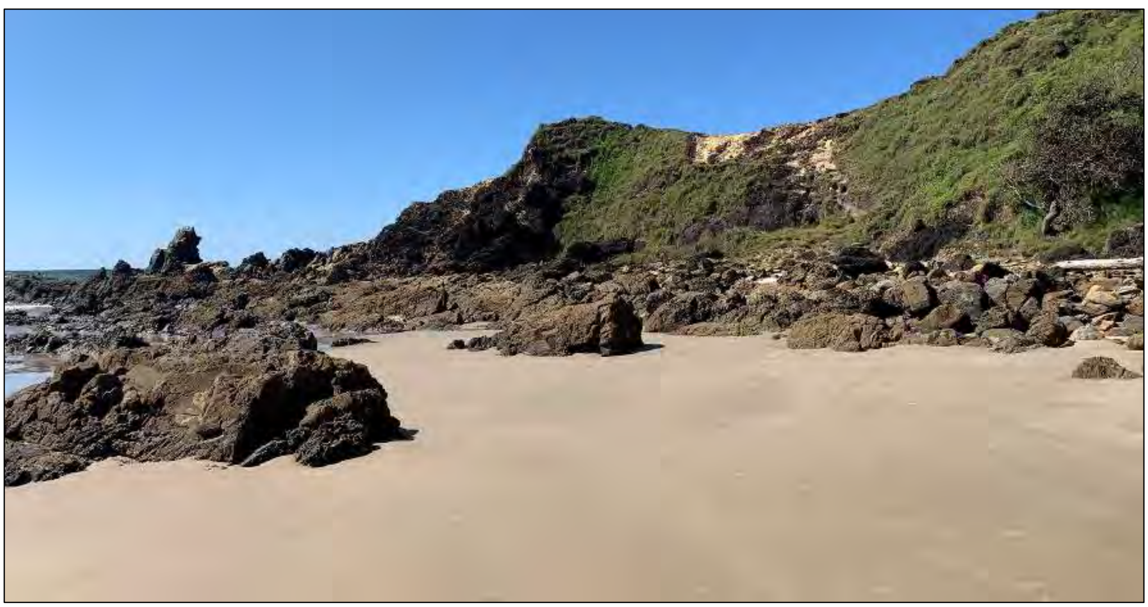


Figure 4: Looking east towards the headland at Cape Byron from the eastern most edge of the Little Wategos Beach.

Figure 5: Looking east towards Broken Head headland along the eastern end of the beach foreshore.

Figure 6: Looking east towards Broken Head headland from the eastern most edge of the beach.

3. Regional Geology

Reference to the Department of Natural Resources, Mines and Energy, MERIN Database, indicates that all sites are located in areas of Devonian Carboniferous aged Neranleigh Fernvale Beds typically comprising '*mudstone, shale, arenite, chert, jasper basic metavolcanics, pillow lava and conglomerate*'. Residual soil is anticipated to overlie the weathered rock.

From the site walk overs, residual soil was observed to overly weathered metasiltstone which conforms with the anticipated and published regional geology, although the metasiltstone observed is considered a slight variation to the '*mudstone and shale'* described in the geological map.

4. Field Work Methods

The field work was undertaken on 20 April 2022 and included a walk over inspection of the sites by a Senior Engineering Geologist experienced in landslip assessments

Given the rugged nature and height of each headland (up to 30 m high in parts), the site walkover was limited to observations from ground level only and then only for a distance of approximately 30 m from the beach edge at each location.

5. Field Work Results

This site walkover was carried out to assess the site for any visual evidence of existing instability or potential instability which might be considered a 'risk to life', and therefore targeted for potential further investigation. The use of a handheld inclinometer was used in part.

The Pass: The headland was approximately 8 m high with an overall slope angle of approximately 55°. The upper 2 m (approximately), of the headland comprised highly weathered metasiltstone underlaid by moderately to slightly weathered metasiltstone, where observed. The following observations were made in regard to the rock mass;

- The joints and foliations were predominantly closed;
- Where minor discontinuities were open, the joint planes were clean;
- Jointing appeared discontinuous with joint planes less than 1 m long;
- Some unfavourable jointing was observed to form 'soccer ball' size wedge blocks;
- Predominantly the rock mass appeared intact;
- Some minor slumping was observed in the upper profile of highly weathered metasiltstone;
- No scree was observed to indicate previous instability; and
- No likely obvious potential instability was observed.

Wategos Beach (eastern headland): The eastern headland was approximately 20 m high with an overall slope angle of approximately 45°. The rock mass comprised moderately to slightly weathered metasiltstone, where observed.

The following observations were made in regard to the rock mass:

- Joints and foliations were predominantly closed;
- Where minor discontinuities were open, the joint planes were clean;
- Jointing appeared discontinuous (<1 m long);
- Some unfavourable jointing was observed to form 'soccer ball' size wedge blocks;
- Predominantly the rock mass appeared intact;
- No scree was observed to indicate previous instability; and
- No likely obvious potential instability was observed.

Wategos Beach (western headland): The western headland was approximately 14 m high with a overall slope angle of approximately 45°. The rock mass comprised moderately to slightly weathered metasiltstone, where observed.

- Joints and foliations were predominantly closed;
- Where minor discontinuities were open, the joint planes were clean;
- Jointing appeared discontinuous (<1 m long);
- Some unfavourable jointing was observed to form 'soccer ball' size wedge blocks;
- Predominantly the rock mass appeared intact;
- Very little scree was observed to indicate previous instability;
- No likely obvious potential instability was observed; and
- Some minor rock fall was observed and associated with an existing drainage gully near the beach/headland interface (wedge block approximately 1 m x 0.8 m x 0.5 m in size).

