REPORT

# Feasibility of Seal Rocks Road Diversion and Local Area Plan

## Probabilistic Coastal Hazard Study

Client: Coffey Services Australia Pty Ltd

Reference: PA2686-ZZ-XX-RP-Z-0002

Status: Final/02

Date: 25 July 2022

Royal HaskoningDHV
*Enhancing Society Together*

**HASKONING AUSTRALIA PTY LTD.**

Level 3
2 Market Street
Newcastle NSW 2300
Australia
Water & Maritime
Trade register number: ACN153656252

+61 2 4926 9500 **T**
project.admin.australia@rhdhv.com **E**
royalhaskoningdhv.com **W**

| | |
|---|---|
| Document title: | Feasibility of Seal Rocks Road Diversion and Local Area Plan |
| Document short title: | Coastal Hazard Study |
| Reference: | PA2686-ZZ-XX-RP-Z-0002 |
| Status: | 02/Final |
| Date: | 25 July 2022 |
| Project name: | Seal Rocks Road Coastal Hazard Assessment |
| Project number: | PA2686 |
| Author(s): | Patrick Lawless |
| Drafted by: | Patrick Lawless |
| Checked by: | Gary Blumberg |
| Date: | 19/7/22 |
| Approved by: | Gary Blumberg |
| Date: | 19/7/22 |

| Classification |
|---|
| Project related |

# Table of Contents

Royal HaskoningDHV



## Table of Tables



## Table of Figures

## Appendices

# 1 Introduction

## 1.1 Background

MidCoast Council (Council) commissioned Tetra Tech Coffey Pty Ltd (Coffey) to develop a local area plan addressing present-day problems with the sustainability, safety and efficiency of the existing transport infrastructure, stormwater runoff, beach accesses and recreational facilities, and environment values of the Seal Rocks precinct.

The key driver for the study is the exposure of the Seal Rocks Road and adjacent parking infrastructure to coastal hazards and to increasing pressure from visitors. Of high concern to Council is that the coastal hazards and the improper use of the road infrastructure may lead to degradation of the road/s, increased erosion and reduced slope stability.

The overarching aim of the study is to set out management options for public assets through the identification and prioritisation of feasible actions for re-routing Seal Rocks Road as per Great Lakes Coastal Zone Management Plan (GL CZMP) Action 2.4.15, and through preparation of a local area plan for the Seal Rocks village as per GL CZMP Action 2.4.16.

Haskoning Australia Pty Ltd, a company of Royal HaskoningDHV (RHDHV), was engaged by Coffey to undertake a probabilistic coastal hazard assessment that specifically addresses the hazards of coastal erosion and recession over a planning horizon extending from present day to 2100.

The purpose of the probabilistic coastal hazard assessment is to assess how and to what extent Seal Rocks Road may be affected by present day geophysical conditions within the Seal Rocks area, including coastal erosion and recession hazards and existing pressures on the road infrastructure. The probabilistic hazard modelling was informed by geotechnical and geophysical investigations of the area and considered sea level rise / climate change projections.

## 1.2 Study Area

The focus of the study is on the area of Seal Rocks village. Seal Rocks is located 277 km north along the NSW coast from Sydney via the Pacific Highway, the Lakes Way and Seal Rocks Road. Beaches in the study area include Number One Beach and Boat Beach. A locality plan for the study area is presented in Figure 1-1.


*Figure 1-1: Locality plan (Image Source: Google Earth)*

## 1.3 Level Datum

All reference to Reduced Level (RL) in this report is given in metres above Australian Height Datum (AHD). AHD is a local datum which is approximately equal to current Mean Sea Level at the coastline of mainland Australia.

Royal HaskoningDHV

## 2 Methodology for Probabilistic Assessment of Coastal Hazards

Traditionally, coastal hazard assessments in NSW have been undertaken using a deterministic approach. In this approach, each parameter that is an input to calculation of the hazard, e.g. design storm demand, sea level rise (SLR) projection, etc. is assigned a single value. The single value is typically a conservative estimate for the parameter.

In the probabilistic approach, each input parameter is allowed to vary randomly according to an appropriate probability distribution function. The randomly sampled parameters are then repeatedly combined in a process known as Monte Carlo simulation. All outputs of the Monte Carlo simulation are collected to develop a probability curve for the shoreline position at the end of a particular adopted planning period.

In the probabilistic approach applied by RHDHV for Seal Rocks, the Monte Carlo simulation involved one million values of a parameter for each year of the planning period.

The three key input parameters to the probabilistic analysis are:

- shoreline recession due to net sediment loss (sediment budget differential), sometimes referred to as ‘underlying recession’;
- SLR and the recession in response to SLR; and
- event based erosion due to storm activity – referred to as ‘storm demand’.

The methodology for the probabilistic approach is set out in a technical note in **Appendix A**. Some general points are noted below:

- where an input parameter can vary randomly but has a distribution that is not fully known, a triangular distribution is typically assigned for the parameter. The triangular distribution is defined by a minimal value, a maximum value, and a peak/modal value (most likely or best estimate value). The peak/modal value does not need to be equidistant between the minimum and maximum values hence a skewness can be assigned to the probability distribution. The triangular distribution is depicted in Figure 2-1;
- recession due to SLR is estimated based on application of the so-called Bruun Rule, which requires an estimate of the magnitude of SLR and the inverse of the average beach slope extending to the depth of closure. For the Monte Carlo simulations, both of these parameters (SLR and inverse beach slope) are defined by separate triangular probability distributions;
- in the case of SLR, the minimum, maximum and modal values in successive years over a given planning period are set so that they follow a specified trajectory, e.g. an Intergovernmental Panel for Climate Change (IPCC) concentration pathway, hence random SLR trajectories are generated in the Monte Carlo simulations in the case of SLR;
- the total long-term recession at each year is calculated by simply summing the separate Monte Carlo results for underlying recession and for recession due to SLR for that year;
- in the case of storm demand, annual exceedance probabilities (AEP values) of storm demand are randomly sampled in each year of the planning period and then converted to a volume using empirical relationships. ‘High demand’ (rip head) values for storm demand as described in Gordon (1987) are adopted;

- storm demand volume is then converted to a setback distance using the methodology outlined in Nielsen (1992), allowing separate determination of the Zone of Wave Impact (ZWI), Zone of Slope Adjustment (ZSA) and Zone of Reduced Foundation Capacity (ZRFC), refer Figure 2-2;
- the total setback for each zone (ZWI, ZSA, ZRFC) is calculated by adding the storm demand setback to the combined long-term recession, randomly, on a year by year basis;
- calculations are performed for each beach profile along a section of shoreline of interest (profiles generally established by a photogrammetric analysis); and
- it is assumed that the beach has recovered from the storm-driven erosion that occurs in a year at the beginning of the subsequent year[1].

A flow chart showing the methodology for the probabilistic assessment of coastal hazard is provided in Figure 2-3.

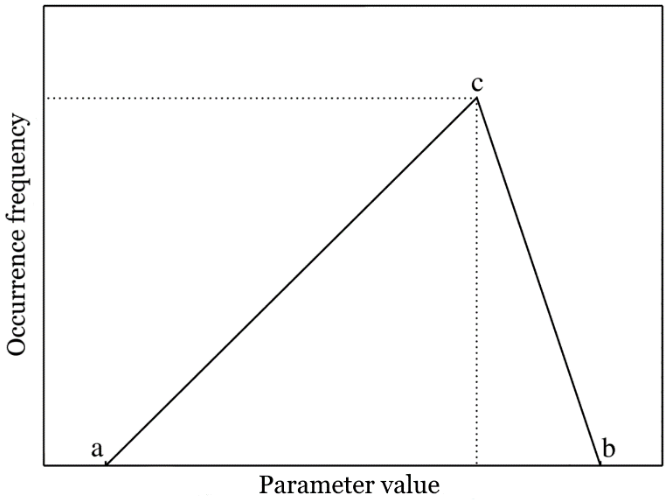



*Figure 2-1: The probability density function of a triangular distribution*

*[1] This assumption is made to reduce computational effort, as the actual storm demand is a function of beach state. It would otherwise be necessary to continually track the beach state, including a recovery algorithm, and continually adjust the storm demand in response to beach state, particularly the larger values of storm demand (by reducing these values). Beaches in an eroded state have lower storm demands due to dissipation of wave energy on offshore bars formed during previous erosion events.*

