Appendix G – Coastal Processes Report (Royal HaskoningDHV, 2024a)

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REPORT

Pebbly Beach Coastal Processes

Implications of a Rock Revetment Wall Construction

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Reference:	PA3962-RHD-PR-AU-RP-C-01
Status:	Final/04
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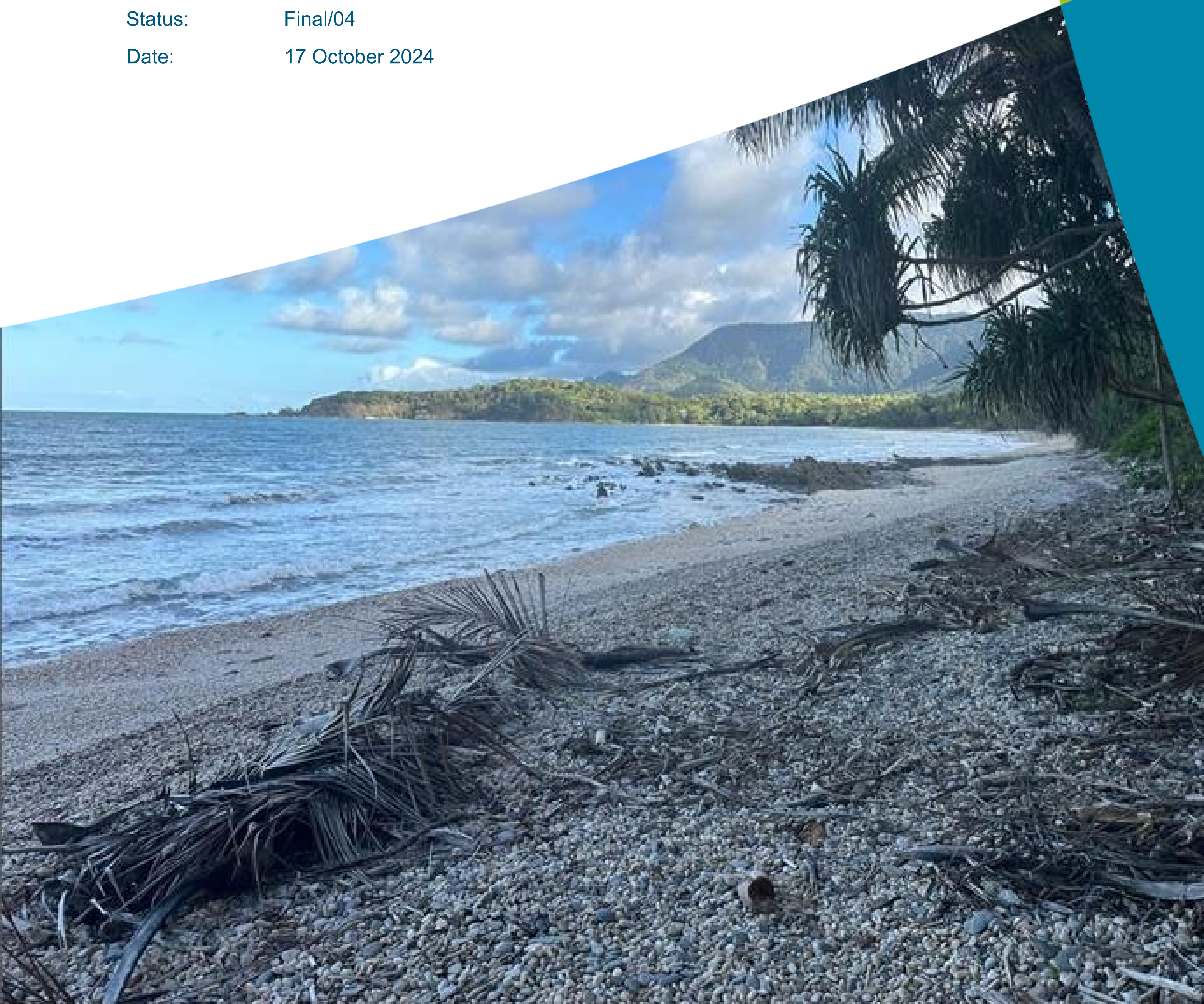

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1 Introduction

Erosion of the foreshore embankment, as a result of Cyclone Jasper, impacted Captain Cook Highway at Pebbly Beach south of Port Douglas (refer Figure 1-1). In response and as part of rectification works a rock revetment wall is proposed to protect the exposed embankments. This report provides an overview of coastal processes to assist in understanding the met-ocean conditions impacting the site and coastal morphology to support both the design process, ensure works minimise impacts and assist in obtaining approvals.

Figure 1-1: Damage to embankment at Pebbly Beach due to Cyclone Jasper

2 Met-ocean Conditions

2.1 Wind Climate

Winds predominantly originate from the easterly direction, ranging from southeast to northeast. Winds from the northern sector generate waves that typically drive sediment southward along the beaches, while winds from the east-southeast create waves that result in northward sediment transport. Waves produced by northeasterly winds usually approach the coast with minimal angle, leading to little or no sediment movement (Beach Protection Authority, 1984).

The wind climate at Pebbly Beach has been characterised using data from the Low Island climate station, operated by Bureau of Meteorology (BOM). The wind station (Low Island) is situated 16 km north of the study site with data collected from 1967 to 2024. The data is considered representative of the local wind climate relevant to met-ocean conditions due to its location off the coast. An analysis of wind data from Low Island shows that southeast winds are dominant, with winds from South through East occurring approximately 70% of the time. During the morning there was a more southerly bias, while during the afternoon there was a more easterly bias (Figure 2-1). Average sustained wind speeds of 20–30 km/h (5.7 to 8.3 m/s) are typical.

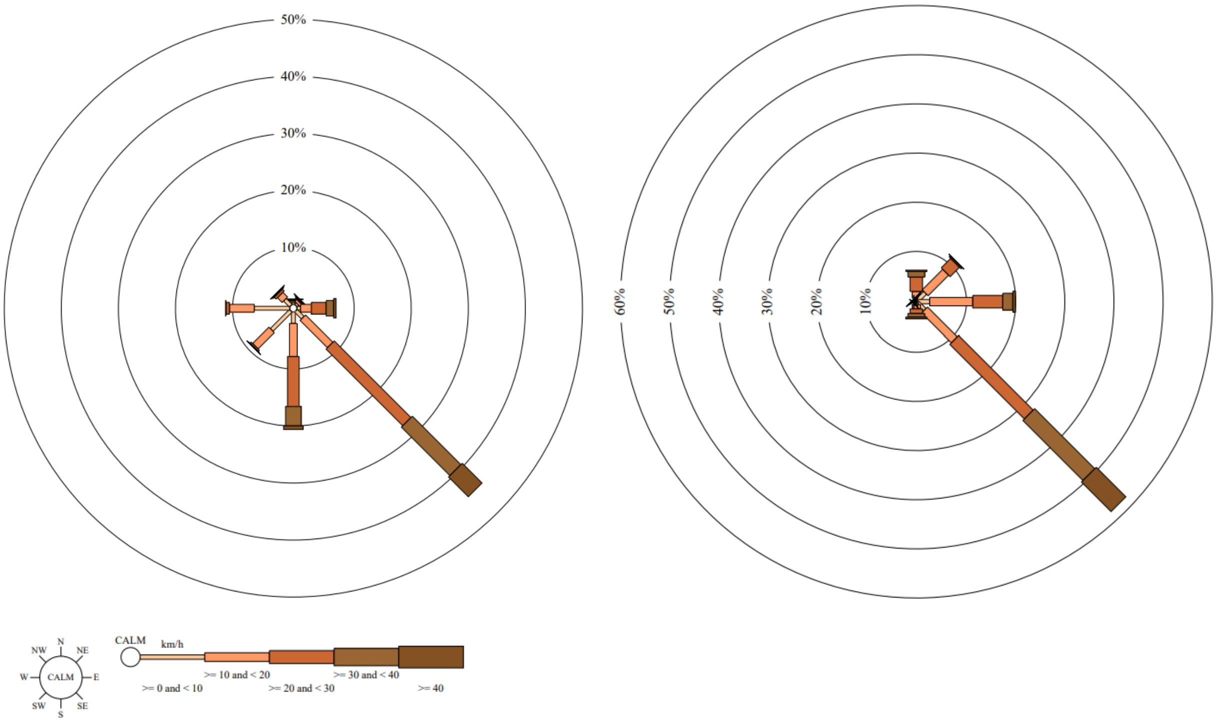

Figure 2-1: Low Island Wind Roses – 9am (left) and 3pm (right) from 1967 to 2024 (BOM, 2024)

2.2 Wave Climate

Pebbly Beach has an east-northeast aspect, situated between Yule Point to the north and the 40-meter-high White Cliffs to the south. The beach is somewhat shielded from ocean swell waves by the Great Barrier Reef, located approximately 30 kilometres east of the site, however, attenuated swell passing through a passage south of Batt Reef does reach the site. As a result, the wave climate is a combination of the shorter period sea waves generated by the winds from the southeast and highly attenuated longer

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period swell waves approaching from east-northeast. The impact of regional setting is presented graphically in Figure 2-2.

Figure 2-2 Impact of Regional Setting on Wave Climate

Nearer to shore Pebbly Beach is located in a shallow embayment featuring rocky outcrops extending up to 300 meters offshore. These outcrops dissipate a significant amount of energy, reducing wave height and energy at the shoreline. Due to the shallow bathymetry, wave heights are largely depth limited, even under the extreme wave conditions. In addition, refraction and diffraction combined with bed friction further reduces the height of waves propagating towards Pebbly Beach.

2.2.1 Ambient Waves

The ambient wave climate at Pebbly Beach has been characterised using data from the Cairns wave rider buoy (WRB), operated by the Department of Environment, Science and Innovation (DESI). The WRB is situated 25 km south of the study area in 12 meters of water, with data collected from 1997 to 2023. Despite its distance from Pebbly Beach, the data is still useful in defining the local wave climate. Wave heights have been analysed in terms of the recorded significant (total) wave height. The associated wave roses are presented in Figure 2-3. This shows two distinct wave conditions, with short period local sea waves approaching form the E through ESE, and longer period swell waves approaching from the NE.

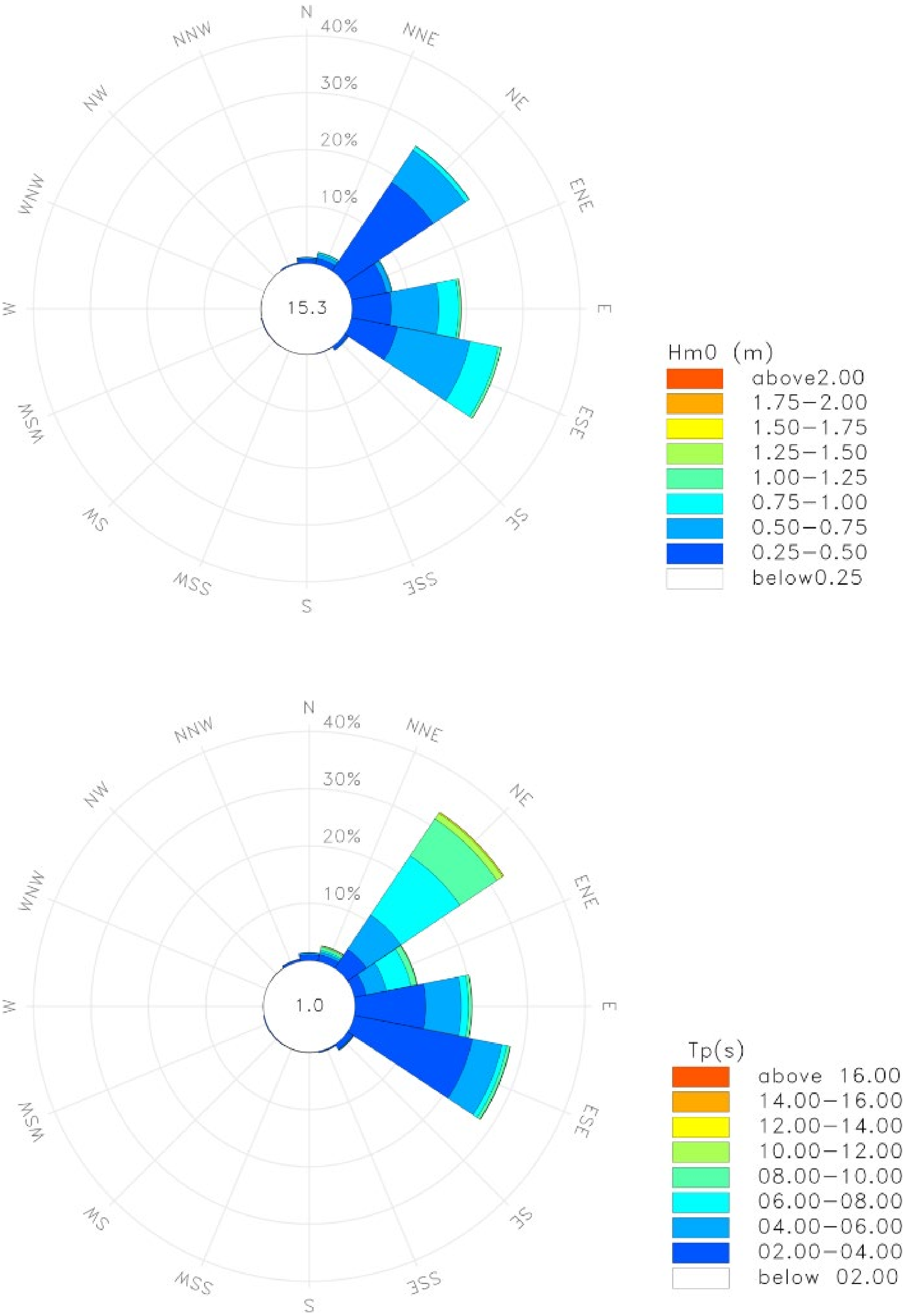

Figure 2-3: Cairns Wave Rider Buoy, wave height (upper) and wave period (lower) roses from 1997 to 2023