Cape Byron: The headland was approximately 8 m high with an overall slope angle of approximately 45°. The rock mass comprised highly to moderately weathered metasiltstone, where observed. The following observations were made in regard to the rock mass.

- Joints and foliation were predominantly closed;
- Where minor discontinuities were open, the joint planes were clean;
- Jointing appeared discontinuous (<1 m long);
- Some surface slumping in upper level highly weathered metasiltstone, in part;
- Some unfavourable jointing was observed to form 'soccer ball' size wedge blocks;
- Predominantly the rock mass appeared intact;
- No scree was observed to indicate previous instability; and
- No likely obvious potential instability was observed.

Broken Head: The foreshore dunal system was approximately 100 m long, was located adjacent to and west of the headland, and comprised residual soil and extremely weathered metasiltstone. This area was observed to have slumped. Signage had been erected to warn people of the potential risk.

Figures 7 and 8 indicate the slumping observed during the inspection.

Figure 7: Looking southwest towards foreshore showing slumped area showing potential rock fall signage.

Figure 8: Looking west towards the headland showing slumping in the foreshore dunal system.

The headland was approximately 6 m high with an overall slope angle of 45°. The rock mass comprised highly to moderately weathered metasiltstone.

The following observations were made in regard to the rock mass.

- Joints and foliation were predominantly closed;
- Jointing appeared discontinuous (<1 m long); and
- Predominantly the rock mass appeared intact. However, some wedge block failure was observed. This movement was localised and in an area that would require climbing over rocks in order to access (see Figure 9).

Figure 9: Looking south east towards a recent wedge-failure.

6. Comments

6.1 Landslip Hazard Risk Assessment and Recommendations

An indicative quantitative and qualitative hazard rating has been calculated and assessed for each site based on existing site conditions as encountered during the field work operations using two methods, from the Australian Geomechanics Society (AGS).

Table 1: Slope Instability Risk Assessment using AGS 'A Method of Zoning Landslip Hazard' – The Pass.

Category	Description	Level of Risk	Factor
Slope of Rock Face	Less than 60°	Medium	0.9
Orientation of defect systems	Most Favourable	Medium	0.8
Evidence of Instability	None apparent	Low	0.5
Relative Frequency			**0.36**

Table 2: Slope Instability Risk Assessment using AGS 'A Method of Zoning Landslip Hazard' – Wategos (western headland).

Category	Description	Level of Risk	Factor
Slope of Rock Face	Less than 60°	Medium	0.9
Orientation of defect systems	Most Favourable	Medium	0.8
Evidence of Instability	None apparent	Low or High	0.5 or 1.5[(i)]
Relative Frequency			**0.36 or 1.1[(i)]**

Note (i) Localised in drainage gully

Table 3: Slope Instability Risk Assessment using AGS 'A Method of Zoning Landslip Hazard' – Wategos (eastern headland).

Category	Description	Level of Risk	Factor
Slope of Rock Face	Less than 60°	Medium	0.9
Orientation of defect systems	Most Favourable	Medium	0.8
Evidence of Instability	None apparent	Low	0.5
Relative Frequency			**0.36**

Table 4: Slope Instability Risk Assessment using AGS 'A Method of Zoning Landslip Hazard' – Cape Byron.

Category	Description	Level of Risk	Factor
Slope of Rock Face	Less than 60°	Medium	0.4
Orientation of defect systems	Most Favourable	Medium	0.8
Evidence of Instability	None apparent	Low	0.5
Relative Frequency			**0.36**

Table 5: Slope Instability Risk Assessment using AGS 'A Method of Zoning Landslip Hazard' – Broken Head.

Category	Description	Level of Risk	Factor
Slope of Rock Face	Less than 60°	Medium	0.9
Orientation of defect systems	Most Favourable	Medium	0.8
Evidence of Instability	None apparent	Low	0.5
Relative Frequency			**0.36 or 2.2(ii)**

Note:(i) The above assessment excludes the foreshore area that has already slumped.
(ii) Localised area only.

Based on the above quantitative analysis, Table 6 indicates the relative frequency and resultant likelihood of instability at each location. Refer to Table 7 for correlation between relative frequency and likelihood of instability.

Table 6: Relative Frequency and Likelihood of Instability

Location	Relative Frequency	Likelihood Reporting
The Pass	0.36	Low
Wategos (western headland)	0.36 or 1.1(i)	Low to Moderate(i)
Wategos (eastern headland)	0.36	Low
Cape Byron	0.36	Low
Broken Head	0.36 or 2.2(i)	Low or High(i)

Note (i) Localised area only.

Tables 7 and 8 below indicate typical implications with respect to site *'risk'* level and the correlation between relative frequency and likelihood rating.

Table 7: Correlation between Relative Frequency and Likelihood Rating

Relative Frequency	Likelihood Rating
<0.2	Very low
0.2-0.6	Low
0.6-2.0	Moderate
2.0-6.0	High
>6.0	Very High

Table 8 - Risk Level Implications

Risk Level		Example Implications[(1)]
VH	Very High	Extensive detailed investigation and research, planning and implementation of treatment options essential to reduce risk to acceptable levels; may be too expensive and not practical.
H	High Risk	Detailed investigation, planning and implementation of treatment options required to reduce risk to acceptable levels.
M	Moderate Risk	Tolerable provided treatment plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options.
L	Low Risk	Tolerable provided treatment plan is implemented to maintain or reduce risks. May be accepted. May require investigation and planning of treatment options.
VL	Very Low	Acceptable. Manage by normal slope maintenance procedures.