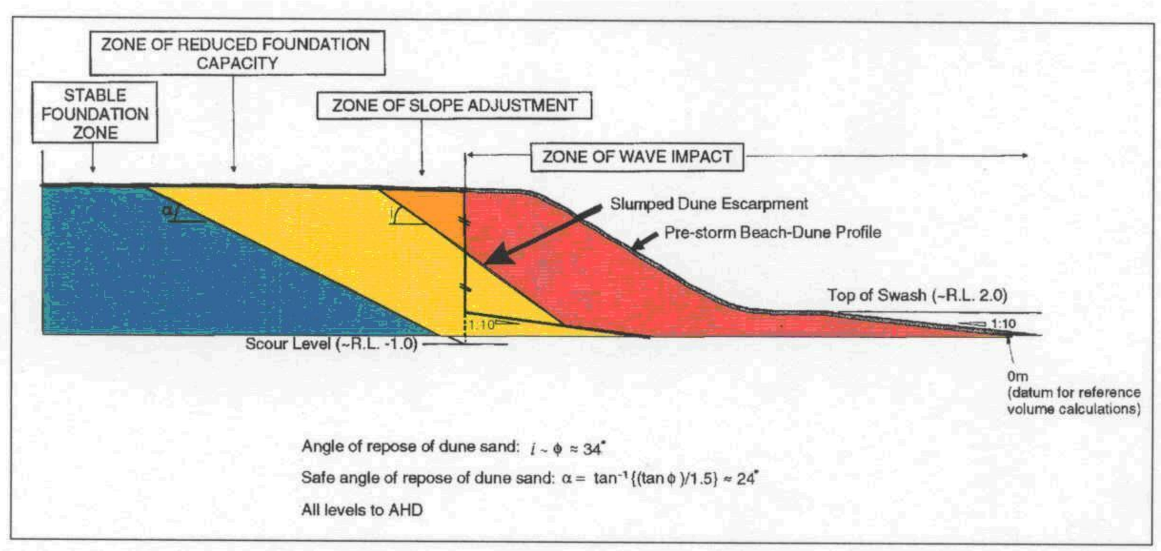



*Figure 2-2: Wedge Failure Plane Model (Source: Nielsen et al, 1992)*

Separate probability curves were developed for regularly spaced profiles distributed across the study area which coincide with the NSW Department of Planning and Environment (DPE) photogrammetric profile locations in Blocks 1, 2 and 3, as indicated in Figure 2-4.

In accordance with the assessment of the geotechnical investigations discussed in Section 5, a constraint on future shoreline erosion/recession was incorporated in the probabilistic coastal hazard modelling due to the presence of seabed materials that are unerodable over the planning period.

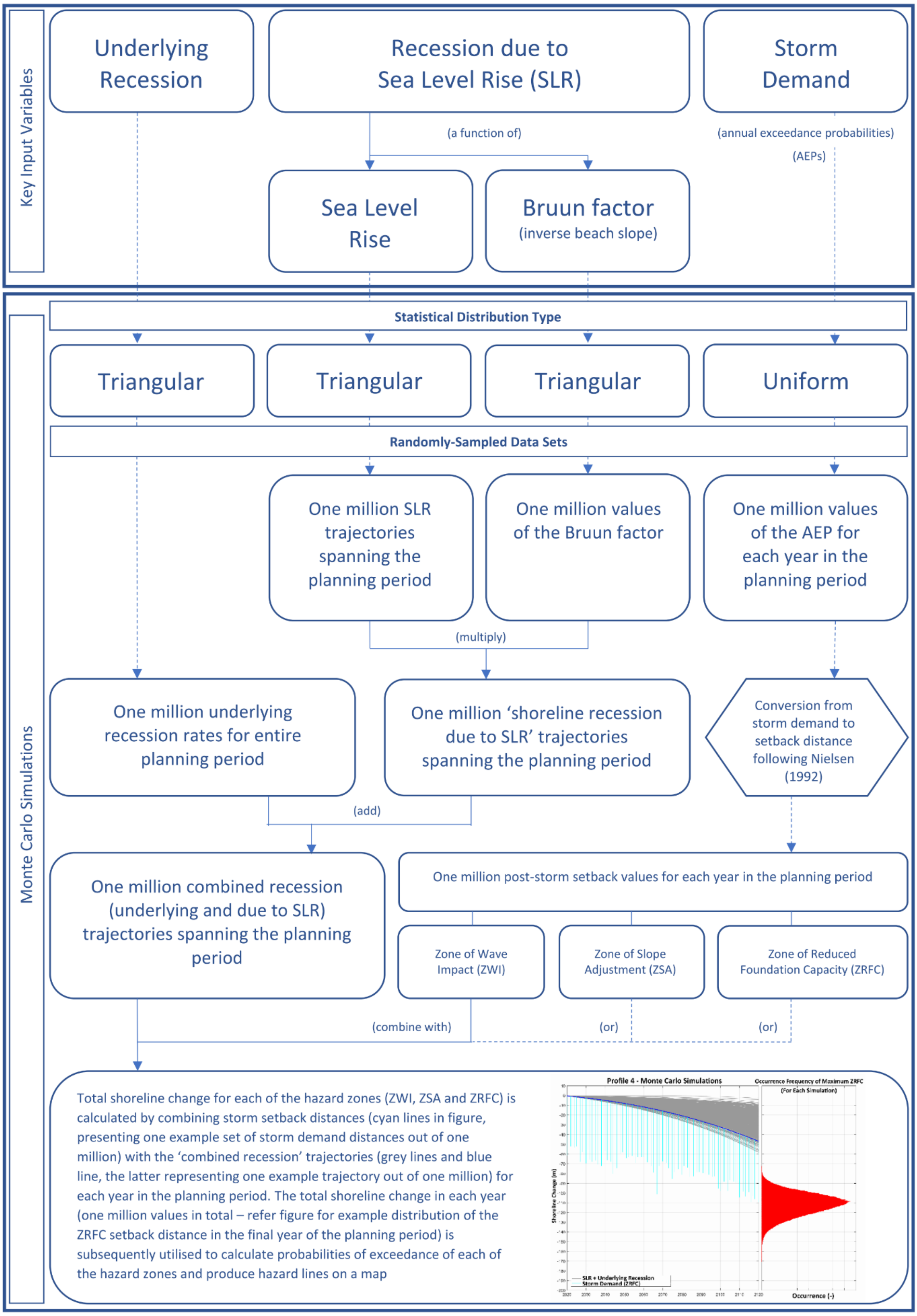



*Figure 2-3: Flow chart for the probabilistic assessment of coastal hazard*

Royal HaskoningDHV

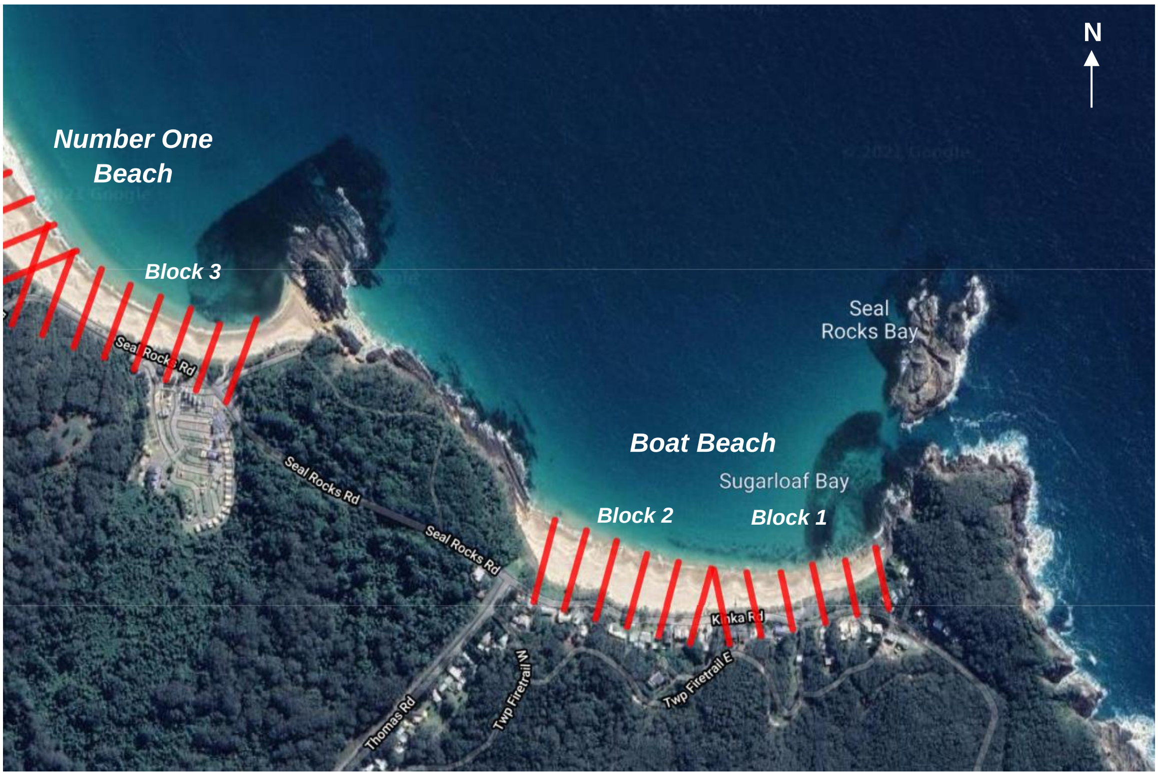



*Figure 2-4: DPE Photogrammetric Profile Locations (Note: profile numbers increase sequentially moving east to west)*