Frequency tables were also calculated for the probability of occurrence (Table 2-1) of wave height for a given wave direction. The wave analysis shows that:

- The most common wave direction is swell waves reaching the Cairns wave rider from NE (33%)
- However, seas waves ESE (28%) and east (20%) are dominant;
- The most common wave height is in the low range from 0.50 to 0.75 metres (43% of the time)
- The wave heights in the study area are relatively low for the majority of time; and,
- During extreme events, significant wave heights up to 3 metres have been measured.

Table 2-1 Probability of occurrence (%) of wave heights for given wave directions at the Cairns WRB

Directional sector; Wave Height Classes, Hs [m]; Probability of occurrence [%]

Wave Height Classes, Hs [m]	N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Total
0.00-0.50	0.38	0.70	6.60	4.03	1.25	0.95	0.58	0.24	0.07	0.10	0.06	0.04	-	-	0.05	0.26	15.33
0.50-0.75	0.74	1.07	18.74	6.26	6.84	8.22	0.67	0.10	0.03	0.04	0.07	0.10	-	-	0.01	0.21	43.10
0.75-1.00	0.24	0.71	6.77	0.91	8.36	13.02	0.12	0.01	-	-	0.03	0.04	0.01	-	-	0.02	30.26
1.00-1.25	0.08	0.30	0.85	0.12	3.46	5.06	0.01	-	-	-	-	-	-	-	-	-	9.94
1.25-1.50	0.02	0.07	0.06	0.03	0.45	0.51	-	-	-	-	-	-	-	-	0.01	-	1.19
1.50-2.00	0.01	0.01	-	-	0.05	0.03	-	-	-	-	-	-	-	-	-	-	0.13
2.00-2.50	-	-	-	-	-	0.01	-	-	-	-	-	-	-	-	-	-	0.02
2.50-3.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Above 3.00	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.01
Total	1.47	2.86	33.02	11.35	20.41	27.80	1.38	0.35	0.10	0.14	0.16	0.18	0.01	0.00	0.07	0.49	

Spectral peak energy periods (Tp) in the Cairns region generally range from 2 to 12 seconds, though most recordings fall within a narrower range of 2.5 to 6.0 seconds. These shorter periods result from the limited fetch distances where the waves are generated. The long period waves with periods greater than 6 seconds are swell waves, generated outside the reef and propagating through gaps with significantly reduced heights. Although sea waves typically have short periods, longer periods can occur during events with wind speeds over 55km/h (Beach Protection Authority, 1984), usually associated with tropical cyclones. Swell waves generally have periods greater than 6 seconds, and as seen in the wave period rose in Figure 2-3 the distribution by direction reveals that waves from the east-southeast and east sectors tend to have shorter periods compared to the northeasterly waves. Meaning these waves are produced by wind (sea waves).

When compared with the Cairns data the wave climate offshore of Pebbly Beach would be different in the following ways:

1. Swell waves would approach from an east-northeasterly direction due to the relative position of the gap in the reef relative to the site (refer Figure 2-2).
2. Sea waves offshore would be larger due to the longer fetches in the dominant SE corridor.

As described previously this wave climate will be heavily modified by the bathymetry with local headlands and reefs and rock platforms reducing the wave heights and restricting angles of approach.

2.2.2 Extreme Waves

Table 2-2 presents the significant wave height and peak wave period for various Average Recurrence Interval (ARI) events, with wave heights provided by BMT WBM (2013) and wave periods based on the observed wave climate during tropical cyclones. The 200-year ARI event will be used as the design condition in accordance with the Queensland Prescribed Tidal Works Code. A significant offshore wave height of 2.8 meters and a period of 6.2 seconds have been selected for this event. It is important to note that this wave height was determined at a depth of approximately 10 meters and will require transformation to obtain the design wave height and period at the structure's toe.

Table 2-2: Offshore Significant Wave Height and wave periods

Parameter	5% AEP 20 yr ARI*	2% AEP 50 yr ARI*	1% AEP 100 yr ARI	0.5% AEP 200 yr ARI	0.2% AEP 500 yr ARI	0.1% AEP 1,000 yr ARI	0.01% AEP 10,000 yr ARI
Hs (m)	2.66	2.71	2.74	2.80	2.85	2.87	2.92
Tp (seconds)	5.2	5.7	6.0	6.2	6.5	6.7	7.0

**Note: The study (BMT WMB, 2013) only provided data for 100 to 10,00 year ARI events. Therefore, interpolation was used to obtain the 20 and 50 year ARI design wave heights.*

2.3 Water Levels

The design water level at the site has been determined based on a combination of:

- astronomical tides
- storm surge due to tropical cyclones; and,
- sea level rise.

2.3.1 Ambient (tidal)

Tidal planes for Port Douglas (approximately 20km north of Pebbly Beach) are provided in Table 2-3.

Table 2-3: Port Douglas Tidal Planes (MSQ, 2024)

Tidal Plane	2024 Water Level m above LAT	2024 Water Level m above AHD
Highest Astronomical Tide (HAT)	3.40	1.82
Mean High Water Springs (MHWS)	2.54	0.96
Mean High Water Neaps (MHWN)	1.88	0.30
Mean Sea Level (MSL)	1.65	0.07
Australian Height Datum (AHD)	1.58	0.00
Mean Low Water Neaps (MLWN)	1.42	-0.16
Mean Low Water Springs (MLWS)	0.75	-0.83
Lowest Astronomical Tide (LAT)	0.00	-1.58

2.3.2 Extreme (cyclonic)

The design water levels from the various studies are presented in Table 2-4.

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Table 2-4: Design storm tide surge levels (including wave setup) for Oak Beach (BMT WBM, 2013)

Location	1% AEP 100 yr ARI	0.5% AEP 200 yr ARI	0.2% AEP 500 yr ARI	0.1% AEP 1,000 yr ARI	0.01% AEP 10,000 yr ARI
Storm Surge (excluding wave setup + runup)	1.29 m AHD	1.60 m AHD	2.01 m AHD	2.31 m AHD	3.13 m AHD
Storm Tide (excluding wave setup + runup)	1.84 m AHD	2.09 m AHD	2.40 m AHD	2.66 m AHD	3.30 m AHD
Storm Tide (including wave setup + runup)	2.96 m AHD	3.26 m AHD	3.61 m AHD	3.88 m AHD	4.55 m AHD

Based on a 100-year design life and a 200-year ARI storm event, the design storm tide is 2.09m. Note that the storm tide design used for rock rise calculation excludes wave setup and runup.

2.3.3 Sea Level Rise (future impacts)

Sea level rise is the projected increase in sea level caused by global warming due to climate change. A sea level rise of 0.8m has been allowed for in this design to coincide with a 100-year design life. This level is based on the IPPC Sixth Assessment report considering the SSP2-4.5 scenario (Table 2-5), which is the most likely scenario to occur based on the changes to the climate to date (2024). It should be noted that the Queensland government (Department of State Development, Infrastructure, Local Government and Planning, 2022) adopt the SSP5-8.5 scenario and adopt a 0.8m increase by 2100.

Table 2-5: SLR projections (Source: IPCC,2021)

	SSP1-1.9	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5	SSP5-8.5 *Low Confidence*
Thermal expansion	0.12 (0.09–0.15)	0.14 (0.11–0.18)	0.20 (0.16–0.24)	0.25 (0.21–0.30)	0.30 (0.24–0.36)	0.30 (0.24–0.36)
Greenland	0.05 (0.00–0.09)	0.06 (0.01–0.10)	0.08 (0.04–0.13)	0.11 (0.07–0.16)	0.13 (0.09–0.18)	0.18 (0.09–0.59)
Antarctica	0.10 (0.03–0.25)	0.11 (0.03–0.27)	0.11 (0.03–0.29)	0.11 (0.03–0.31)	0.12 (0.03–0.34)	0.19 (0.02–0.56)
Glaciers	0.08 (0.06–0.10)	0.09 (0.07–0.11)	0.12 (0.10–0.15)	0.16 (0.13–0.18)	0.18 (0.15–0.21)	0.17 (0.11–0.21)
Land-water Storage	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)	0.03 (0.02–0.04)	0.03 (0.01–0.04)	0.03 (0.01–0.04)
Total (2030)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.09 (0.08–0.12)	0.10 (0.08–0.12)	0.10 (0.09–0.12)	0.10 (0.09–0.15)
Total (2050)	0.18 (0.15–0.23)	0.19 (0.16–0.25)	0.20 (0.17–0.26)	0.22 (0.18–0.27)	0.23 (0.20–0.29)	0.24 (0.20–0.40)
Total (2090)	0.35 (0.26–0.49)	0.39 (0.30–0.54)	0.48 (0.38–0.65)	0.56 (0.46–0.74)	0.63 (0.52–0.83)	0.71 (0.52–1.30)
Total (2100)	**0.38 (0.28–0.55)**	**0.44 (0.32–0.62)**	**0.56 (0.44–0.76)**	**0.68 (0.55–0.90)**	**0.77 (0.63–1.01)**	**0.88 (0.63–1.60)**
Total (2150)	0.57 (0.37–0.86)	0.68 (0.46–0.99)	0.92 (0.66–1.33)	1.19 (0.89–1.65)	1.32 (0.98–1.88)	1.98 (0.98–4.82)
Rate (2040–2060)	4.1 (2.8–6.0)	4.8 (3.5–6.8)	5.8 (4.4–8.0)	6.4 (5.0–8.7)	7.2 (5.6–9.7)	7.9 (5.6–16.1)
Rate (2080–2100)	4.2 (2.4–6.6)	5.2 (3.2–8.0)	7.7 (5.2–11.6)	10.4 (7.4–14.8)	12.1 (8.6–17.6)	15.8 (8.6–30.1)

The extreme water level adopted for the design of coastal defences is 2.89m AHD (2.09 + 0.80).

2.4 Nearshore Water Depth

The nearshore bathymetry of the area surrounding Pebbly Beach in Cairns was obtained from the Intergovernmental Committee on Surveying and Mapping's Elevation Information System (ELVIS), as illustrated in Figure 2-4. The bathymetric data reveals that the waters around Pebbly Beach are relatively shallow, with depths of less than 1 meter above Australian Height Datum (AHD) extending up to 250 meters offshore. Therefore, the foreshore slope off Pebbly Beach is quite gentle, with an approximate gradient of 1 in 100.