Notes: 1. *The implications for a particular situation are to be determined by all parties to the risk assessment; these are only given as a general guide.*
2. *Judicious use of dual descriptors for Likelihood, Consequence and Risk to reflect the uncertainty of the estimate may be appropriate in some cases.*

Parameters were determined and assigned, as shown in Table 9, for the AGS qualitative landslip assessment, as per ASG *'Landslide Task Force, Landslip Practice Note Working Group'* for existing site conditions.

Table 9: Slope Instability Risk Assessment for Properties using AGS *'Landslide Task Force, Landslip Practice Note Working Group' – All Sites*

Hazard	Likelihood	Consequence	Risk
Creep of natural residual soils	Possible to Likely	Insignificant	Very low to low
Deep seated instability within the site	Barely Credible	Catastrophic	Low

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

The results of this assessment indicate that for both quantitative and qualitative landslip risk methods the investigated areas have, generally a 'very low to low' risk of instability, with localised areas of 'moderate to high' risk of instability.

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

Based on the site walkover of the observed areas, and considering the access limitations and vegetation in part, no significant areas require further detailed assessment at this time, where observed. Furthermore, none of tht areas observed were considered a 'risk to life' at this time. However, as site conditions can change rapidly depending on climate and weathering, it is recommended that annual inspections be carried out by duly qualified coastal or geotechnical engineer to review each site and to update comments and recommendations, as required.

It may be prudent to also erect warning of potential 'rock fall' signage at each beach and headland interface.

In the area of slumping along the foreshore dunal system at Broken Head, it is recommended that the slumped material be removed and slumped zones be battered back at the shallowest angle possible without causing damage to the ecosystem, and the newly battered slope be planted out to assist in minimising erosion.

It must be noted that this is a preliminary assessment based on a brief site walkover and observations made where limited access was possible, and as such there may be areas on the sites that may have a 'higher' risk of instability than that indicated in this report.

7. Limitations

Douglas Partners Pty Ltd (DP) has prepared this report for the preliminary landslip hazard assessment, Byron Bay and Broken Head in accordance with DP's proposal 205203.00 dated 21 May 2021. The work was carried out under DP's *'Conditions of Engagement'.* This report is provided for the exclusive use of Bluecoast Consulting Engineer Pty Ltd, for the purposes as described in the report. It should not be used by or relied upon for other projects or purposes on the same or other site or by a third party. Any party so relying upon this report beyond its exclusive use and purpose as stated above, and without the express written consent of DP, does so entirely at its own risk and without recourse to DP for any loss or damage. In preparing this report DP has necessarily relied upon information provided by the client and/or their agents.

The results provided in the report are indicative of the observation only made during the site visit at the time the work was carried out. Site conditions can change abruptly due to variable geological processes and also as a result of human influences. Such changes may occur after DP's site walkover has been completed.

DP's advice is based upon the conditions encountered during this investigation. The accuracy of the advice provided by DP in this report may be affected by undetected variations in ground conditions across the site. The advice may also be limited by budget constraints imposed by others or by site accessibility.

The assessment of atypical safety hazards arising from this advice is restricted to the geotechnical components set out in this report and based on known project conditions and stated design advice and assumptions. While some recommendations for safe controls may be provided, detailed 'safety in design' assessment is outside the current scope of this report and requires additional project data and assessment.

This report must be read in conjunction with all of the attached and should be kept in its entirety without separation of individual pages or sections. DP cannot be held responsible for interpretations or conclusions made by others unless they are supported by an expressed statement, interpretation, outcome or conclusion stated in this report.

This report, or sections from this report, should not be used as part of a specification for a project, without review and agreement by DP. This is because this report has been written as advice and opinion rather than instructions for construction.

8. References

Australian Geomechanics Society, Volume 36, No. 3, September 2001 *A Method of Zoning Landslide Hazard*.

Practice Note Guidelines for Landslip Risk Management, AGS Landslide Task Force, Landslide Practice Note Working Group, Australian Geomechanics, Vol 42, No. 1, March 2007.

Douglas Partners Pty Ltd

Appendix A

About This Report

About this Report

Douglas Partners

Introduction

These notes have been provided to amplify DP's report in regard to classification methods, field procedures and the comments section. Not all are necessarily relevant to all reports.

DP's reports are based on information gained from limited subsurface excavations and sampling, supplemented by knowledge of local geology and experience. For this reason, they must be regarded as interpretive rather than factual documents, limited to some extent by the scope of information on which they rely.

Copyright

This report is the property of Douglas Partners Pty Ltd. The report may only be used for the purpose for which it was commissioned and in accordance with the Conditions of Engagement for the commission supplied at the time of proposal. Unauthorised use of this report in any form whatsoever is prohibited.

Borehole and Test Pit Logs

The borehole and test pit logs presented in this report are an engineering and/or geological interpretation of the subsurface conditions, and their reliability will depend to some extent on frequency of sampling and the method of drilling or excavation. Ideally, continuous undisturbed sampling or core drilling will provide the most reliable assessment, but this is not always practicable or possible to justify on economic grounds. In any case the boreholes and test pits represent only a very small sample of the total subsurface profile.