# 3 Adopted Values for Key Parameters

## 3.1 Introduction

The following sections set out the adopted values for the key parameters in the probabilistic analysis. Consideration of the adopted values has been based on coastal hazard parameters adopted in SMEC (2013), photogrammetric data covering the period 1963 to 2021, as well as the experience of RHDHV. In addition to a nominated pre-storm beach profile and planning period, the key parameters for input to the probabilistic analysis are:

- underlying recession;
- recession due to SLR (includes projected amount of SLR and Bruun slope factor); and
- storm demand.

The adopted values are summarised in Section 3.2 to Section 3.6, together with a discussion.

## 3.2 Pre-Storm Beach Profile

Selection of the pre-storm profile upon which to apply the shoreline recession and storm demand is important as this influences the ultimate position of the future coastal hazard lines.

In selecting the pre-storm profile, the aim should be to adopt a relatively accreted beach profile, typically referred to by RHDHV as an ‘average beach full’ profile, as the high storm demands selected in hazard assessments can only be realised in practice if accreted profiles exist (as noted in Footnote 1, in the situation of eroded profiles there are large quantities of sand in offshore bars which dissipate wave energy giving lower storm demands). The selected pre-storm profile should also, ideally, be a ‘real’ profile (not synthesised) and be contemporary, i.e. recent.

Figure 3-1 and Figure 3-2 show example beach profiles available from the NSW Beach Profile Database at Number One Beach (Block 3 Profile 2) and Boat Beach (Block 2 Profile 1) for the recent period 2018 to 2021. The locations of these example profiles are indicated in Figure 2-4. The trends evident in Figure 3-1 and Figure 3-2 are generally representative of all the beach profiles in the study area over the period 2018 to 2021.

Firstly, it is evident that the 2018 and 2021 profiles represent a relatively eroded beach state and are therefore not suitable for adoption. The 2019 beach profile is generally representative of the most accreted beach state of the available data, so selection of this profile would be unconservative (give a hazard line more seaward) as it’s the ‘most full’ out of the presented profiles. Further inspection shows that the 2019 beach profiles are not suitable for adoption due to the surface ’noise’ in the profile (these profiles were derived by LiDAR and it is apparent the laser has reflected off dunal vegetation).

The 2020 profile is therefore considered to be generally representative of a recent ‘average-beach full’ profile as its active beach profiles are positioned between the 2018 and 2021 profiles, with the LiDAR derived 2019 profile discarded due to aberrations from reflections due to vegetation. Hence, the 2020 profile was adopted as the pre-storm profile for the probabilistic coastal hazard assessment.

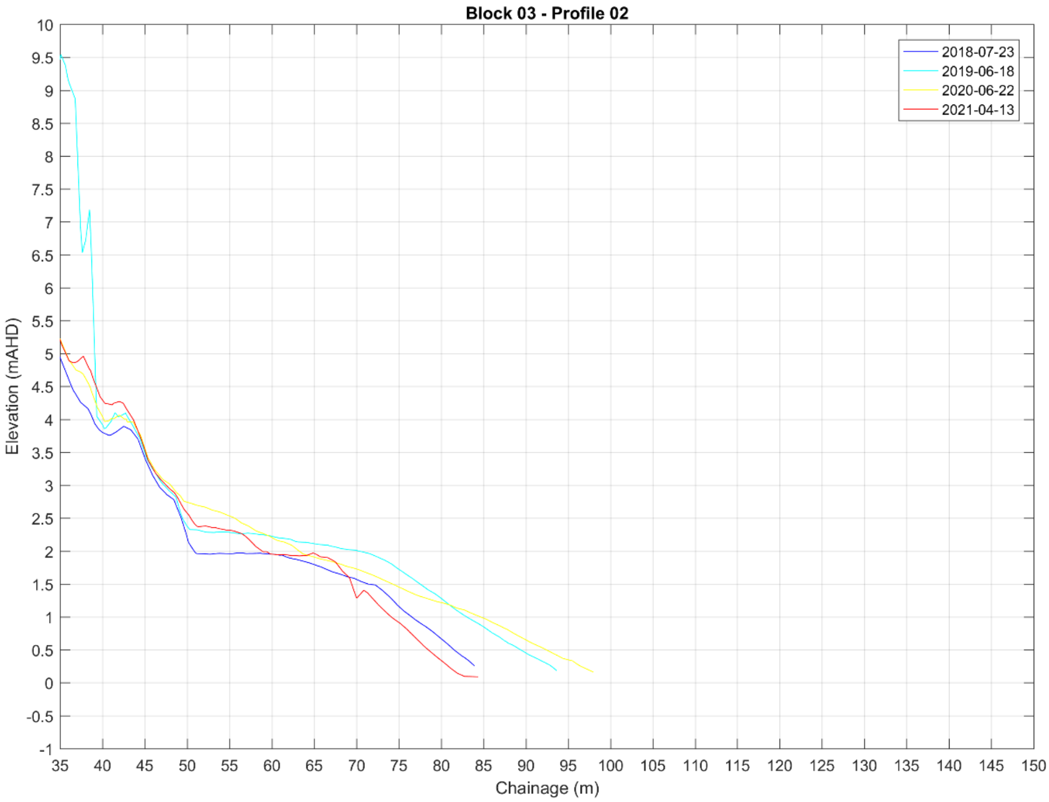



*Figure 3-1: Beach profiles at Block 3 Profile 2 (Number One Beach) for the period 2018-2021*

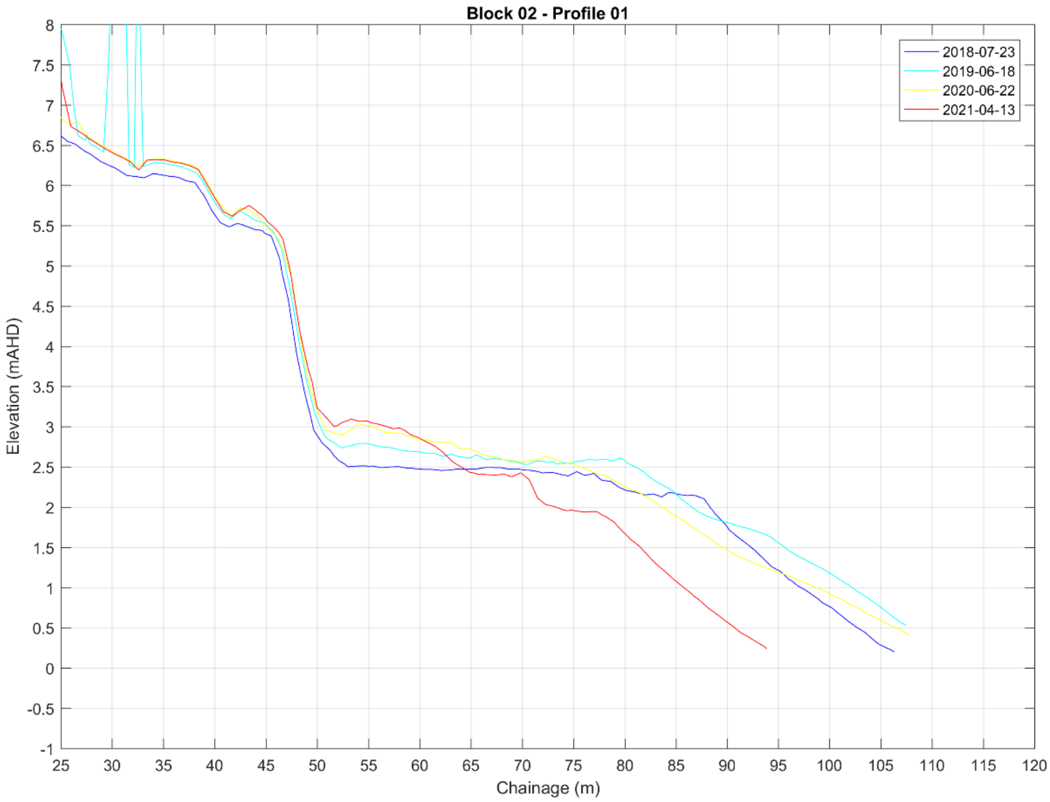



*Figure 3-2: Beach profiles at Block 2 Profile 1 (Boat Beach) for the period 2018-2021*