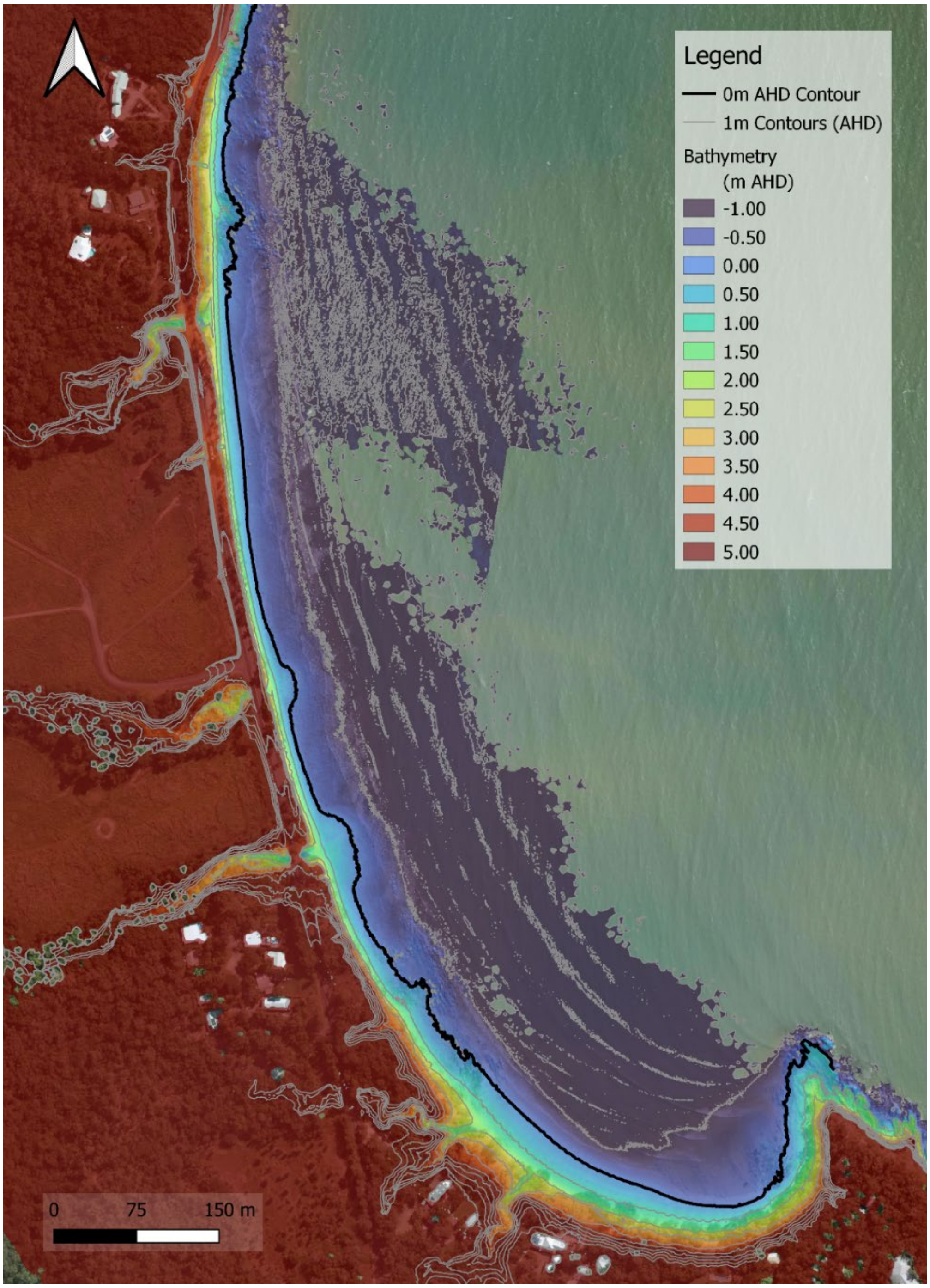

Figure 2-4: Nearshore bathymetry of Pebbly Beach

Additionally, there is a rocky bed platform beneath the beach area, which extends into the offshore region. This reef platform is situated at around 0 meters AHD, providing a stable and relatively flat underwater landscape. The presence of this rocky platform likely influences the coastal dynamics and sediment distribution in the area, contributing to the unique marine environment of Pebbly Beach.

3 Design Inputs (Rock Revetment Wall Design)

3.1 Design Life and Design Event

A revetment wall would be classified as Facility Category 3 (equivalent to a standard commercial structure) with a design working life of 50 years, as per AS4997. However, this revetment wall is a small component of a much larger project, for which a 100-year design life has been chosen. This extended design life was selected due to the project's proximity to the shoreline.

According to the Queensland Government's Coastal Protection and Management Regulation 2017, Schedule 3 (Prescribed Tidal Works Code), a revetment must withstand the effects of waves or a combination of waves and water levels resulting from a storm event with a 2% Annual Exceedance Probability (AEP), taking sea level rise into account. Typically, a revetment is designed for a 50-year lifespan, making the 2% AEP appropriate. However, given the 100-year design life of this project, a more stringent 0.5% AEP design event has been selected. This includes a 200-year wave height combined with a 200-year water level. Although this approach is conservative, as the likelihood of a 200-year wave coinciding with a 200-year water level is very low, it ensures robust protection.

The rock structure is designed to sustain up to 5% damage in a 200-year ARI event, balancing stability with cost-effectiveness. It is also capable of withstanding a 20-year ARI event with no damage.

3.2 Toe Level

After reviewing the provided cross-sections of the existing surface and aerial imagery, it has been determined that the toe will be founded on a non-erodible rock profile, found at 0 m AHD or above. Since this rock bed is a non-erodible surface, no specific toe design is required for this section. Although the rock bed extends across the entire length of Pebbly Beach, the levels are to be confirmed.

The toe elevation has been designed at 0.35 m AHD but may extend as low as 0 m AHD. This variation has been addressed by applying a conservative sea-level rise (SLR) allowance. However, if the toe extends significantly below 0 m AHD, the design will need to be reassessed.

3.3 Design Water Levels

The design water level has been taken 200-year ARI storm tide plus future sea level (**Section 2.3**):

- Storm Tide: 2.09m AHD
- SLR: 0.8m

Therefore, the design water level for this site is 2.89m AHD.

3.4 Design Wave Conditions

3.4.1 Offshore Design Wave Conditions

The offshore design wave conditions for a 200-year ARI event are (**Section 2.2**):

- Significant wave height of 2.8 m
- Peak wave period of 6.2 seconds

3.4.2 Wave Conditions at the Structure

The nearshore height is the minimum of the shoaled wave height and the depth limited wave height, which are calculated below.

Shoaled Wave Height

The shoaled height of the wave at the structure toe as defined by (USACE, 2006):

$$H_1 = H_0 K_s K_r$$

Where:

H_0= Deepwater wave height

K_s = coefficient of wave shoaling for straight and parallel contours

K_r = coefficient of wave refraction for straight and parallel contours

Wave refraction is the bending of waves caused by a change in bed level. The shoaling coefficient on a coast with straight, parallel depth-contours is given by (USACE, 2008):

$$K_r = \left(\frac{1 - sin^2\theta_0}{1 - sin^2\theta_1}\right)$$

Where:

K_r = coefficient of wave refraction for straight and parallel contours

θ_0 = deepwater wave angle

θ_1 = wave angle in shallow water

The shallow water wave angle is given by (USACE, 2008):

$$\sin\ \theta_1 = \frac{C_1 \sin\theta_0}{C_o}$$

Where:

C_1 = shallow water wave celerity

C_0 = deep water wave celerity

θ_0 = deepwater wave angle

θ_1 = wave angle in shallow water

The deepwater group velocity is given by (USACE,2006):

$$C_o = \frac{gT}{2\pi}$$

Where:

T = wave period

g = acceleration due to gravity 9.81m/s^2

The shallow water group velocity is given by (USACE, 2008):

$$C_1 = \sqrt{gh}$$

Where:

h = water depth at the location of the shallow water wave height

g = acceleration due to gravity 9.81m/s^2

For this study it is assumed the waves moves perpendicular to the shoreline, therefore the offshore angle is 0 and the K_r is equal to 1 (no wave refraction).

Wave shoaling is the effect by which surface waves entering shallower water change in wave height. The shoaling coefficient on a coast with straight, parallel depth-contours is given by (USACE, 2008):

$$k_s = \left(\frac{C_{g0}}{C_{g1}}\right)^{\frac{1}{2}}$$

Where:

K_s = coefficient of wave shoaling for straight and parallel contours
C_{g0} = group velocity in deep water
C_{g1} = group velocity in shallow water

The group velocity in deepwater is given by (USACE, 2008):

$$C_{go} = \frac{gT}{4\pi}$$

Where:

T = wave period
g = acceleration due to gravity 9.81m/s^2

In shallow water the group velocity is calculated using the same equation as the shallow water wave celerity.

The shoaling coefficient is provided in Table 3-1 and the shoaled wave height at the structure toe is provided in Table 3-2 (2.97m wave height).

Table 3-1: Shoaling coefficient.

ARI (years)	T (s)	d (m MSL)	C_{go} (m/s^2)	C_{g1} (m/s^2)	K_s
100	9.20	5.30	7.18	6.30	1.07

Table 3-2: Wave height and period at structure toe

ARI (years)	Deepwater wave height (H_0) (m)	Depth at structure toe (m)	Refraction coefficient (K_r)	Shoaling coefficient (K_s)	Wave height at structure (H_1) (m)	Wave Period Shallow (sec)
100	2.80	2.54	1.00	1.06	2.97	7.23

Depth Limited Wave Breaking

EurOtop (2018) and CIRIA (2007) indicates that the nearshore breaking wave height (H_{mo}) can be determined from the breaker index, which is dependent on nearshore beach slope and the relative water depth determined from the breaker water depth at structure toe (h) and deepwater wave length (Lo). Based on a typical average slope of 1V:100H, a suitably conservative breaker index can be derived from the graphical fitted curve in Figure 3-1 where:

$S_{op} = H_{mo\ deep}/L_{op}$
H_{mo} = depth limited significant wave height at toe of structure
$H_{mo\ deep}$= depth limited significant wave height in deep water

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L_{op} = peak wave length in deep water
h = water depth at toe of structure

For $H_{m0\ deep}$ = 2.80m (calculated in Section 3.4.1) and L_{op} = 60 (6.2 second period) in deep water, S_{op} ~ 0.04. Assuming a water depth at the toe of the structure of 2.54m and L_{op} = 60, h/L_{op} =0.04. With a foreshore slope of 1:100, H_{mo}/h ~0.54m (Figure 3-1).

It should be noted that breaker height is dependent on wave period, water depth near the structure and beach slope and it is independent of the offshore wave height. Therefore, a storm event with a lower offshore wave height and similar wave period would result in the same breaker height, unless of course the transmitted nearshore wave height is too low. Conversely, a storm that lacks the energy to generate a sufficient amount of scour would result in a lower depth limited wave height near the structure.

The depth-limited wave height at the structure toe is provided in Table 3-3. The depth-limited breaking wave height is 1.37m for rock size. This is the maximum wave height that can occur in a water depth of 2.54m. As the depth-limited wave breaking height is smaller than the 100 year ARI shoaled wave height calculated above the depth limited wave height was chosen as the design wave height.