Interpretation of the information and its application to design and construction should therefore take into account the spacing of boreholes or pits, the frequency of sampling, and the possibility of other than 'straight line' variations between the test locations.

Groundwater

Where groundwater levels are measured in boreholes there are several potential problems, namely:

- In low permeability soils groundwater may enter the hole very slowly or perhaps not at all during the time the hole is left open;
- A localised, perched water table may lead to an erroneous indication of the true water table;
- Water table levels will vary from time to time with seasons or recent weather changes. They may not be the same at the time of construction as are indicated in the report; and
- The use of water or mud as a drilling fluid will mask any groundwater inflow. Water has to be blown out of the hole and drilling mud must first be washed out of the hole if water measurements are to be made.

More reliable measurements can be made by installing standpipes which are read at intervals over several days, or perhaps weeks for low permeability soils. Piezometers, sealed in a particular stratum, may be advisable in low permeability soils or where there may be interference from a perched water table.

Reports

The report has been prepared by qualified personnel, is based on the information obtained from field and laboratory testing, and has been undertaken to current engineering standards of interpretation and analysis. Where the report has been prepared for a specific design proposal, the information and interpretation may not be relevant if the design proposal is changed. If this happens, DP will be pleased to review the report and the sufficiency of the investigation work.

Every care is taken with the report as it relates to interpretation of subsurface conditions, discussion of geotechnical and environmental aspects, and recommendations or suggestions for design and construction. However, DP cannot always anticipate or assume responsibility for:

- Unexpected variations in ground conditions. The potential for this will depend partly on borehole or pit spacing and sampling frequency;
- Changes in policy or interpretations of policy by statutory authorities; or
- The actions of contractors responding to commercial pressures.

If these occur, DP will be pleased to assist with investigations or advice to resolve the matter.

About this Report

Site Anomalies

In the event that conditions encountered on site during construction appear to vary from those which were expected from the information contained in the report, DP requests that it be immediately notified. Most problems are much more readily resolved when conditions are exposed rather than at some later stage, well after the event.

Information for Contractual Purposes

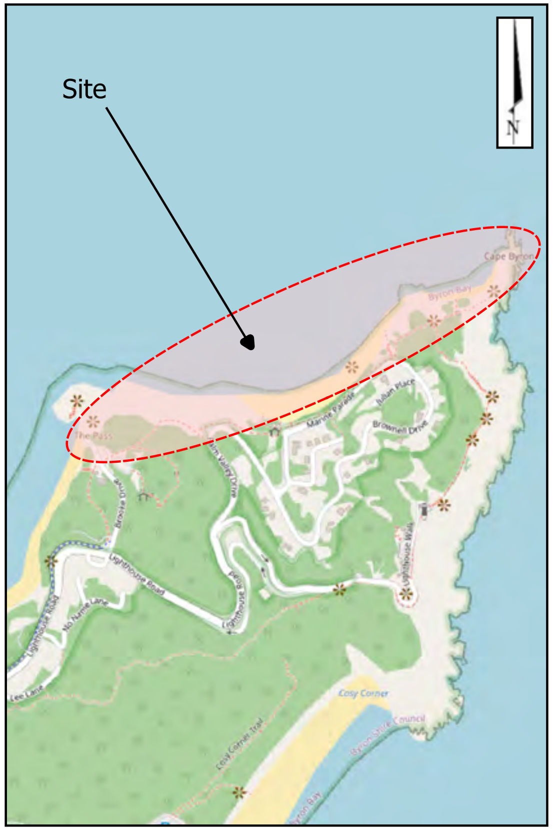
Where information obtained from this report is provided for tendering purposes, it is recommended that all information, including the written report and discussion, be made available. In circumstances where the discussion or comments section is not relevant to the contractual situation, it may be appropriate to prepare a specially edited document. DP would be pleased to assist in this regard and/or to make additional report copies available for contract purposes at a nominal charge.

Site Inspection

The company will always be pleased to provide engineering inspection services for geotechnical and environmental aspects of work to which this report is related. This could range from a site visit to confirm that conditions exposed are as expected, to full time engineering presence on site.

Appendix B

Drawing 1 – Site Location Plan (Byron Bay)
Drawing 2 – Site Location Plan (Broken Head)



Site Locality

Legend:

Assessment Location

Image taken from metro map

Locality taken from open street map

Douglas Partners Geotechnics / Environment / Groundwater	CLIENT: Bluecoast Consulting Engineers Pty Ltd	**Site Location Plan**	PROJECT No:	205203.00
	OFFICE: Gold Coast	**Landslip Hazard Risk Assessment**	DRAWING No:	1
	DATE: May 2022	**Byron Bay Headlands**	REVISION:	0

Site Locality

Legend:

Assessment location

Image taken from metro map

Locality taken from open street map

Douglas Partners
Geotechnics | Environment | Groundwater

CLIENT:	Bluecoast Consulting Engineers Pty Ltd	**Site Location Plan**	PROJECT No:	205203.00
OFFICE:	Gold Coast	**Landslip hazard risk assessment**	DRAWING No:	2
DATE:	May 2022	**Broken Head Headland**	REVISION:	0

Appendix F: XBeach local coastal inundation assessment

Technical note – detailed coastal inundation assessment

To	Byron Shire Council
From	Bluecoast Consulting Engineers
Date	21 November 2023
Subject	**FINAL - Byron Shire Coastal Management Program - Stage 2 – detailed coastal inundation assessment**

1. Introduction

This technical note describes the methodology, results and limitations of a detailed coastal inundation assessment applied to map the present (immediate) and future coastal inundation hazard. The inundation assessment is limited to the storm-related flooding by seawater due to elevated ocean water levels (storm surge) and wave processes. Coastal inundation, as an action of the sea, is distinguished from more traditional definitions of flooding which are typically associated with rainfall and runoff hazard. This technical note is to be read as an appendix to the Byron Shire CMP Stage 2 Coastal Hazard Assessment report.