Royal HaskoningDHV

## 3.3 Planning Period

Planning periods of 2020 ('present day'), 2060 and 2100 were adopted for coastal hazard assessment. Yearly probabilistic data were also provided to Coffey for detailed interrogation of the results.

## 3.4 Underlying Recession

### 3.4.1 Introduction

Underlying or long-term shoreline recession rates were estimated by analysis of photogrammetry data. Rates of shoreline movement (for each beach profile) of the frontal dune for an appropriate elevation contour position(s) were derived by linear regression. In addition, rates of shoreline movement were determined by assessment of volumetric change (for each beach profile) above RL 0, also derived by linear regression. Underlying shoreline recession rates typically vary spatially (i.e. within a beach compartment) and temporally (i.e. depending on the analysis period considered). In all cases the interpretation of underlying recession needs to be developed in the framework of a strong coastal processes understanding.

A triangular probability distribution, as a rough approximation of a random variable with unknown distribution, is used to generate a set of random underlying recession values (refer Figure 2-1 and Section 2).

The assessment of underlying recession for the study area has considered the investigations reported in SMEC (2013), as well as an updated assessment by RHDHV that considers the most recent photogrammetry which post-dates the data included in SMEC (2013).

### 3.4.2 SMEC (2013) Assessment

SMEC (2013) analysed photogrammetry data for Number One Beach and Boat Beach for the following dates of aerial photography:

- 1963
- 1972
- 1975
- 1986
- 1994
- 2001
- 2008

Long-term beach movement based on volumetric change indicated that Boat Beach was accreting at an average rate of 0.54 $m^3$/m/year between 1963 and 2008, while Number One Beach (Block 3) was assessed to be receding landward by 0.21 $m^3$/m/year.

Long-term beach movement based on positional change in the active beach zone indicated that Boat Beach was accreting at an average rate of 0.1 m/year between 1963 and 2008, while Number One Beach (Block 3) was assessed to be receding landward by up to 0.03 m/year.

SMEC (2013) adopted the following long-term recession rates for the study area:

- Number One Beach – 0.1 m/year
- Boat Beach – nil (stable).

### 3.4.3 Update of Underlying Recession Rates

RHDHV have updated the underlying recession rates for this study by including additional photogrammetric data collected since 2008, including five additional aerial photography dates (in 2013, 2017[2], 2018, 2019, 2020 and 2021). That is, the entire available photogrammetric dataset spanning 1963 to 2021 has been utilised. Generally, a complete dataset provides greater confidence in statistical values, rather than utilising a subset.

For each of the profiles, the rates of change of the RL 2 and RL 3 contour positions were derived by linear regression; that is, by determining the line of best fit (least squares error) in each case[3]. Time series plots of shoreline change at example beach profiles at Number One Beach (Block 3 Profile 2) and Boat Beach (Block 2 Profile 1) are presented in Figure 3-3 and Figure 3-4, respectively.

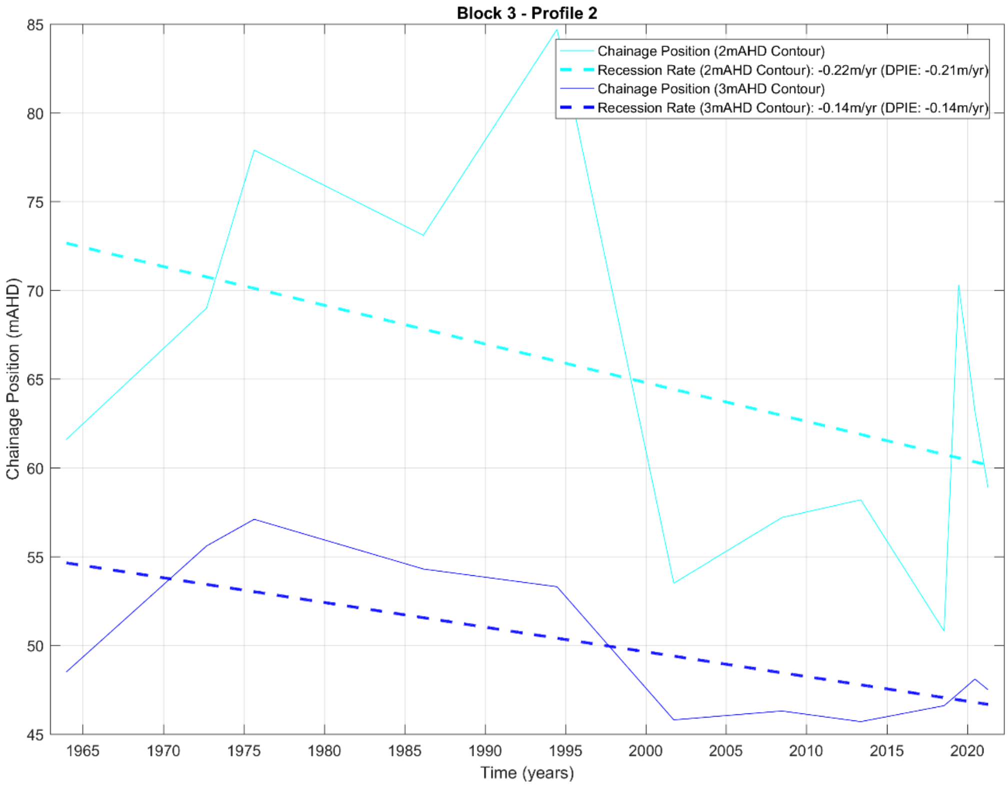



*Figure 3-3: Beach contour time-series at Block 3 Profile 2 (Number One Beach)*

[2] *2017 photogrammetry data is available for Blocks 1 and 2 (Boat Beach) only.*

[3] *This does not imply that there were uniform rates of positional change between dates of aerial photography.*