Table 3-3: Depth-limited wave height at structure (EurOtop, 2018)

ARI (years)	Slope	h_b/L_0	h/L_{op}	H_{m0}/h	h (m)	H_b (m)
200	100	0.04	0.04	0.54	2.54	1.37

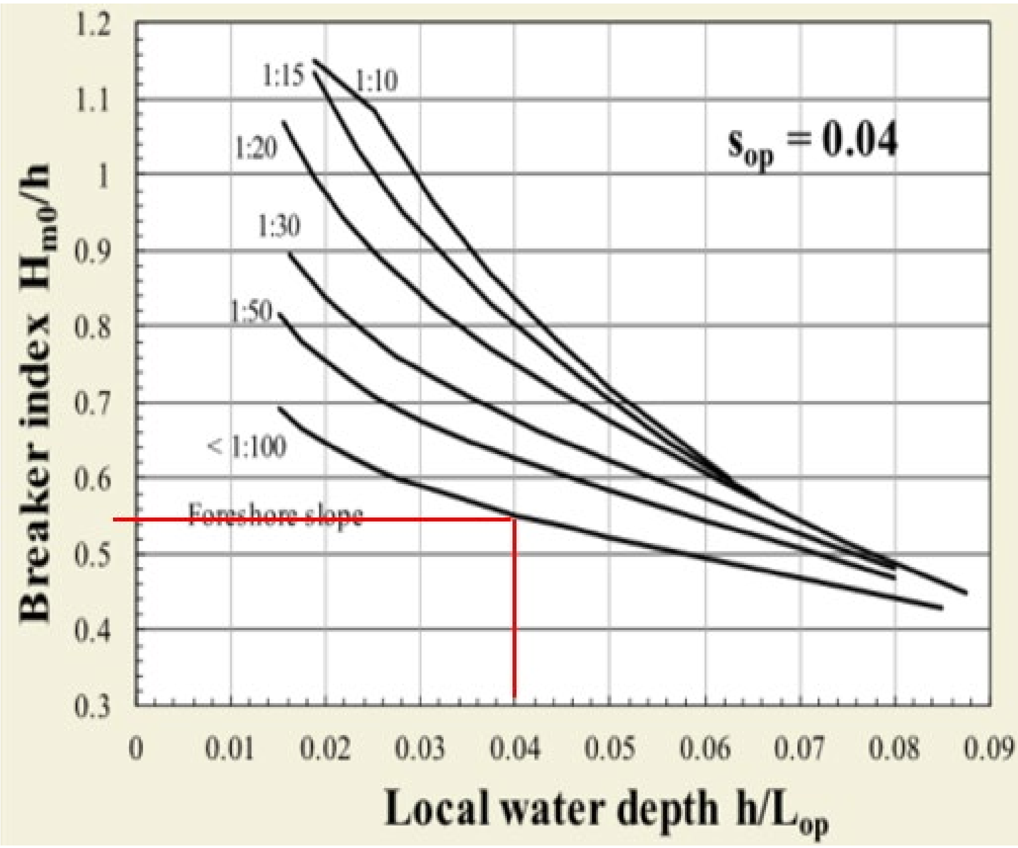

Figure 3-1: Depth-limited significant wave heights for uniform foreshore slopes (Figure 2.4, EurOtop 2018).

4 Geographic Indicators and Site Observations

The geography of the site reveals much about the coastal morphology of the beach and is a reliable indicator of processes driving the system. Interpreting these natural indicators can inform the assessment of coastal processes and likely responses to any changes. Many of the findings are summarised in Figure 4-1.

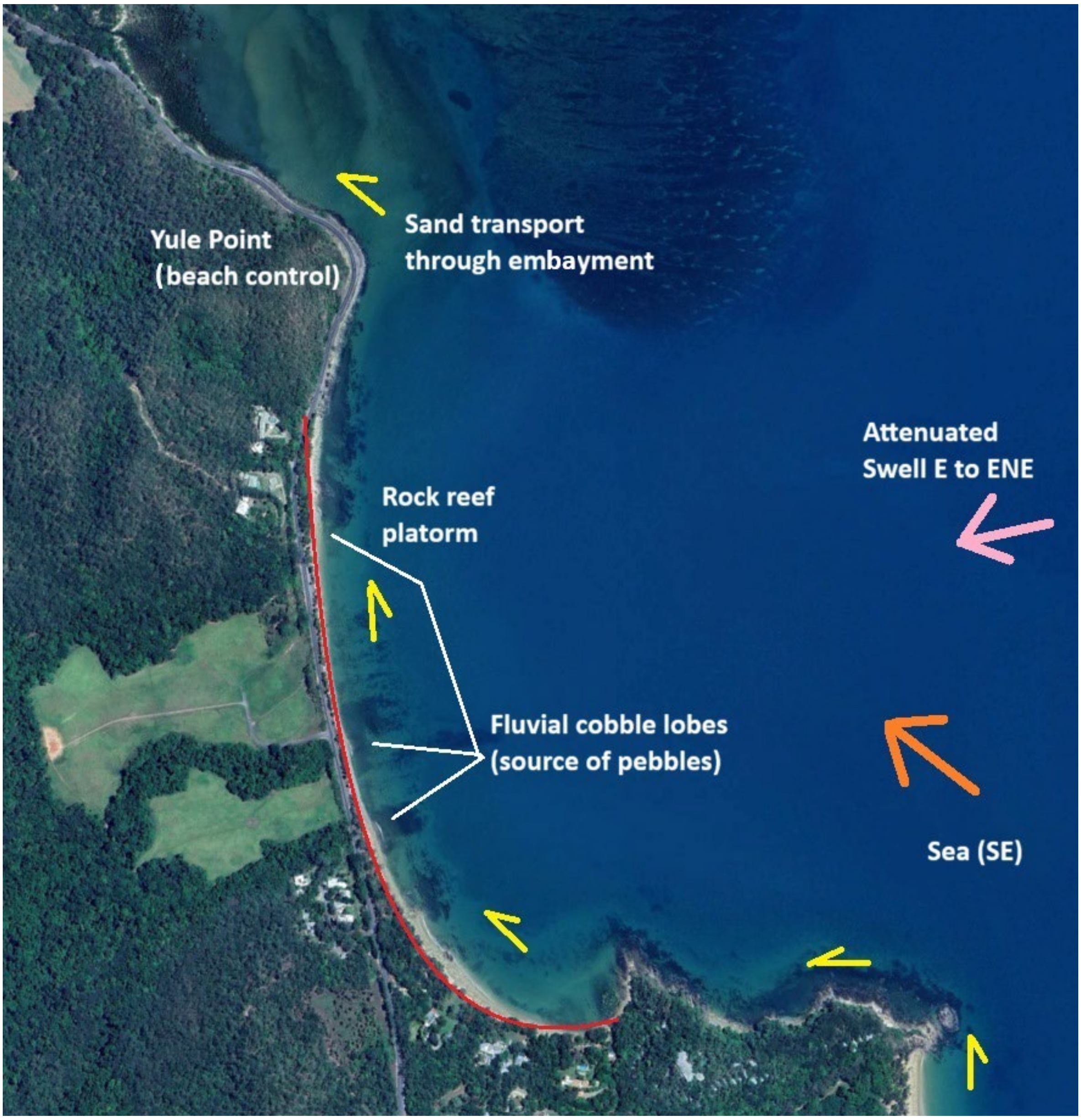

Figure 4-1: Overview of geographic evidence

4.1 Rocky Headlands

Prominent rocky headlands with exposed rock reefs extending offshore reveal that the beaches in the area are controlled by the headlands. Further, the sediment transport potential (what waves and currents are able to move) is significantly exceeding the sediment availability around the heads.

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Yule Point is the control for this section of coast and effectively anchors the coast here. These features are important as it reveals the coastline will have good stability when considering long term erosion.

4.2 Beach Plan Form

The beach has a zeta plan form (see red line in Figure 4-1), revealing that the longshore sediment transport regime is towards the north, in line with wave climate and regional coastal processes. The depth of the embayment at the southern end of the beach reveals that sediment infeed from the south is low relative to the transport potential of that section of the coast (refer to Figure 4-2).

Figure 4-2: Yule Point is a significant barrier to longshore transport of pebbles and anchors Pebbly Beach

The orientation of the northern end of the beach broadly indicates that the averaged wave energy direction approaching the coast in this area is just south of east.

4.3 Low Tide Platform

The low tide platform, a common feature in tide dominant systems, impedes the cross-shore movement of sediments, especially during storm events. As seen in Figure 4-3, unlike most beaches in this region, the platform on this this beach is rocky, rather than fine sand. The platform results inhibited responses to storm waves, with erosion of the upper profile limited.

Figure 4-3: Rock platform limiting gravel cross-shore movement

4.4 Nature of Sediments

The beach and adjacent areas lack fine sediments (muds or even fine sand). This reveals that despite the relatively mild wave climate only coarser material has persisted at the beach. The lack of fine material reveals that the coast is not receiving large volumes of sediment.

4.4.1 Pebbles

The pebbles that make up much of the beach material are rounded and often pale in colour. Similar pebbles are not found on adjacent beaches and do not even extend to the northern or southern extremities of Pebbly Beach.

There are two large lobes of cobble and pebble sized material found on the southern end of the Pebbly Beach and a smaller lobe at the norther end of the beach. These lobes are linked to creeks that discharge onto the beach (refer Figure 4-4, Figure 4-5 and Figure 4-9).

Figure 4-4: One of two lobes of cobble and pebble sized material resulting from fluvial discharges (note culvert in distance)

Figure 4-5: Southernmost fluvial lobe seen from the shore

These lobes of fluvial deposits are the likely source for the pebbles found on the beach. Unlike the sand, there is no evidence that the pebbles are being transported under wave action out of this embayment. Due to their behaviour under wave action, the pebbles are effectively trapped by Yule Point to the north and the rock platform underlying the profile to the east.

The pebbles on the beach have been sorted under wave action with pebbles at the northern end of the beach typically smaller than those at the southern end as seen in Figure 4-6. This effect should be noted in managing pebbles during excavation for the rock revetment wall to ensure pebbles are returned to the beach near where they were excavated.

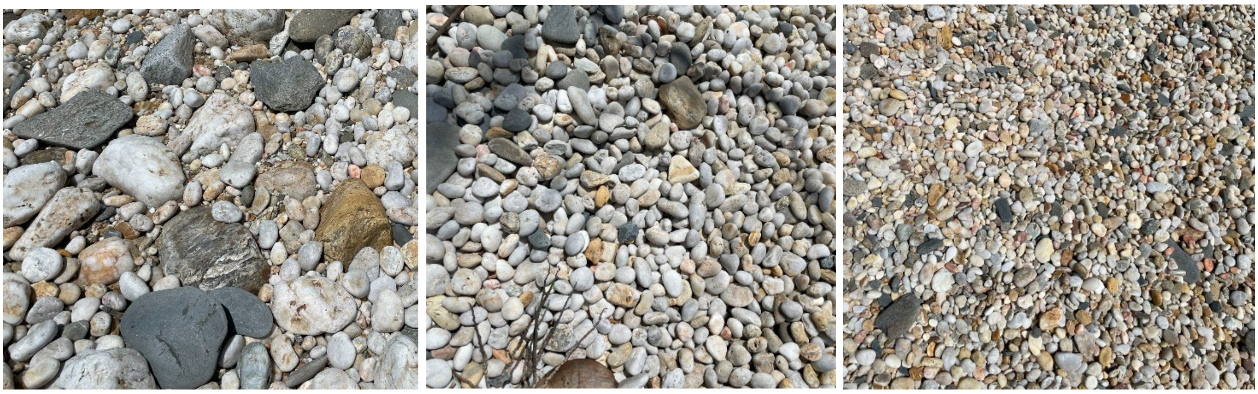

Figure 4-6: Pebbles graded along beach from course near the southern lobes (left) to finer at the northern end (right)

4.4.2 Sand

The beaches north and south of Pebbly Beach are comprised entirely of sand as seen in Figure 4-7 and Figure 4-8.

Figure 4-7: Southern end of Pebbly Beach all sand beyond high rock outcrop

Figure 4-8: Beyond Yule Point, to the North, a wide sandy beach sheltered by extensive offshore reef (note distant breaking waves)

As seen Figure 4-1 sand is moving northward under wave action and can travel past Yule Point in deeper offshore areas. This sand is also seen transiting through Pebbly Beach (refer Figure 4-9), but the relatively minor volumes reveal that the steep beach profile combined with the exposure to both sea and swell waves prevent significant accumulations.

Figure 4-9: Sandy material apparent on the lower profile, note smaller northern lobe of cobble and pebble sized material to left

4.5 Road Embankment and Beach Interactions

The road embankment comprises soil that is very distinct from the beach material. This reveals that the embankment is not an extension of the beach profile, rather this material and the profile are only exposed to coastal processes during extreme events, as seen in Figure 4-10.

The nature of the embankment indicates that, unlike the beach, when exposed to wave action permanent reshaping and erosion can be expected. It is because of this response that the foreshore requires protection from wave action despite the coastline in this area being stable over longer timelines. Effectively the embankment can be seen as separate from the beach. The embankment is an independent morphological feature that has not developed a resilient profile and is vulnerable.

Figure 4-10: Eroding embankment comprises no material consistent with the beach sediments (not the source).

5 Longer Term Beach Erosion

Satellite imagery can determine shoreline position and behaviour from over 40 years of satellite imagery. Satellite platforms include Landsat 5 (1984 - 2013), 7 (1999 - present), 8 (2013 - present) and Sentinel-2 (2015 - present), pixel resolution ranging between 10 m and 15 m and image capture varying from 5 to 16 days.