In line with the Coastal Management Act 2016 and the NSW Coastal Management Manual Part B (the Manual - NSW Government, 2018), a coastal inundation hazard assessment for the Byron Shire open coast has been undertaken.

A two staged coastal inundation hazard assessment has been completed for the entire Byron Shire LGA open coast. The first-pass assessment involved the calculation of wave runup levels using empirical formulae for regular shore-normal coastal profiles (same profiles used in erosion and recession hazard assessment, see main study report) along the entire Byron Shire coast. Areas potentially exposed to coastal inundation were identified. For those areas identified as high risk as part of the first pass, a detailed (local) assessment was carried out.

Based on the findings of the first pass, the following locations were selected for a detailed coastal inundation assessment:

- Belongil Beach
- New Brighton Beach
- South Golden Beach

The detailed coastal inundation assessment mapped the extents and inundation depths by employing a state-of-the-art hydrodynamic and hydrological model, XBeach (Roelvink et al., 2009).

2. Coastal inundation assessment

2.1 Approach

To simulate wave overwash and overtopping with consideration of complex nearshore wave processes (including wave setup and runup) a high-resolution XBeach (Roelvink et al., 2009) model was developed for each location. XBeach is a numerical model that includes the hydrodynamic processes of short-wave transformation (refraction, shoaling and breaking), long wave (infragravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. XBeach has been widely adopted in coastal inundation assessments and has been validated against field measurements of runup and overtopping in physical model testing (Roelvink et al., 2017). The XBeach model was applied to estimate maximum inundation extents and depths and wave overwash discharge at the selected locations.

2.2 Model setup

The XBeach model was setup in surfbeat mode (wave group mode) where wave forcing in the shallow water momentum equation is obtained from a time dependent version of the wave action balance equation. Hence, in surfbeat mode short waves are not fully resolved but rather simulated as wave groups, and overtopping volumes presented herein are predominantly driven by temporary water level increases in the infragravity (wave group) spectrum. Wave-driven currents caused by wave groups as well as runup and rundown of long waves are fully resolved. Short-wave processes such as short wave runup are included in the XBeach model through empirical formulae as described in Roelvink (1993).

For this study, only the hydrodynamic module was implemented, and the morphological updating was turned off. Front and back boundaries were set to absorbing-generating (weakly-reflective) in all simulations. Lateral boundaries were set to Neumann, imposing a longshore gradient to zero. Other XBeach parameters were set to default.

A JONSWAP wave spectrum was parametrically defined and run for a 3-hour simulation (1-hour warm-up period).

2.3 Model domains

Three local model domains were established for the areas identified during the first pass assessment as being most exposed to coastal inundation.

The XBeach model utilises a varying grid resolution that allows for a fine spatial resolution in the nearshore area. This allows for less computational cells in offshore areas where fine resolution is not required. For each model domain the grid resolution ranges from up to 30m in offshore areas to 3m in the nearshore and land areas. The longshore spacing was fixed to 3m. The 2018 Coastal LiDAR dataset collected by the Department of Planning and Environment (DPE) was used to describe the model's bathymetry and topography. This is a combined topographic and bathymetric dataset at 5-meter resolution.

The model extents, computational grids as well as the adopted bathymetry for the three selected locations are presented in Figure 1.