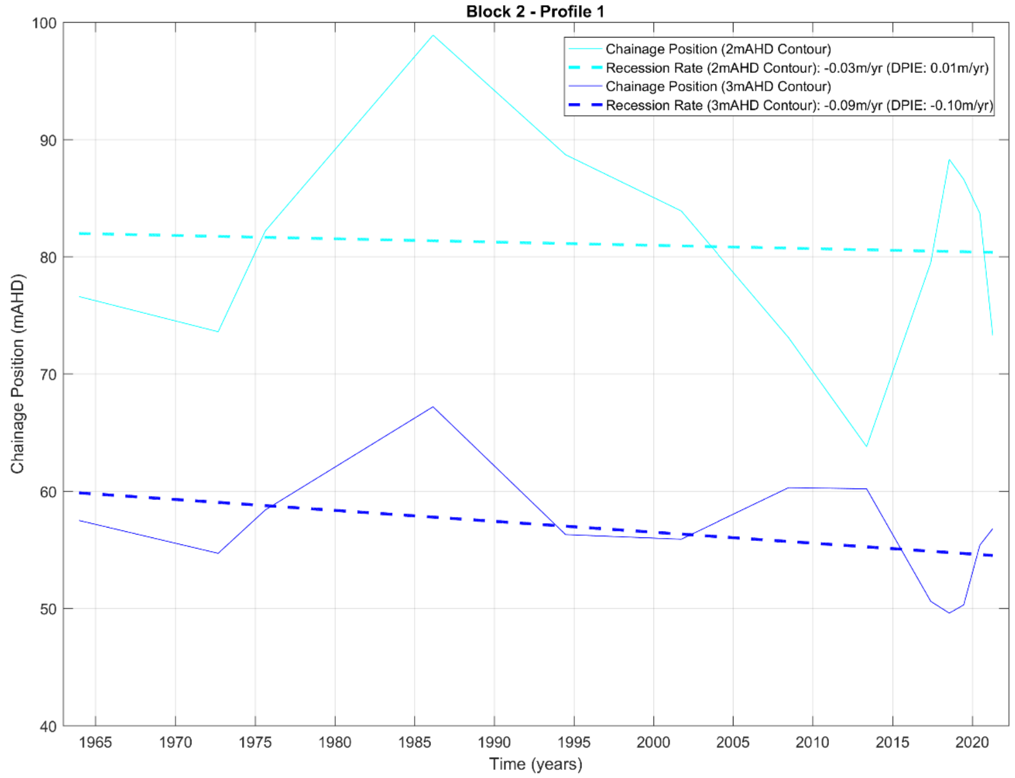



*Figure 3-4: Beach contour time-series at Block 2 Profile 1 (Boat Beach)*

Positional change of the RL 3 contour is considered to represent a better approximation of long-term change in the study area compared to the RL 2 contour because it is subject to reduced variability associated with typical (day to day) beach fluctuations but is below the dune crest and very much part of the active coastal profile. Average rates of shoreline movement at the RL 3 contour position are plotted in Figure 3-5 (Number One Beach) and Figure 3-6 (Boat Beach). Key statistics summarising these results are presented in Table 3-1. Note that positive values indicate shoreline accretion, and negative values indicate shoreline recession.

*Table 3-1 Updated underlying recession rates (RL 3 contour position)*

| Statistic | Rate of Positional Change (m/year) | |
|---|---|---|
| | Boat Beach | Number One Beach |
| Minimum | -0.28 | -0.34 |
| Maximum | 0.01 | -0.02 |
| Median | -0.07 | -0.17 |
| Mean | -0.08 | -0.17 |

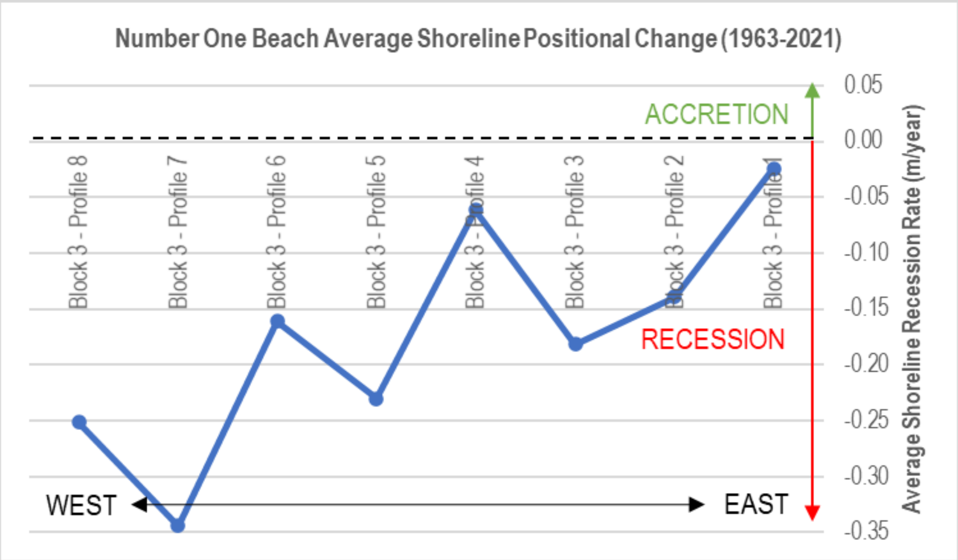



*Figure 3-5: Number One Beach Shoreline Change Analysis (RL 3 contour)*

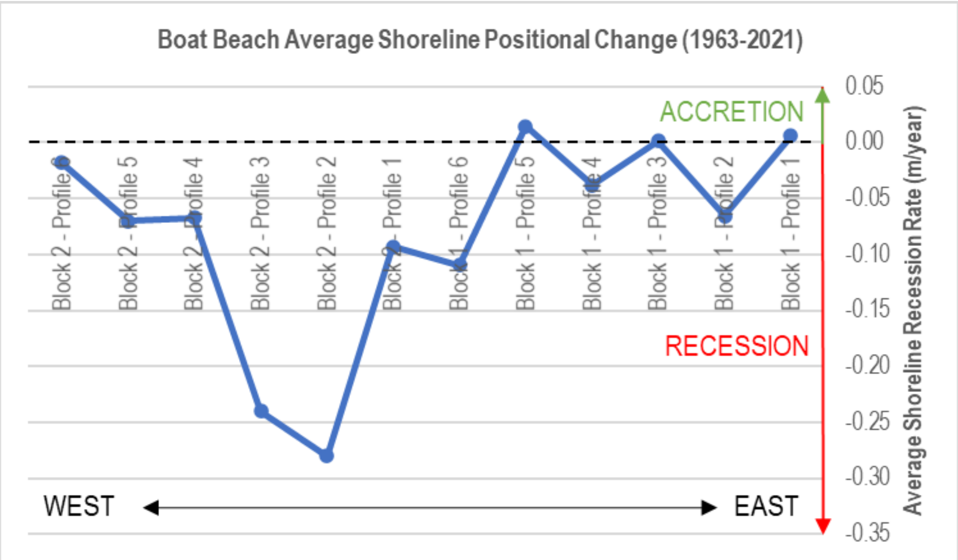



*Figure 3-6: Boat Beach Shoreline Change Analysis (RL 3 contour)*

These results indicate that Number One Beach experienced recession during the analysis period, with average rates of shoreline positional change varying between -0.02 and -0.34 m/year, and a median rate of -0.17 m/year. Recession rates generally increased moving west along the beach.

The results for Boat Beach indicate that this beach was slightly more stable than Number One Beach, although a recessionary trend was generally evident. Average rates of shoreline positional change varied between 0.01 m/year (accretion) and -0.28 m/year (recession), and a median rate of -0.07 m/year (recession). Recession rates were generally highest in the central portion of the beach, with greater stability near the eastern and western ends.

Based on the range of shoreline recession values determined from beach profile analysis, the adopted input values for the probabilistic coastal hazard assessment are summarised in Table 3-2. The following should be noted:

- The preliminary lower and upper estimates correspond to the statistical 95th and 5th percentile values, respectively.
- The preliminary best estimate corresponds to the statistical median values. This was considered to be appropriate because the median rate of shoreline movement is considered to represent the most likely outcome for the entire length of the study area, which is the required input for a triangular distribution.
- The preliminary values were adjusted to account for any SLR recession that may have occurred in the study area during the analysis period. This was based on an average SLR of 0.8 mm/year over the historic record (1966 to 2010, White et al., 2014) and a modal Bruun factor of 50 (refer Section 3.5). This resulted in a reduction in recession of 0.04 m/year.

*Table 3-2 Shoreline Recession – Adopted Inputs for Probabilistic Analysis*

| Estimate[4] | Rate of Positional Change (m/year) | | | |
|---|---|---|---|---|
| | Boat Beach | | Number One Beach | |
| | Preliminary Values | Adopted Values[5] | Preliminary Values | Adopted Values[5] |
| Lower Estimate | -0.26 | -0.22 | -0.31 | -0.27 |
| Best Estimate | 0.01 | 0.05 | -0.04 | 0.00 |
| Upper Estimate | -0.07 | -0.03 | -0.17 | -0.13 |

## 3.5 Recession due to Sea Level Rise

### 3.5.1 Introduction

SLR is predicted to result in shoreline recession due to re-adjustment of the beach profile to the new coastal water levels. Bruun (1962; 1983) proposed a methodology to estimate shoreline recession due to SLR, the so-called Bruun Rule. The Bruun Rule is based on the concept that SLR will lead to erosion of the upper shoreface, followed by re-establishment of the original equilibrium profile. This profile is re-established by shifting it landward and upward. The Bruun Rule is illustrated in Figure 3-7, where a number of parameters apply (refer Table 3-3) (reference can also be made to **Appendix A**).