Two independent tools have been developed to analyse the satellite imagery, which are:

1 CoastSat a Python tool that enables extraction of shoreline position from individual satellite images at any coastline worldwide using sub-pixel extraction methods (Vos et al., 2019a, 2019b). While the horizontal errors for detected shoreline range have been reported to be between 7.3m and 12.7m Root Mean Square Error (RMSE) considering individual images, the bias of the data is much lower (Vos et al., 2019a). As such, the temporal resolution of the data means that signals can be discerned at seasonal and greater timescales.

2 Digital Earth Australia is a tool to accurately map the boundary between land and water (the 'waterline') (Bishop-Taylor et al, 2019). The tool uses the same sub-pixel extraction method as CoastSat. However, Digital Earth Australia combines aerials to provide a single, annualised shoreline position and is therefore suited to determining long-term trends.

5.1 CoastSat Analysis

CoastSat is an open-source software toolkit developed to analyse satellite imagery to accurately map the boundary between land and water (the 'waterline'). Each satellite image is applied through a shoreline detection algorithm, which maps the shoreline at the time of the satellite image (Vos et al., 2019, Figure 4-11). Pebbly Beach satellite imagery was analysed from 1987 to 2024 to determine long-term trends.

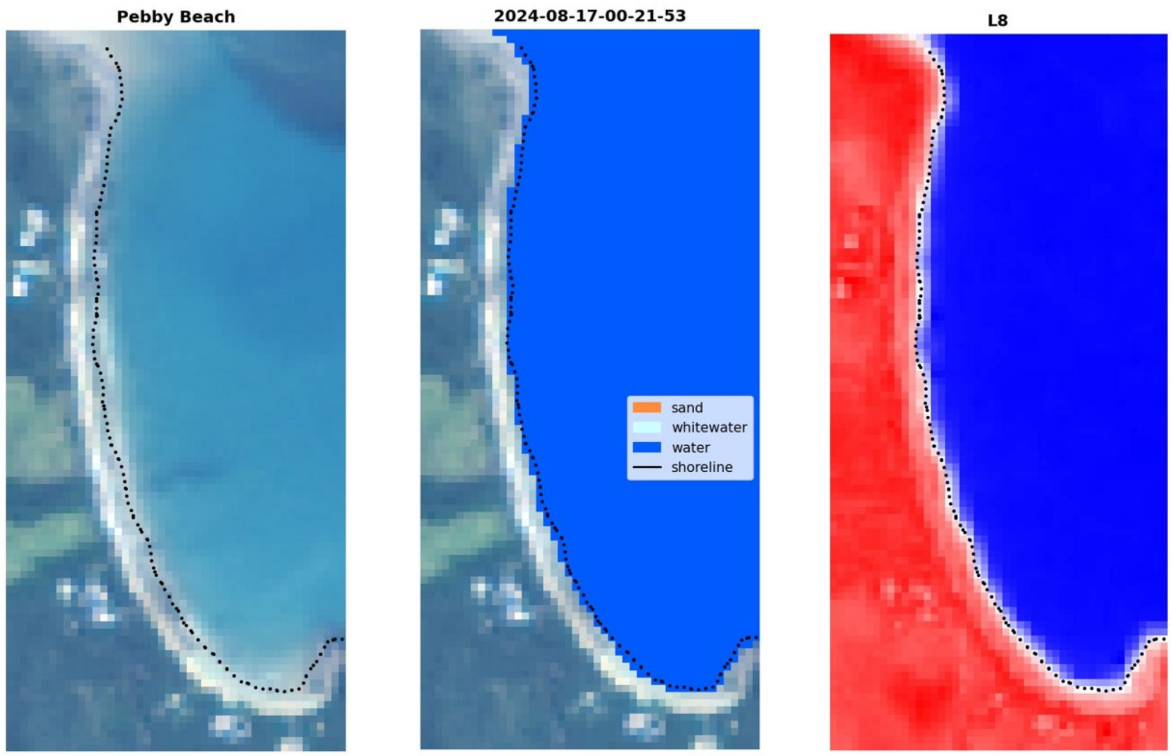

Figure 4-11: CoastSat shoreline detection algorithm for Pebbly Beach

Results from the CoastSat analysis are presented in Table 4-1. **Appendix A1** shows the periods of erosion and accretion for each transect**.**

Table 4-1: CoastSat erosion estimates (refer Appendix A1)

Line	1	2	3	4	5	6	7	8	9	10	11
Setting	South			South of lobes	Between Lobes	North of lobes		Rock Platform	Rock Platform	Rocky Coast	Yule Pt North
Beach Material	Sand	Sand	Sand	Pebble	Pebble	Pebble	Pebble	Pebble	Pebble	N/A	N/A
Change (m/y)	-0.20	-0.18	-0.20	-0.22	-0.14	-0.22	-0.23	-0.08	-0.05	-0.06	-0.04

- Southern End (Transects 1 to 7) – Indicates recession in the order of 0.2 m/year since 1987.
- Northern End (Transects 8 to 11) – This part of the embayment has remained net stable since 1987.

5.2 Digital Earth Australia Analysis

Interrogation of the Digital Earth Australia (DEA) site provides results as seen in Figure 4-12. The results indicate a slight shoreline recession in the central to the north and no movement to the south.

Figure 4-12: DEA recession analysis of Pebbly Beach

The DEA results can be used to examine broader areas, allowing for comparisons between Pebbly Beach and nearby beaches. The beaches north of Pebbly Beach are highly dynamic, with no substantial control structures to the north, resulting in significant areas of erosion (up to 2.5 m/year) and accretion. Oak Beach remains fairly stable, with the headland at its northern end acting as a control.

Figure 4-13 DEA Analysis looking at adjacent coastlines

5.3 Longer Term Recession Summary

The results of the CoastSat and DEA analysis both indicate that Pebbly beach is relatively stable, with potentially minor rates of recession through the central and southern parts of the beach. The northern end of the embayment has very little available sediment and will not experience recession. If we accept this analysis on face value, the mobile beach is experiencing slow rates of recession.

It is noted that the visual analysis of the data from both methods contains a significant variability (10's of meters) and that the beach location today is roughly found in the middle of the observed data. It is likely that the beach is actually stable (not experiencing recession).

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6 Impacts of Proposed Rock Revetment Wall

The proposed works will not impede broad coastal processes with the seawall not impacting sand morphology through the embayment and the pebbles remaining trapped on the platform. This section explores the nature of the solution and discusses commonly identified concerns, including:

- Impact on beach stability in front of the rock revetment wall (erosion).
- Accelerated erosion of foreshores beyond the rock revetment wall (end effects).
- Loss of trees.
- Reduction in beach width.

6.1 Proposed Solution

As described above the road embankment is an engineered structure that is vulnerable to erosion during extreme marine events. Because of this vulnerability, a rock revetment wall is proposed to protect approximately 600 m of the foreshore. The proposed solution is for a robust rock revetment wall that will protect the embankment from waves.

Key features of the draft design for the proposed solution include:

- Robust section (designed for 200 year ARI event)
  - Heavy duty geotextile to contain embankment material.
  - Rock fill below the armour that is at least 0.8 m thick
  - Double layer primary rock armour (M_{50} = 600 kg) that is 1.23 m thick
  - The section width (horizontal) is 3.7 m
- Toe founded on non-erodible strata or 0.0 m AHD if not on rock
  - Anticipate finding rock above 0.0 m AHD under beach in many locations.
  - No toe detail required as undermining by scour will not be an issue
- Crest found at 4 m AHD
  - Level defined based on no damage overtopping analysis in extreme events (<35 l/m/s)
  - Adopted level is at least 1 m below the crest of the embankment.
- Profile position, relative to the existing embankment is defined by geotechnical analysis.
- All beach material found below the rock revetment wall footprint is to be returned to the beach
  - Due to grading gravel returned to the beach should be located in close proximity to where it was excavated.
  - Material need only be placed on a rough profile; waves will reshape the beach profile to a new natural form.
- Stairs are to be installed at a key location over the rock revetment wall to allow access.
- Existing storm water (creeks) outlets will be preserved with the works to tie into culverts under road

These features are presented in Figure 6-1 Proposed extent and solution. Further the Landscaping plan is presented in Figure 6-4.

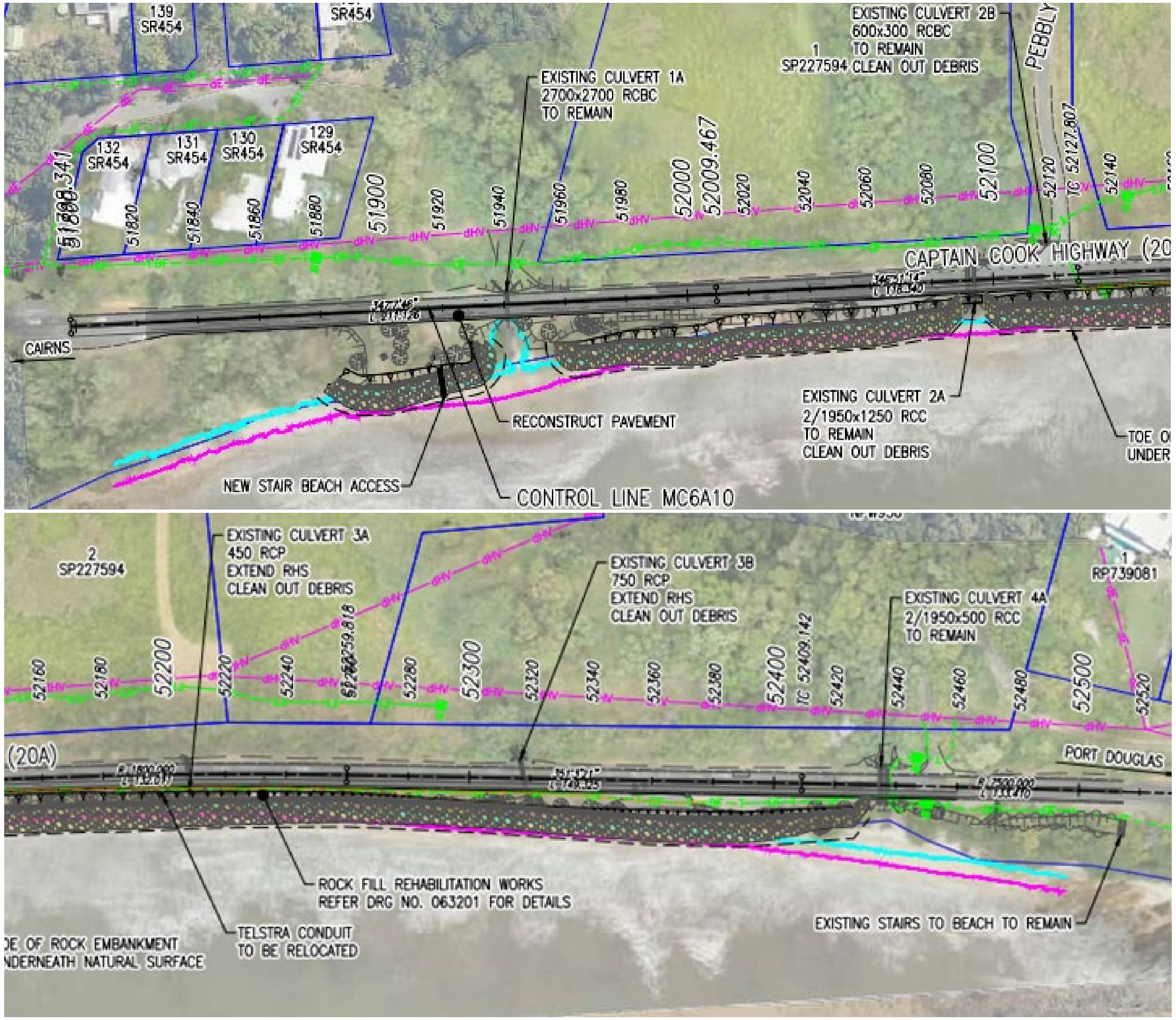

Figure 6-1 Proposed extent and solution (80% design)