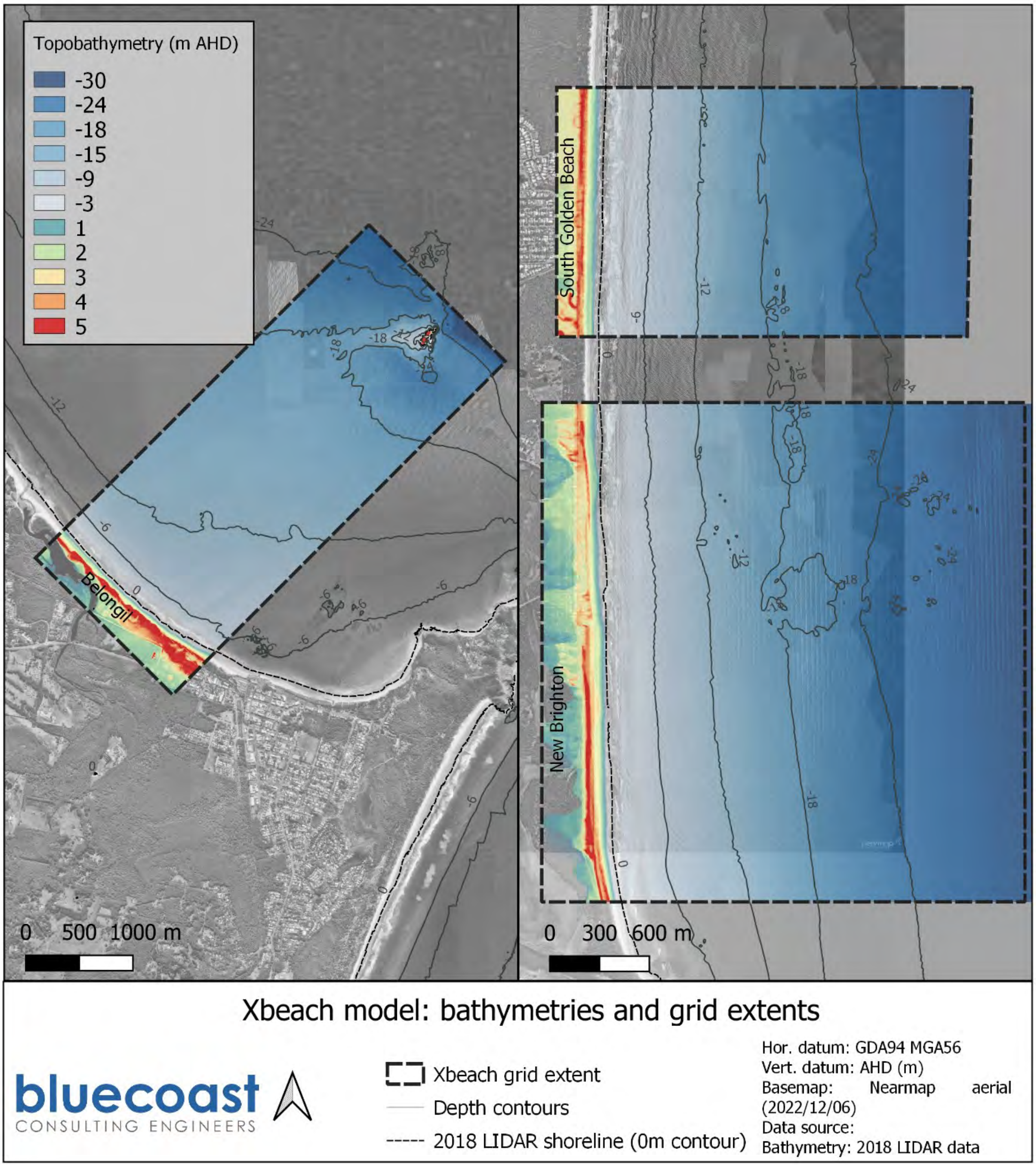


Figure 1: XBeach bathymetry and domains for Belongil Beach, New Brighton and South Golden Beach models.

2.4 Model scenarios

The adopted planning periods for the coastal inundation assessment are present day (immediate), 2050 and 2120. A hazard likelihood of 1% Annual Exceedance Probability (AEP) or 100-year Average Recurrence Interval (ARI) has been adopted for the coastal inundation assessment and associated mapping.

When assessing wave overtopping and overwash it is important to consider the joint probability of nearshore wave conditions and ocean water levels. As such, a joint probability analysis was completed using:

- a 29-year hindcast of nearshore wave data derived from the NSW Coastal Wave Model (OEH, 2017) at 30m depth (provided by Manly Hydraulics Laboratory)
- measured water levels from MHL's Tweed Heads offshore water level gauge.

The 100-year ARI joint probability of the maximum significant wave height with the associated water level was estimated. Sea level rise was added to the 100-year ARI joint probability event water level for the 2050 and 2120 planning periods.

Given the proximity of New Brighton and South Golden Beach, the same wave and water level conditions were adopted for the two sites. The joint probability analysis results for New Brighton/South Golden Beach and Belongil Beach are presented in Figure 2. Table 1 presents the selected wave and water level conditions for the joint 100-year ARI (one-hour) and each planning period. Wave direction was set to the worst-case scenario, which is when the storm waves are most perpendicular to the coast. Based on sensitivity testing a peak wave period of 14s was adopted for all simulations. This wave period was shown to produce the most conservative results.

Projected sea level rise (above 1995 - 2014 baseline) was included based on the latest published projections (AR6) by the Intergovernmental Panel on Climate Change (IPCC) for Yamba, NSW (Garner et al., 2021). Refer to Section 5.3.3 of the main report (Table 16).