*Table 3-3 Bruun Rule parameters*

| Parameter | Description |
|---|---|
| R | Horizontal recession |
| B | Width of the active beach profile (cross-shore distance from the initial dune crest to the depth of closure) |
| S | Sea Level Rise |
| H | Active dune/berm height |
| dc | Depth of closure |

*[4] 5, 50 and 95 percentile values were taken as the upper, best and lower estimates, respectively, placing less importance on outliers*

*[5] Adjusted with the modal Bruun factor and a SLR rate of 0.8 mm/year (White et al., 2014).*

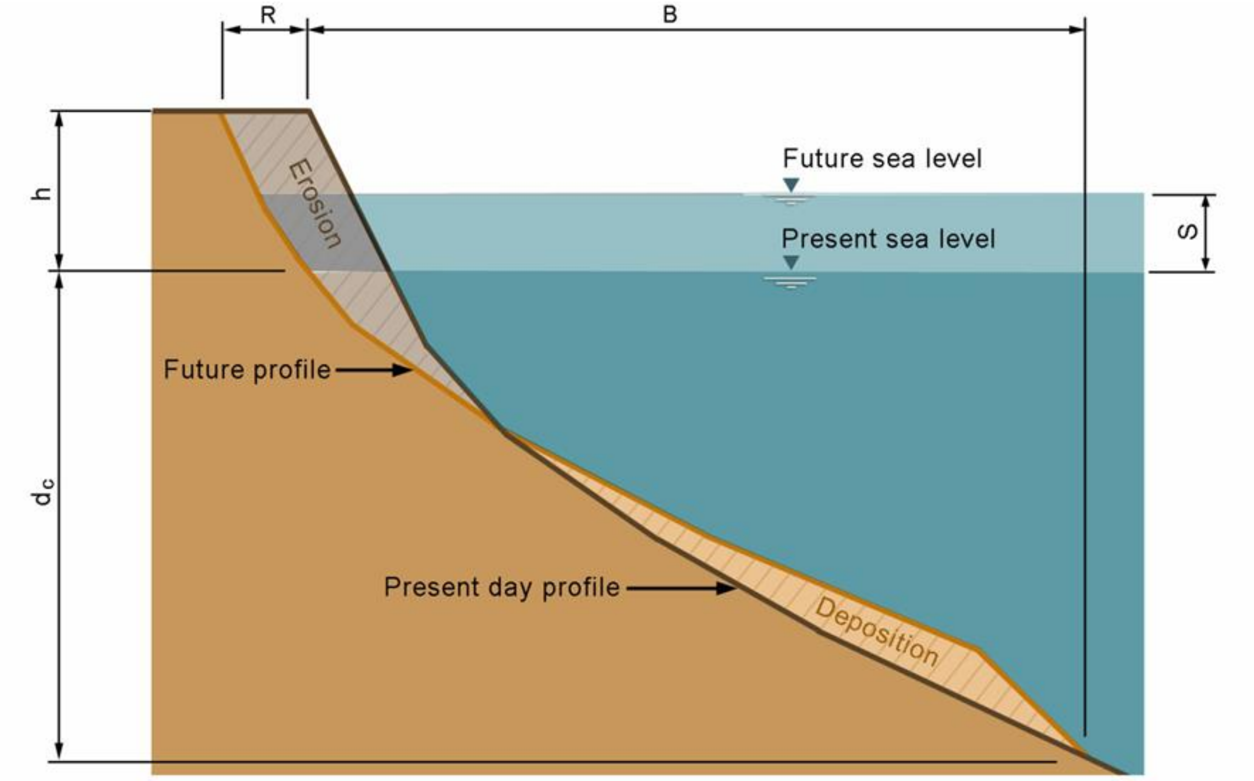



*Figure 3-7: Illustration of the Bruun Rule*

A recession rate can be estimated using the Bruun Rule equation, which divides SLR by the average slope of the active beach profile extending to the depth of closure (the outer limit for the nearshore littoral drift and exchange zone of littoral material between the shore and the offshore bottom area. Bruun, 1962):

$$R = \frac{S}{(h + d_c)/_B}$$

The inverse beach slope is also referred to as the 'Bruun factor':

$$Bf = \frac{1}{(h + d_c)/_B} = \frac{B}{h + d_c}$$

Shoreline recession due to SLR is therefore a function of both SLR and the Bruun factor:

$$R = S * Bf$$

Similar to underlying recession (refer Section 3.4), there is uncertainty around the distribution of both of these parameters, i.e. the values for SLR and for the Bruun factor. As such, for the Monte Carlo simulations, both of these parameters are defined by separate triangular probability distributions and hence minimum, maximum and peak/modal SLR and Bruun factor values are required.

Royal HaskoningDHV

### 3.5.2 Sea Level Rise

SMEC (2013) adopted SLR projections consistent with NSW Government's *Sea Level Rise Policy Statement* (DECCW, 2009), which included SLR planning benchmarks of 0.4 m at 2050 and 0.9 m at 2100 (both relative to 1990), with the two benchmarks allowing for consideration of SLR over different timeframes. However, it is noted that DECCW (2009) is no longer NSW government policy. Furthermore, advice was provided by the NSW Government in April 2014 that Councils are to obtain expert advice in using a range of SLR projections as well as document the methodology and approach applied.

The latest global mean SLR projections are provided in IPCC (2021), which is the Technical Summary for the forthcoming Sixth Assessment Report (AR6) that is being progressively released by IPCC through 2021 and 2022.

IPCC (2021) provides global mean sea level projections for five (5) Shared Socioeconomic Pathways (SSPs). Each SSP comprises a narrative of future socioeconomic development used to develop scenarios of energy use, air pollution control, land use, and greenhouse gas emissions to which Representative Concentration Pathways (RCPs) are applied to achieve an approximate radiative forcing level at the end of the 21$^{st}$ century. The SSPs considered in IPCC (2021) are indicated on Figure 3-8 and include:

- SSP1–1.9 - Very Low emissions scenario;
- SSP1–2.6 - Low emissions scenario;
- SSP2–4.5 - Intermediate emissions scenario;
- SSP3–7.0 - High emissions scenario; and,
- SSP5–8.5 - Very High emissions scenario.

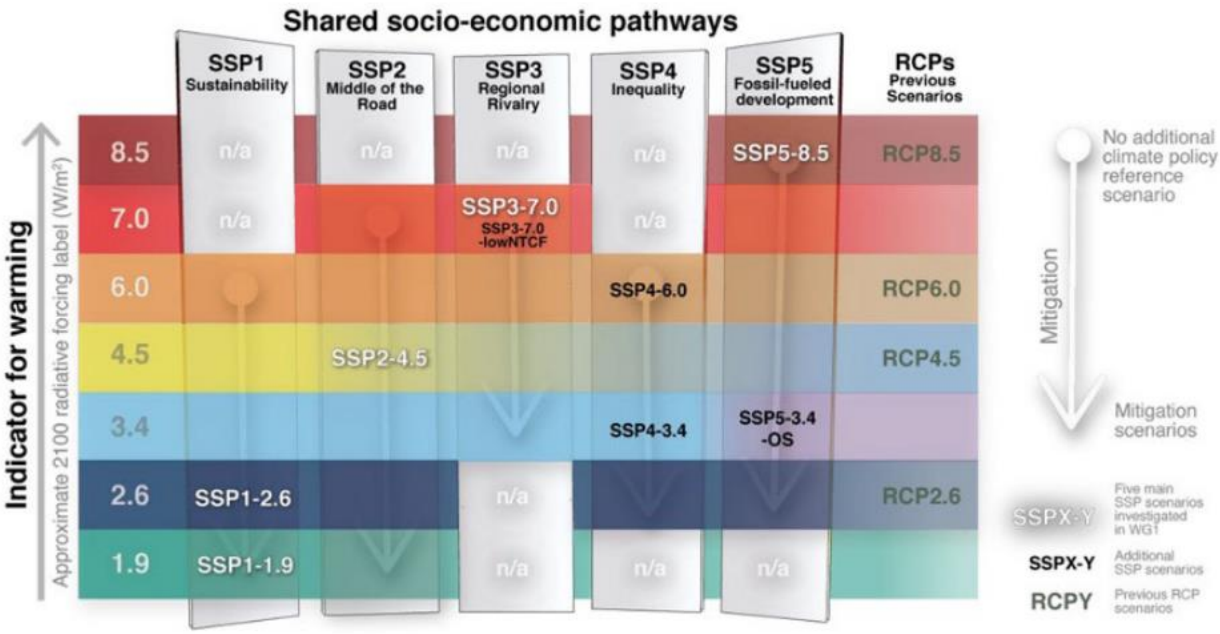



*Figure 3-8: Shared Socioeconomic Pathway Scenarios, Radiative Forcing Categorisation, and the Storylines Upon Which They Are Built (Source: IPCC, 2021)*

For each SSP scenario, IPCC (2021) provides SLR projections for future years up to 2150 comprising median values along with a likely range (medium confidence)[6].