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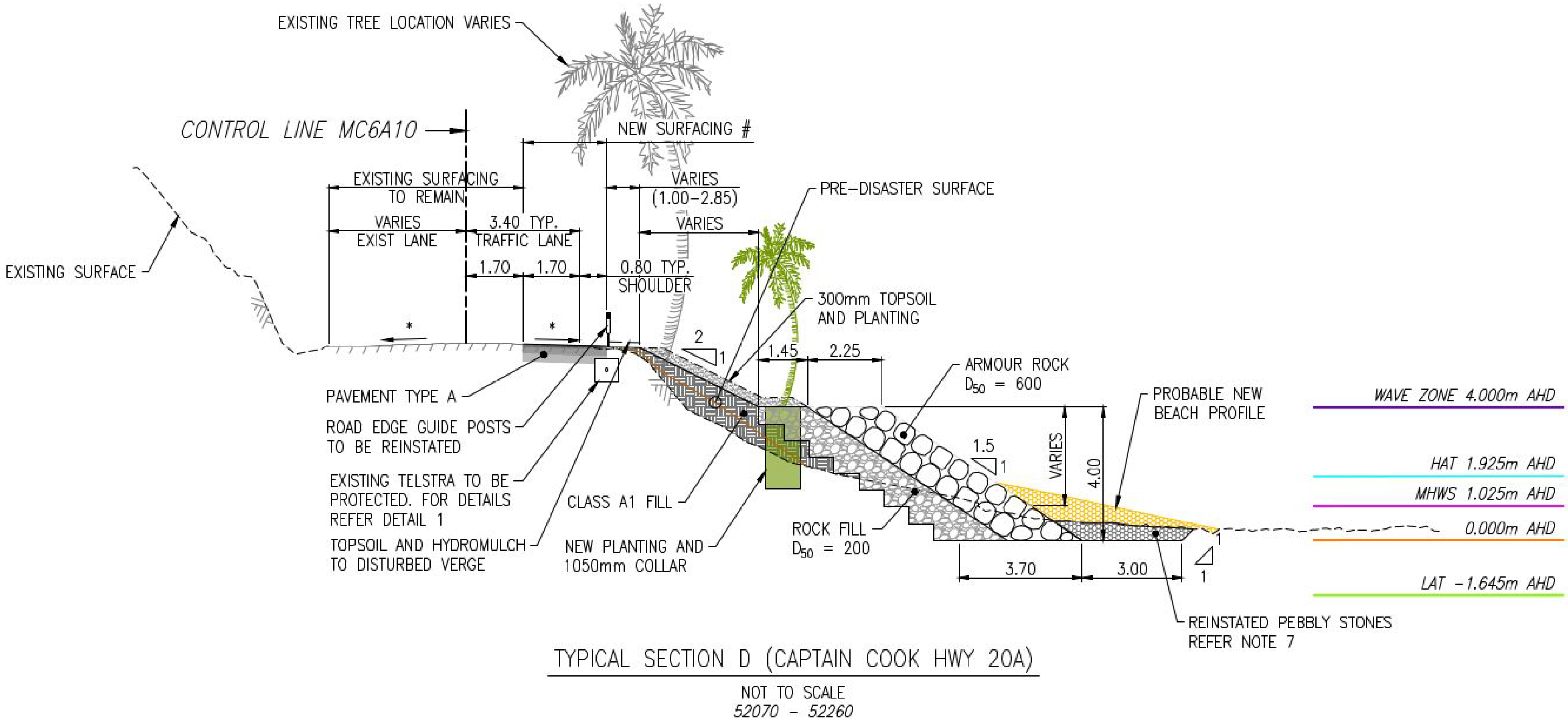

Figure 6-2 Typical Wider Section with allowance for berm (planting and future ride widening)

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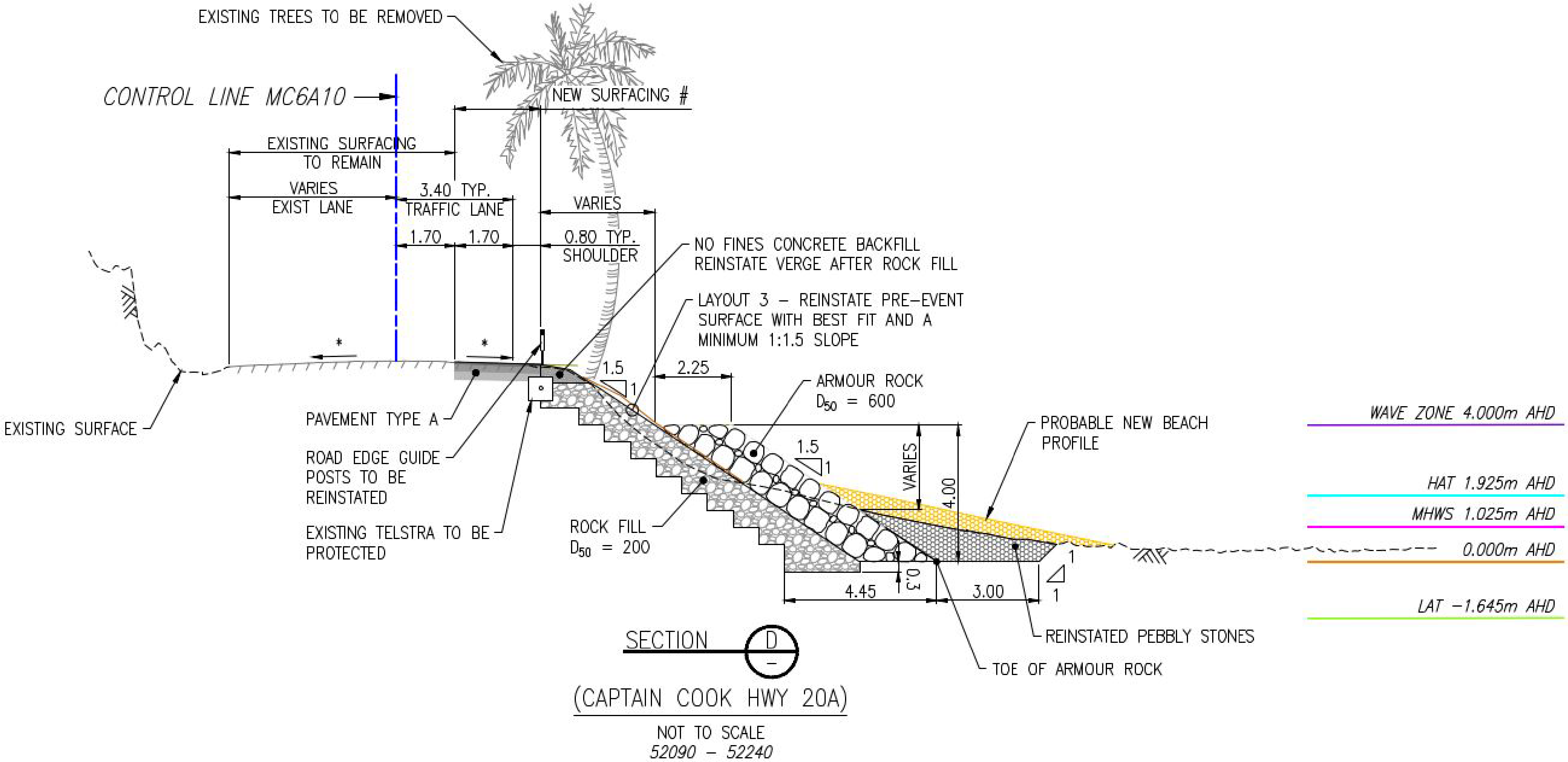
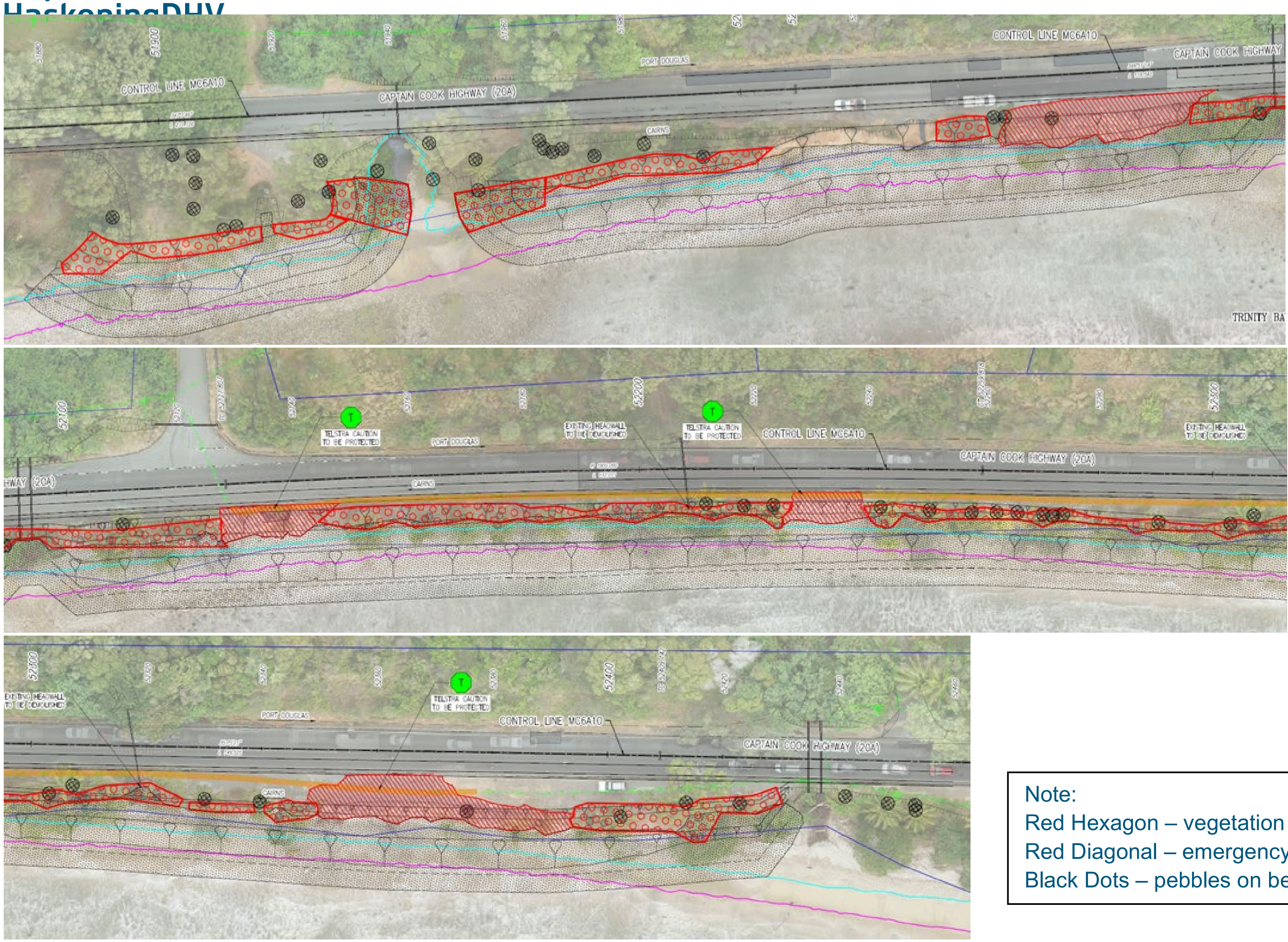


Figure 6-3 Typical Narrow Section (alternative)



Note:
Red Hexagon – vegetation
Red Diagonal – emergency rock defences
Black Dots – pebbles on beach

Figure 6-4 Landscaping plan - reveals trees saved and lost along with proposed plantings

It is noted that the design development has included various iterations and options. The process has stability of the embankment, minimising the footprint and maximising the vegetation retention or replanting. Broadly speaking the option of reducing the seaward extent (footprint) is linked with more vegetation loss. The current solution is pushed forward to permit retention of vegetation. Alternatives considered that are not incorporated in the preferred solution include:

- A seawall that extended vertically to the crest of the embankment (5 m AHD).
- Profile pushed further seaward to increase width behind seawall.
- Seawall pushed further shoreward requiring road widening to extend into western embankment.
- More targeted seawall extent resulting a fluctuating shoreline, exacerbating beach impacts.

6.2 Beach Profile and the Impact of Rock Revetment Walls

The beach profile, in front of the embankment, has recovered since Cyclone Jasper and largely buried the eroded embankment profile and emergency works. A wave formed pebble berm now exists at the rear of the beach profile as seen in Figure 6-5.