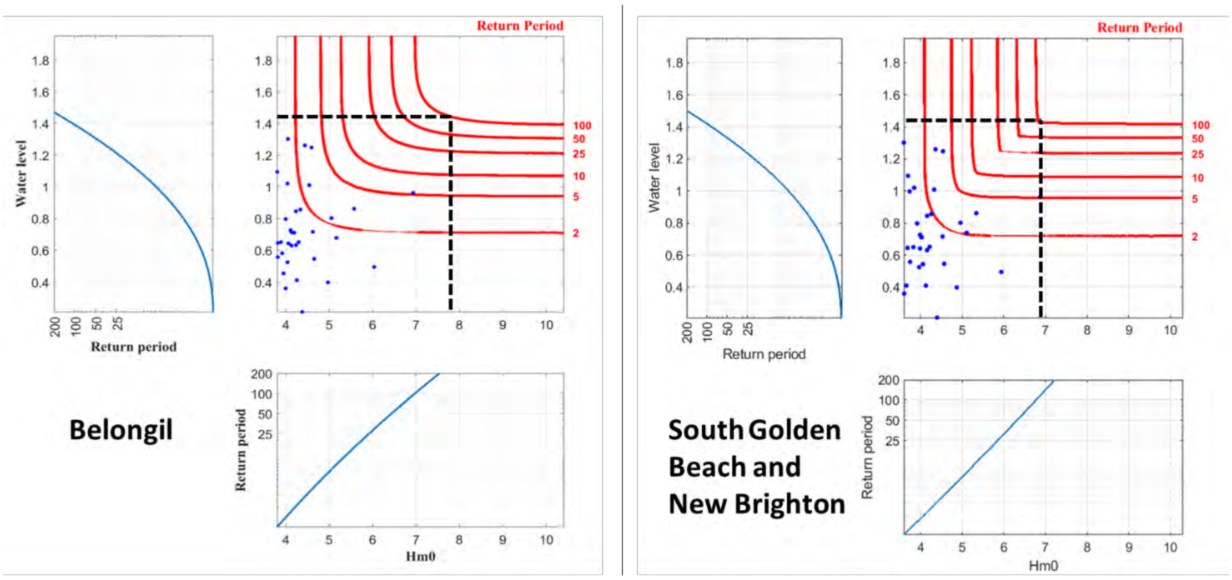


Figure 2: Joint probability of Byron Shire nearshore wave data and ocean water level from Tweed Heads.

Note: (Left) Belongil Beach and (right) South Golden and New Brighton Beach. Black dotted line show joint 100-year ARI estimate.

Table 1: Summary of adopted wave and water level conditions for the detailed coastal inundation assessment (three-hour simulation).

Site	Planning period	Sig. wave height (m)	Peak wave period (s)	Peak wave direction (deg N)	Water level (m AHD)
Belongil Beach	Immediate	7.8	14	90	1.42
	2050 (SLR +0.23m)	7.8	14	90	1.65
	2120 (SLR +0.93m)	7.8	14	90	2.35
New Brighton and South Golden Beach	Immediate	6.8	14	90	1.42
	2050 (SLR +0.23m)	6.8	14	90	1.65
	2120 (SLR +0.93m)	6.8	14	90	2.35

3. Results

Coastal inundation maps showing the maximum inundation extent and depth for the joint 100-year ARI wave and water level simulations for a three-hour storm duration are presented for each planning period in the map compendium in the main report.

Wave overtopping of the coastal barrier (overwash) at each location has been assessed using the XBeach model for the selected joint water level and waves scenarios. A summary of the overwash and overtopping discharge volumes for several observation points (see Figure 3) along each location is provided in Table 2. Measures of the mean overtopping volume (Qx) in litres per seconds per metre (l/s/m) during the three-hour simulations as well as maximum volumes (Qx_{max}) in litres per metre (l/m) and the peak water level behind the coastal barrier are provided. For a given mean overtopping discharge, small waves only give small overtopping volumes, whereas large waves may give many cubic metres of overtopping water in one wave and their severity are thus better described by the maximum volumes. EurOtop (2018) provide guidance on safe mean and maximum overtopping volumes in consideration of impacts to people and infrastructure in the lee of seawalls or dikes. For context, these are presented in Table 3. While not directly applicable, the colour scale adopted in Table 2 was aligned with the safe overtopping volumes in EurOtop (2018) for the use of vehicles in such areas as a proxy for the hazard level.

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

- Belongil Beach: The height of dune crests varies along the coast, with the most vulnerable sections being those where the dune crest is below 5 meters and where beach accesses exist. Belongil Spit is a low-lying area between the creek and the beach which enhances the inundation risk. Beach front properties and areas with beach access are shown to be affected by coastal inundation for the immediate scenario. The coastal inundation hazard increases with sea level rise, and properties located further away from the beach might also be affected. Significant barrier overwash extending to Belongil Creek is seen for the 2120 planning period.

- New Brighton Beach: Along this stretch of coast there is a greater buffer between private properties and the dune crest which reduces the coastal inundation risk. For the immediate scenario, only beach front properties located in southern New Brighton Beach are affected. However, for the 2120 planning period most beach front properties along the southern and northern section of New Brighton Beach might be affected.
- South Golden Beach: The lowest points along the dune crest are around 4.6m AHD. Behind the dune crest, the elevation drops and is around 2m AHD towards the Brunswick River. For the immediate scenario, some beach front properties are shown to be affected by coastal inundation. For the 2120 planning period, significant overwash is shown to occur along the entire beach section resulting in significant coastal inundation at South Golden Beach.
- At the 2120 planning horizon, the mean overtopping volumes presented herein exceed the safe volumes (EurOtop, 2018) for most locations. This suggests that there is likely a safety hazard for people and property in the immediate overwash areas. Safe maximum overtopping volumes are also exceeded for the immediate planning horizon at Belongil Beach and 2050 planning horizon at South Golden Beach.