Global plots of percentage deviation from the global SLR are provided in IPCC (2013) and indicate that the local variation along the east coast of Australia is up to 10% higher than the global trend. IPCC global SLR projections, with adjustment of plus 10% to account for local variation in SLR relative to the global mean, have been adopted, for example, by Eurobodalla Shire Council, Shoalhaven City Council, Wollongong Council, Shellharbour Council and Sutherland Shire Council. This approach is described in several recent probabilistic assessments of coastal hazards carried out by RHDHV (RHDHV, 2018; 2020a; 2020b).

The IPCC (2021) SLR scenarios and associated values that were adopted for the present study (all IPCC values increased by 10%) are summarised in Table 3-4.

*Table 3-4 IPCC (2021) Sea Level Rise – Adopted Inputs for Probabilistic Analysis*

| Year | Minimum Trajectory SSP1-1.9 (lower) | Modal Trajectory SSP3-7.0 (median) | Maximum Trajectory SSP5-8.5 (upper) |
|---|---|---|---|
| 2020 | 0.00 | 0.00 | 0.00 |
| 2030 | 0.06 | 0.07 | 0.08 |
| 2040 | 0.10 | 0.13 | 0.16 |
| 2050 | 0.13 | 0.20 | 0.27 |
| 2060 | 0.16 | 0.27 | 0.38 |
| 2070 | 0.19 | 0.37 | 0.52 |
| 2080 | 0.23 | 0.46 | 0.67 |
| 2090 | 0.25 | 0.57 | 0.86 |
| 2100 | 0.28 | 0.71 | 1.06 |

The following is noted:

- The 'upper' and 'lower' trajectories correspond with the 17th and 83rd percentile values (respectively) that constitute the 'likely' range of projections. While a wider range of values is statistically possible, consideration of the 'likely' range projections is considered to be reasonable for the purpose of this assessment because they only include processes that can be projected skilfully with at least medium confidence (based on agreement and evidence) (IPCC, 2021). For example, the 'likely' range projections do not include ice-sheet-related processes that are characterised by deep uncertainty.
- The adoption of SSP1–1.9 (lower) and SSP5–8.5 (upper) for the minimum and maximum trajectories respectively represents a wide range of SLR projections but is considered to be reasonable given IPCC (2021) noted that all SSPs are plausible.

*[6] The 'likely' range is associated with the 17th to 83rd percentile range for each SSP. IPCC (2021) also report low confidence projections for the SSP5-8.5 scenario, which includes a 'very likely' upper bound projection, i.e. 17th to 95th percentile range.*

- Adoption of the 'median' value within SSP3–7.0 as the peak/modal trajectory is potentially conservative but is considered appropriate[7].
- In each case the projections were 'normalised' to a zero SLR value at the start of the planning period of 2020.

### 3.5.3 Bruun Factor

Selection of an appropriate Bruun factor depends on the adopted depth of closure. There are a number of methods available to estimate the closure depth, including:

- analytical methods based on wave characteristics and sediment grain size characteristics;
- field methods based on survey data; and
- field methods based on sedimentological data.

A detailed assessment of closure depths in the study area is provided in **Appendix B**. Based on this assessment, the Bruun factors presented in Table 3-5 were adopted for the probabilistic assessment.

*Table 3-5 Bruun Factor – Adopted Inputs for Probabilistic Analysis*

| Statistic | Bruun Factor | |
|---|---|---|
| | **Number One Beach** | **Boat Beach** |
| Minimum | 35 | 30 |
| Mode | 50 | 40 |
| Maximum | 65 | 50 |

## 3.6 Storm Demand

SMEC (2013) assessed historical observations of short-term erosion at the beaches in the study area using available photogrammetry data to estimate the storm demand. Based on this assessment:

- a storm erosion demand of 120 m$^3$/m was adopted for the eastern end of Number One Beach (i.e., Block 3 comprising the study area assessed in this investigation);
- adopted storm erosion demand values for Boat Beach were as follows:
  - 30 to 50 m$^3$/m – eastern end;
  - 120 m$^3$/m – middle section; and
  - 80 m$^3$/m – western end.

Additional analyses of storm demands have not been possible for the study area (suitable beach profiles immediately 'before' a severe storm and immediately 'after' a severe storm do not exist). It is therefore proposed to adopt storm demand as estimated by SMEC (2013), which are considered to be reasonable values.

It should be noted that the actual beach erosion realised along the study area in future storm events will be influenced by a wide variety of factors including wave direction and the possible formation of rip cells at

---

[7] *SSP3-7.0 is a high emissions scenario resulting from no additional climate policy in a fragmented world of "resurgent nationalism", with "particularly high non-$CO_2$ emissions, including high aerosols emissions" (IPCC, 2021). SSP3-7.0 lies between AR5 scenarios RCP6.0 and RCP8.5 and represents the medium to high end of the range of future forcing pathways.*

discrete locations. Furthermore, the presence of non-erodible materials at the back of the beach and rock platforms beneath the beach will limit the supply of sand to accommodate the potential storm demand volume. This is discussed further in Section 5.

An average recurrence interval (ARI) for these storm demands was not nominated but based on Gordon (1987) and the experience of RHDHV it would be approximately equal to the 100-year ARI 'high' demand value at a rip head. Based on measurements at NSW beaches, Gordon (1987) derived relationships between storm demand and average recurrence interval, in both 'high demand' (at rip heads) and 'low demand' (away from rip heads) areas. It was estimated by Gordon (1987) that the storm demand above RL 0 was about 220 $m^3$/m for the 100-year ARI event, for exposed NSW beaches at rip heads, and that the relationship between storm demand and the logarithm of ARI could be considered linear.

The relationship developed by Gordon (1987) was adopted for estimation of storm demand values with the following adjustments:

- the ARI values are re-expressed as annual exceedance probability (AEP) to facilitate the probabilistic methodology; and
- the range of ARI (AEP) is extended to cover both more frequent events (1-year ARI) and rarer events (1000-year ARI) than those considered in Gordon (1987). The extrapolation is based on a linear relationship between storm demand and the logarithm of ARI up to the 1000-year ARI event, which is likely to be conservative (a downward concave 'tail' to the relationship is expected to be the most physically realistic).

The original relationship in Gordon (1987) is shown in Figure 3-9.