Figure 6-5 Pebble beach berm pushed up similarly in front of eroded embankment and emergency rock wall

A common concern regarding rock revetment walls is that the constructed revetments lead to increased erosion of the foreshore due to reflections or end effects. The theory is that the sea wall structure increases reflections and thus increases energy on the beach, leading to sediment profiles reshaping and preventing sediment from accumulating in front of the structure. It is noted that rock revetment walls are typically only built on eroding coastlines and that erosion issues pre-date their construction (not caused by the seawalls). Extensive experience with similar structures reveals that this issue is significantly overstated and as seen in Figure 6-5 the beach profile is not altered by the different embankment treatments on this beach.

6.3 Vegetation Loss and Management

The foreshore is known for its highly attractive vista with mature trees found in the embankment above the pebble beach. The common trees seen during the site inspection included:

- Coconut palms with small ball type root systems (refer Figure 6-6).
- Beach Almonds with large shady canopies and expansive shallow root systems (refer Figure 6-6).
- Casuarinas (She oaks) with expansive roots (refer Figure 6-6).
- Pandanus Palms with concentrated pyramid over a ball of roots (refer Figure 6-6).
- River and Orange Mangroves with expansive roots (refer Figure 6-7).
- Coastal Cottonwood with an expansive root system (refer Figure 6-7).

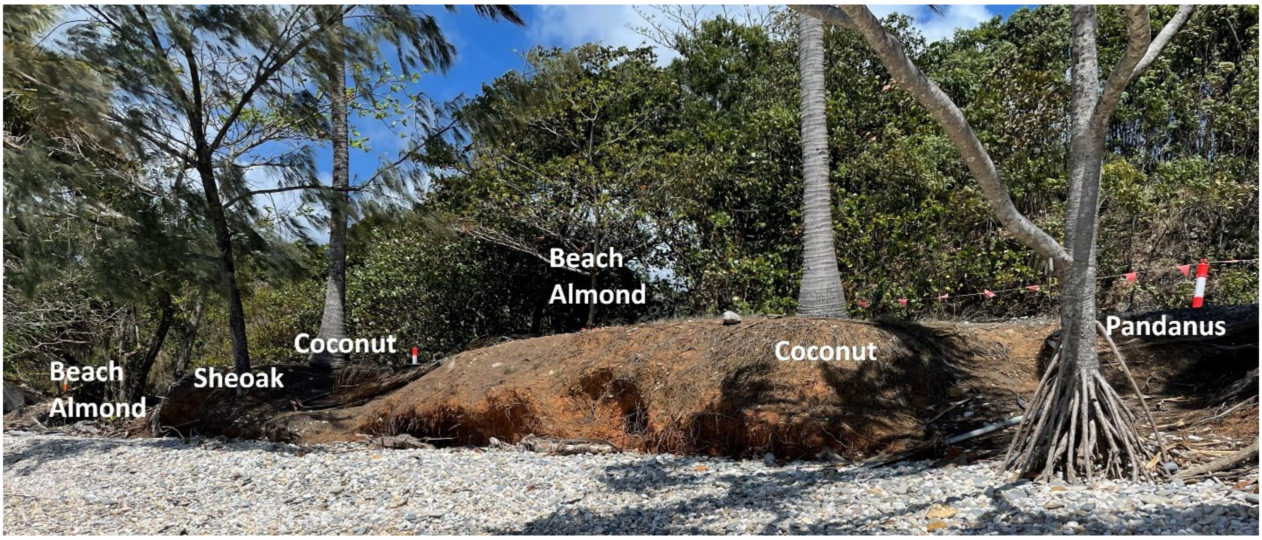


Figure 6-6 Trees common on the foreshore

Figure 6-7 Around drains mangroves can colonise despite high energy beach

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As discussed previously there has been a concerted effort to minimise the impact of the structure on the existing vegetation with the rock revetment wall sited in front of the embankment with a crest at 4 m AHD (at least 1 m below the road level). This level was assessed using detailed assessment of wave run-up and overtopping impacts during extreme events and will offer protection to current and future road works constructed behind the foreshore.

This crest level will preserve a significant number of the mature terrestrial trees. Despite this all vegetation along the length of the rock revetment wall with a base below 4 m AHD will be lost. The landscaping plan presented in Figure 6-4 provides insights into the extent of vegetation retention or loss.

It is noted that the seawall profile (protruding 3.7 m) provides opportunities for shallow rooted revegetation over the seawall.

6.4 End Effects

The term “End effects” describes the scenario whereby erosion is exacerbated on unprotected foreshores beyond the end of a rock revetment wall. There are two identified issues:

1. The rock revetment wall prevents material from the protected section of coastline being available to nourish beaches further along the coast.
2. Long shore currents are increased in intensity on the smooth engineered works that scour the unprotected ends of the breakwater.

Both of these effects are real, however, on this coastline the effects will not be appreciable. As identified in this report the coastline is not experiencing significant ongoing erosion and this combined with the structure being located high on the beach will reduce the risk of this occurring.

6.5 Footprint of the Rock Revetment Wall into Beach Profile

The rock revetment wall will be sited at the rear of the beach, with all beach material placed in front of the rock revetment wall. Despite this, the 3.7 m wide structure at a slope of 1 in 1.5 will encroach into the existing beach profile. The impact will be less severe than the plan indicates with the toe of the rock revetment wall at 0 m AHD, buried under the beach and the pebble material from the footprint of the warks placed on the beach profile. The forecast beach profile that will exist after the seawall is constructed is presented in Figure 6-2 and Figure 6-3.

With the anticipated beach response to the nourishment the likely intersection with the beach will be approximately 1.5 to 2.5 m above AHD. Effectively the beach width will be reduced by a few meters and, despite the nourishment during very high tides, there is a risk that there is not any dry beach exposed.

6.6 Alternative Works Extent (piecemeal wall)

It is noted that alternative options for the extent of works have considered with piecemeal solution focussing only on sections that experience erosion during the recent event proposed as a more affordable solution to a contiguous seawall. The use of a piecemeal solution would result in several additionally seawall ends that would require special turned in details to secure the ends of the seawalls. More critically this option would leave the intermediate sections of unprotected embankment vulnerable to erosion during future events. Based on this assessment it is recommended that a contiguous seawall along the vulnerable stretch of coast be the preferred solution.

7 Conclusion

The Pebbly Beach embayment is exposed to wind waves (sea) from the SE and attenuated swell waves from the east, driving a northerly sediment transport regime. This northerly drive is reflected in the movement of sand into and through the embayment, with the location of the beach controlled by Yule Point.

Unlike the sand, the pebbles in the embayment are derived locally from several small stream discharges. The pebbles though reworked by the waves are effectively trapped above a rocky low tide platform that restricts cross shore movement. Thus, despite a small inflow the beach has a pebble profile between rocky outcrops to the north and south. The assessment reveals that the coastline here is relatively stable, with the pebble beach resilient to wave conditions.

The embankment at the rear of the beach profile is largely a built (not natural) profile and is vulnerable to erosion when large waves can impact the exposed embankment, as happened during Cyclone Jasper in December 2023. To protect the embankment a contiguous rock revetment wall constructed of large rock armour is proposed. The rock revetment wall will have a relatively low crest at 4 m AHD and will be founded at 0 m AHD or above if a non-erodible (rock) surface is encountered. The rock revetment wall will be 3.7 m wide at a slope of 1 in 1.5.

The assessment concluded that the proposed rock revetment wall will not exacerbate coastal erosion and that the coastal processes will continue unimpeded. The works will necessitate the loss of trees with a base below 4.0 m AHD, though many trees will be saved. The new rock revetment wall will push into the beach profile, reducing the width of the beach and increasing the risk of the beach being completely flooded at high tide. The impact of the encroachment will be minimised by placing all beach material located within the footprint of works back on the beach in front of the rock revetment wall.

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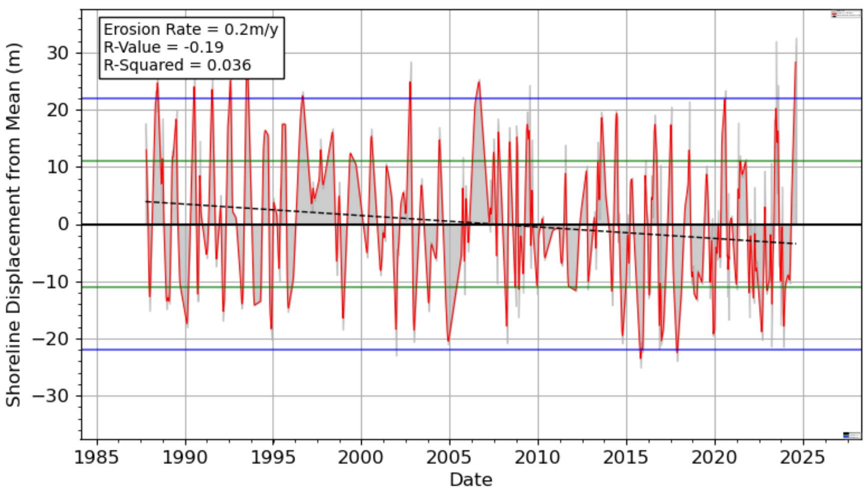
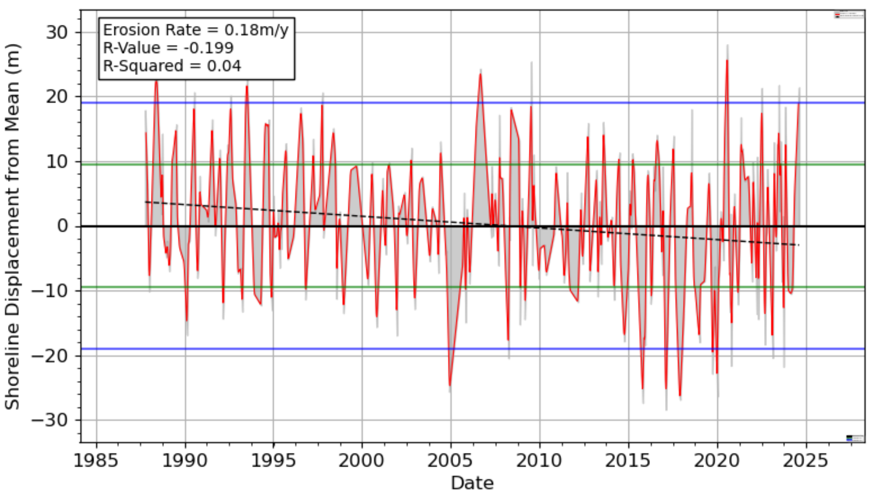
Appendix A – Coastsat Transect Shoreline Timeseries Plots

Figure A 1 CoastSat transect locations with line of best fit rates of change.

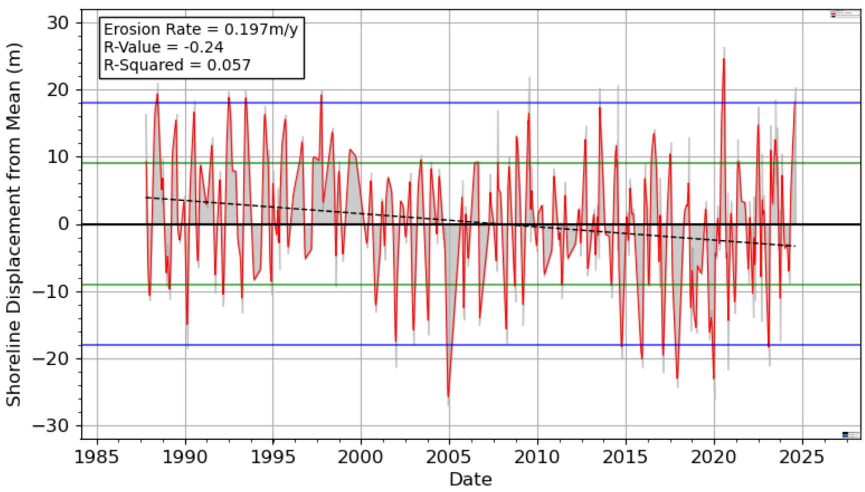
Pebbly Beach Shoreline Displacement from Mean (Transect T1)