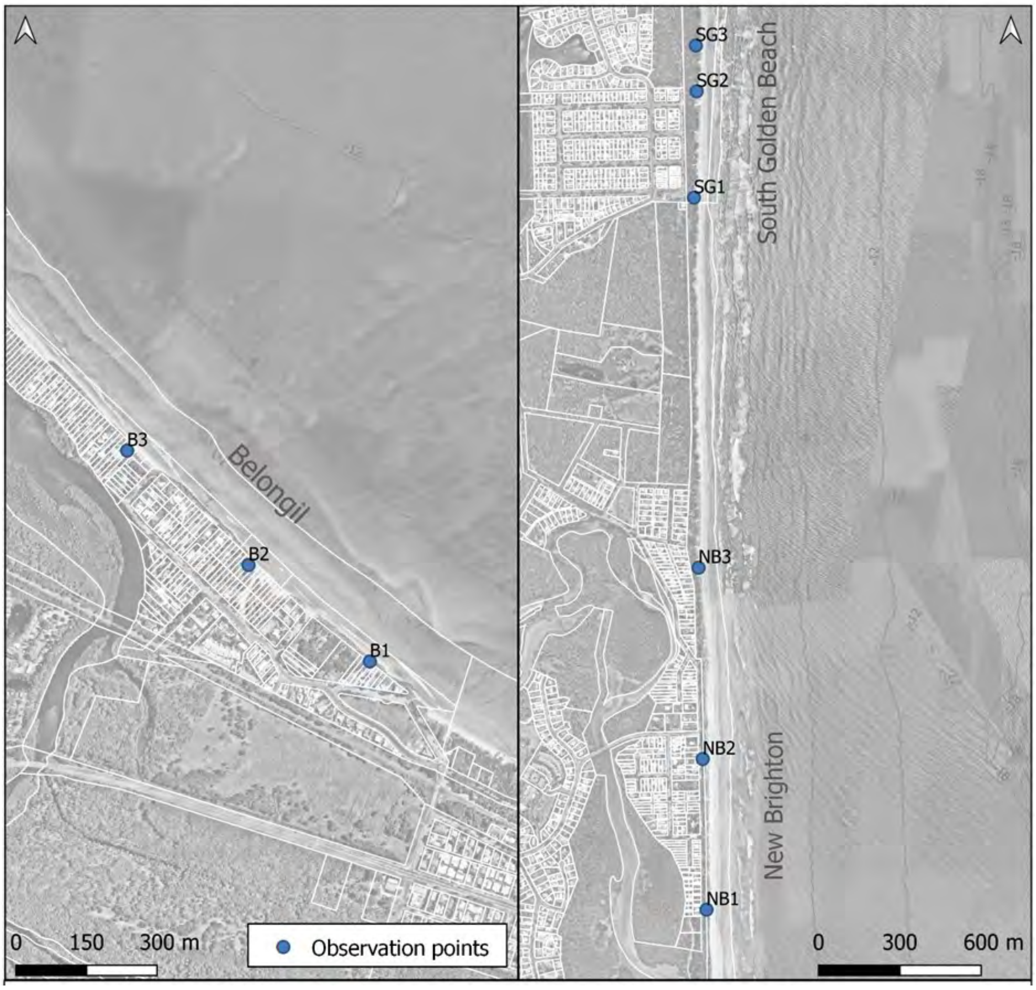


Figure 3: Location of the observation points where overtopping discharges and peak water levels were obtained.

Table 2: Peak water level and overtopping discharges (Qx) from the XBeach modelling.

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

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

Table 3: Overview of safe overtopping volumes for seawalls or dikes provided in EurOtop (2018).

Hazard type and reason	Offshore significant wave height (m)	Mean discharge Qx (l/s per m)	Max volume Qmax (l per m)
People at seawall (clear view of the sea)	3	0.3	600
	2	1	600
	1	10-20	600
	<0.5	No limit	No limit
Cars on seawall (close behind crest)	3	<5	2,000
	2	10-20	2,000
	1	<75	2,000

4. Limitations

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

- Morphological response of the beach during the storm as well as long-term adjustment to net sand loss (i.e., recession) and sea level rise have not been included. Any landward movement of the coastal barrier would also affect the inundation extents and depth. Changes to the nearshore bathymetry due to profile adjustments as well as higher sea levels may change nearshore wave processes that could exacerbate the inundation risk.
- Stormwater drainage, vegetation and infiltration have not been included in the modelling undertaken herein and would likely reduce the presented inundation extents and depth presented.
- The effects of wind on wave overwash and overtopping were not included. Heavy rainfall, antecedent precipitation and catchment flooding were also not considered in this study. These factors could exacerbate inundation. Wave forces and momentum of overtopping jets were also not considered herein.
- The accuracy of the Digital Elevation Model (2018 Coastal LiDAR) used herein is stated as IHO 1B and has a 5 x 5m horizontal resolution which may not be sufficient to precisely describe coastal barrier elevations and steeper slopes.

5. References

Garner, G. G., T. Hermans, R. E. Kopp, A. B. A. Slangen, T. L. Edwards, A. Levermann, S. Nowikci, M. D. Palmer, C. Smith, B. Fox-Kemper, H. T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S. S. Drijfhout, T. L. Edwards, N. R. Golledge, M. Hemer, R. E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I. S. Nurhati, L. Ruiz, J-B. Sallée, Y. Yu, L. Hua, T. Palmer, B. Pearson, 2021. *IPCC AR6 Sea-Level Rise Projections. Version 20210809*. PO.DAAC, CA, USA

EurOtop, 2018. *Manual on Wave Overtopping of Sea Defences and Related Structures*. An Overtopping Manual Largely Based on European Research, but for Worldwide Application, 2nd ed.; Van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H.F.R., Troch, P., Zanuttigh, B., Eds.; 2018; Available online:www.overtopping-manual.com.

Roelvink, J.A., 1993. *Dissipation in random wave groups incident on a beach*. Coastal Engineering, 19(1-2), pp.127-150.

Roelvink, D., Reniers, A., Van Dongeren, A.P., De Vries, J.V.T., McCall, R. and Lescinski, J., 2009. *Modelling storm impacts on beaches, dunes and barrier islands*. Coastal engineering, 56(11-12), pp.1133-1152.

Roelvink, D., McCall, R., Mehvar, S., Nederhoff, K. and Dastgheib, A., 2018. *Improving predictions of swash dynamics in XBeach: The role of groupiness and incident-band runup*. Coastal Engineering, 134, pp.103-123.