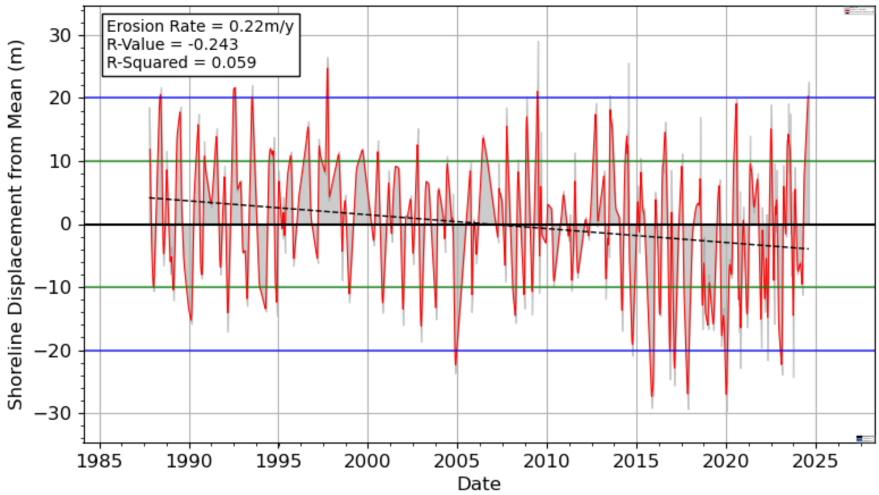
Pebbly Beach Shoreline Displacement from Mean (Transect T2)



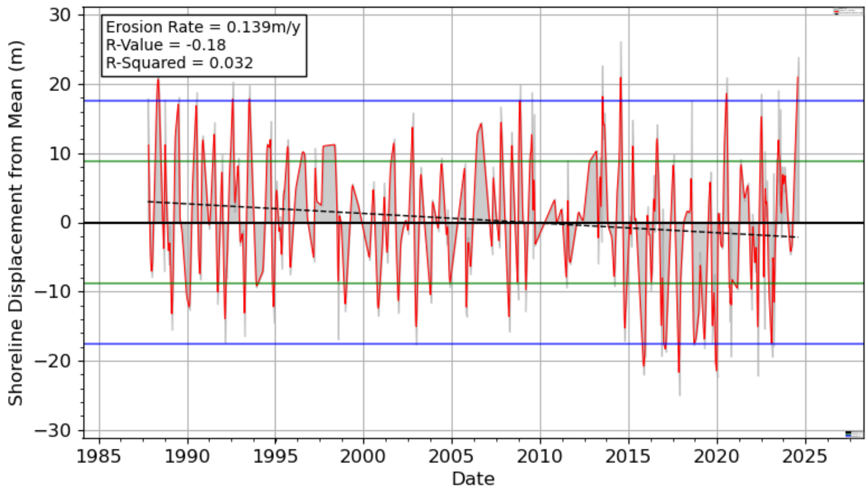
Pebbly Beach Shoreline Displacement from Mean (Transect T3)



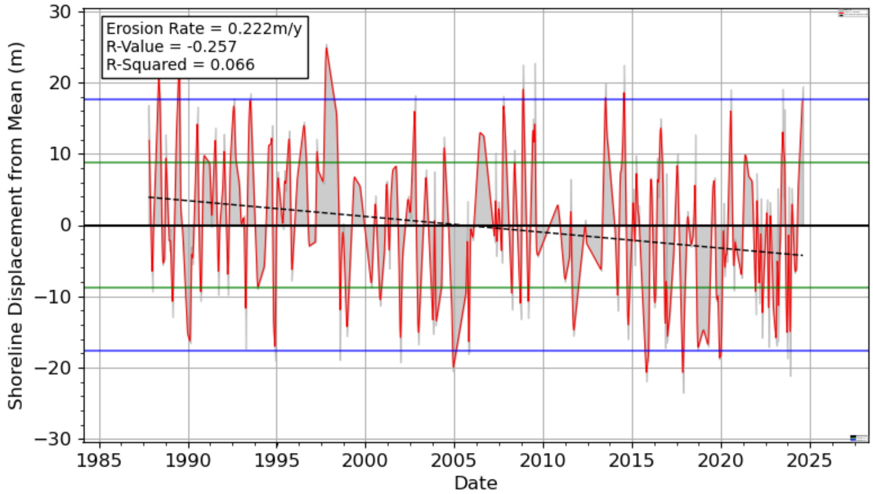
Pebbly Beach Shoreline Displacement from Mean (Transect T4)



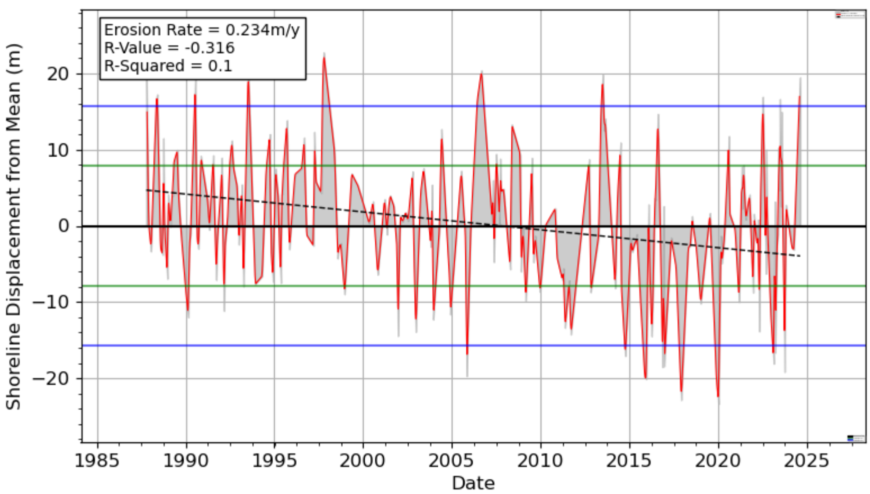
Pebbly Beach Shoreline Displacement from Mean (Transect T5)



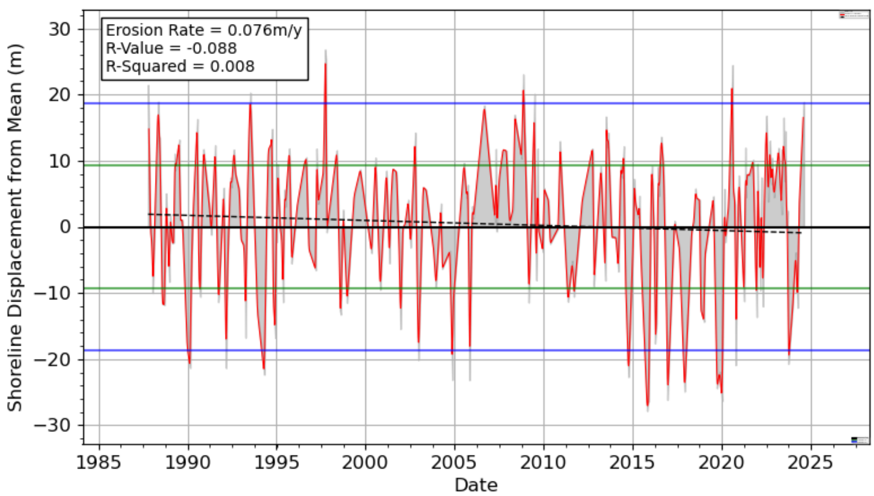
Pebbly Beach Shoreline Displacement from Mean (Transect T6)



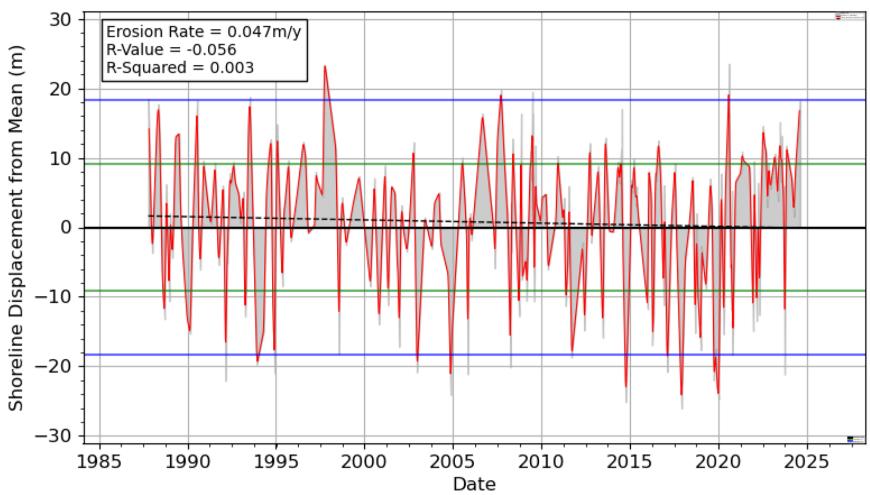
Pebbly Beach Shoreline Displacement from Mean (Transect T7)

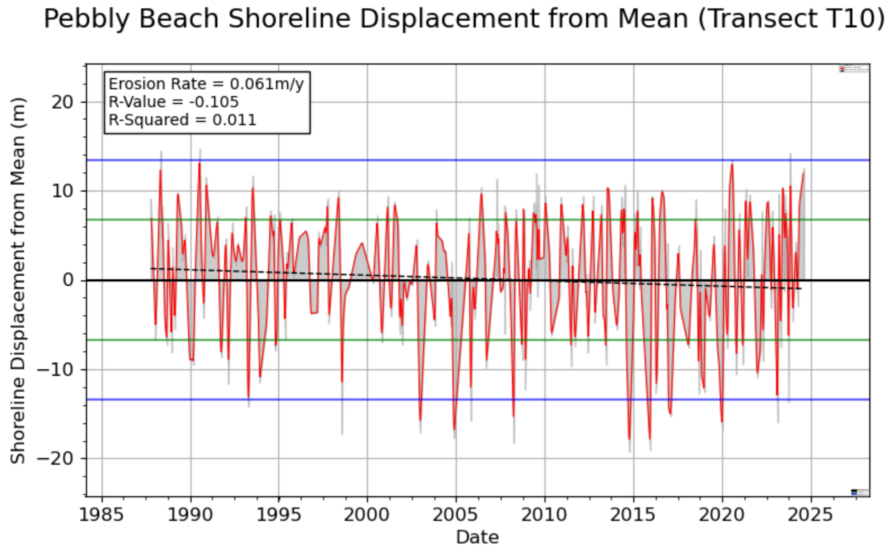


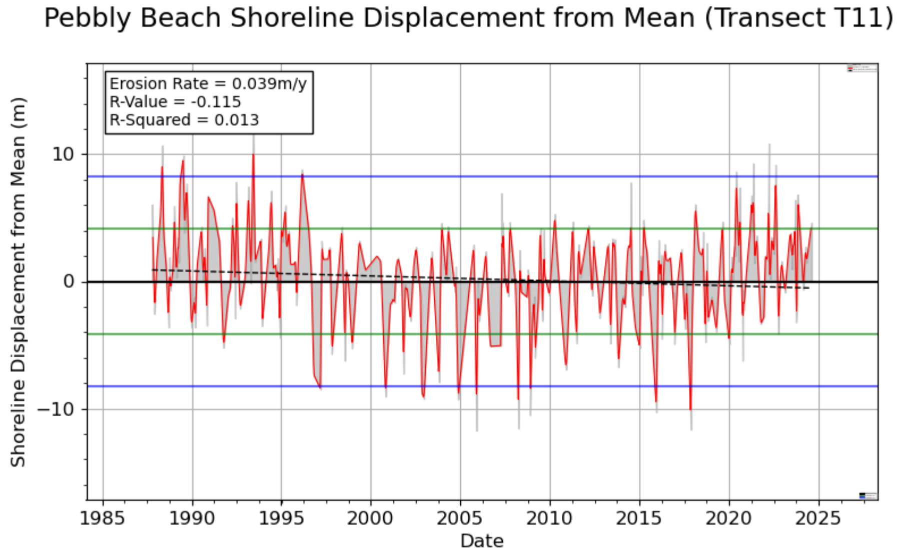
Pebbly Beach Shoreline Displacement from Mean (Transect T8)



Pebbly Beach Shoreline Displacement from Mean (Transect T9)




Pebbly Beach Shoreline Displacement from Mean (Transect T10)
Erosion Rate = 0.061m/y
R-Value = -0.105
R-Squared = 0.011
Shoreline Displacement from Mean (m)
20
10
0
−10
−20
1985
1990
1995
2000
2005
2010
2015
2020
2025
Date


Pebbly Beach Shoreline Displacement from Mean (Transect T11)
Erosion Rate = 0.039m/y
R-Value = -0.115
R-Squared = 0.013
Shoreline Displacement from Mean (m)
10
0
−10
1985
1990
1995
2000
2005
2010
2015
2020
2025
Date