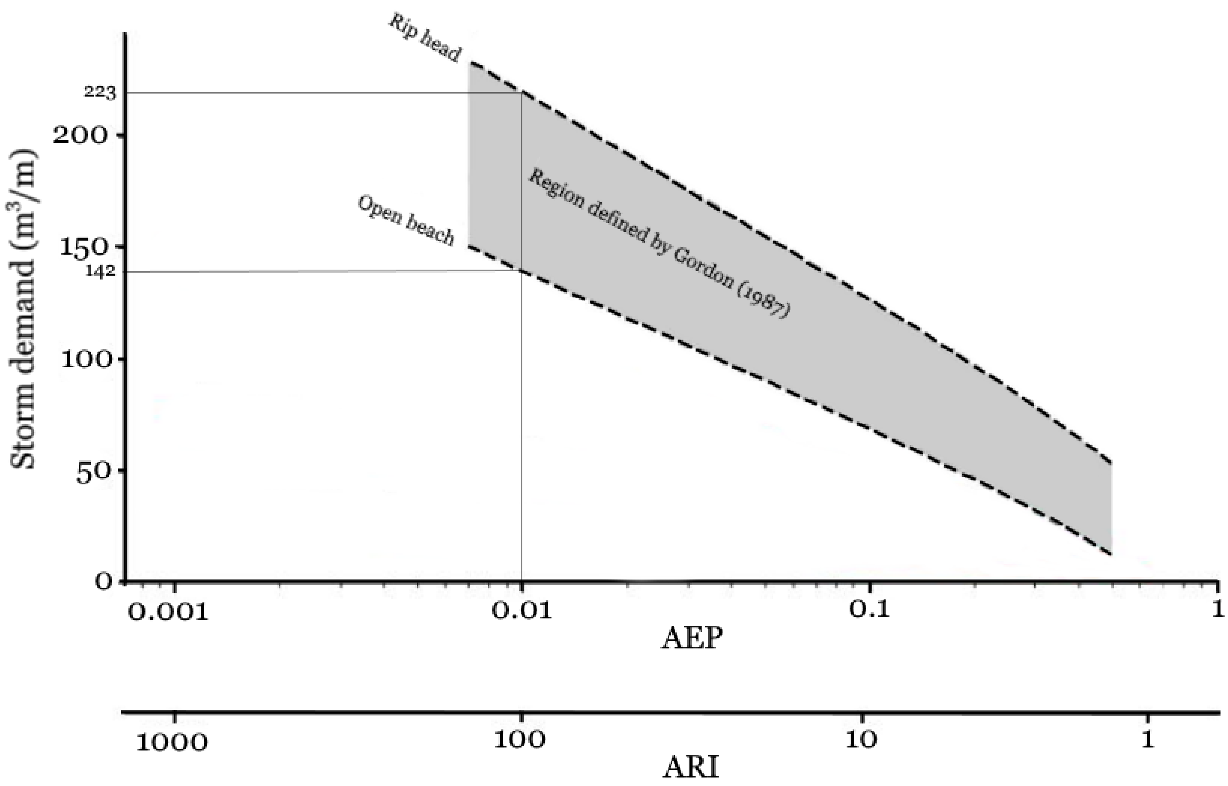



*Figure 3-9: Gordon (1987) relationship between storm demand and ARI/AEP*

# 4 Influence of Existing Protective Structures

There is an existing “rockfill batter” structure at Number One Beach that was designed to stabilise the slope adjacent to Seal Rocks Road over a length of around 50 m as indicated in Figure 4-1.

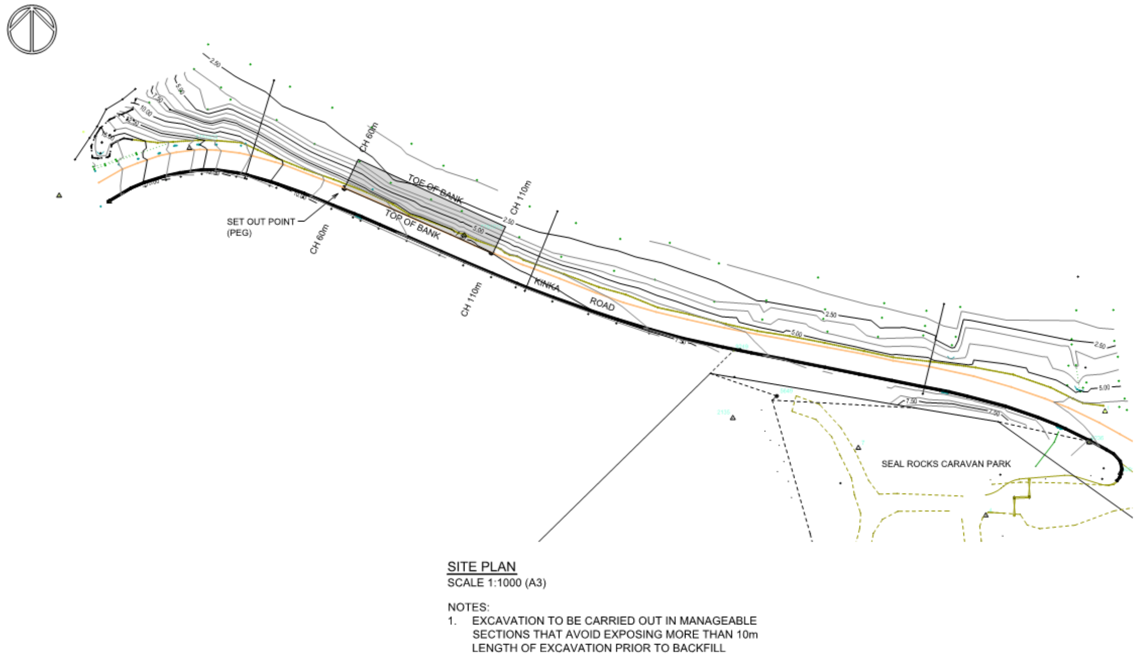



*Figure 4-1: Rockfill batter structure - site plan (Source: RGS, 2014)*

Typical design sections for the structure are shown in Figure 4-2. It is evident that the rock fill is founded at approximately RL 3. In NSW, a foundation level of approximately RL -1 is commonly adopted for flexible coastal structures located at the back of the active beach area. This is based on stratigraphic evidence of historic scour levels and observed scour levels during major storms in front of existing permeable and non-permeable seawalls along the NSW coast (Nielsen et al, 1992; Foster et al, 1975).

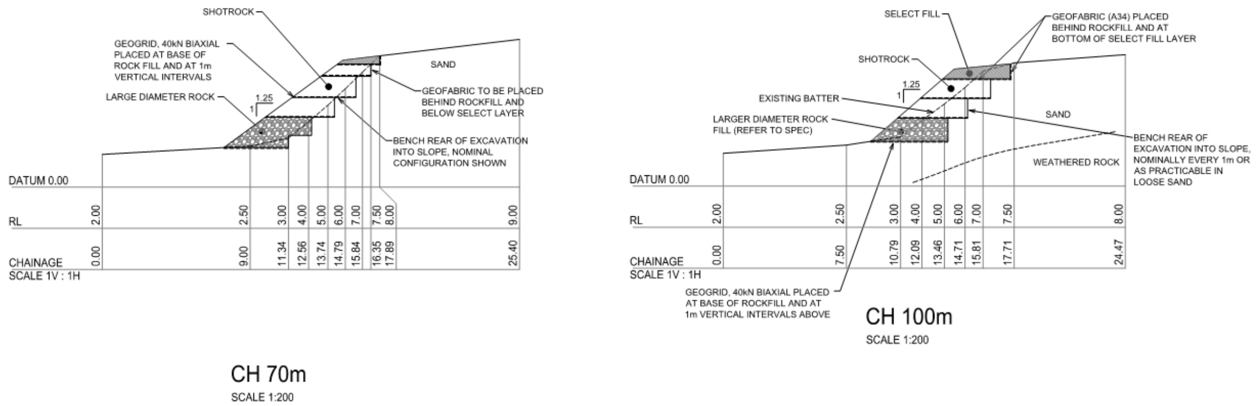



*Figure 4-2: Rockfill batter structure – typical sections (Source: RGS, 2014)*

As such, it is evident that this structure has not been designed for a coastal protection function. For the purpose of the coastal hazard assessment, it was assumed that the structure would be undermined during extreme erosion events and would not limit the amount of shoreline erosion that occurs landward of the structure.

In reality, it is likely that the rockfill materials would at least partially resist shoreline erosion at the structure, particularly in consideration of the large diameter (>900 mm) rock material that is included in the lower terrace. However, for the purpose of the coastal hazard assessment it is considered reasonable to conservatively assume that the existing rockfill batter structure would not limit the amount of landward shoreline erosion that occurs during extreme erosion events.

Royal HaskoningDHV

# 5 Influence of Unerodable Materials

## 5.1 Introduction

In general, the presence of unerodable materials such as stiff clays or bedrock would be expected to limit (either entirely or partially) the amount of shoreline erosion that occurs above and landward of these features during extreme erosion events.

Of particular significance to this coastal hazard assessment is the existence of underlying rock material as this would be unerodable compared to the adjacent sand deposits. However, it should be noted that the overlying sand and fill materials may be eroded during significant storm events, particularly where the profile of unerodable materials is relatively low and can be overtopped by waves. This may have implications for the selection of feasible options for management of Seal Rocks Road.

## 5.2 Geotechnical and Geophysical Investigations

Coffey carried out geotechnical and geophysical investigations in the study area to provide general input to the feasibility study and the local area plan, as reported in Coffey (2022). The investigations were undertaken specifically to inform:

- this coastal hazard assessment; and,
- the road realignment options study.

In the low-lying areas near Boat Beach and Number One Beach, boreholes were taken at a total of nine (9) locations to develop a geological / geotechnical model focusing particularly on the sand profile and its interface with underlying rock.

The depth to rock in the boreholes varied between 1.7 m to greater than 10.5 m. The overlying soils typically comprised fill material of variable thickness, underlain by aeolian wind deposited dune sands. Thin, extremely weathered layers of clay were rarely encountered across the site at the soil-rock interface. The rock encountered in the boreholes was siltstone, and argillaceous sandstone and typically of high to very high strength. Borehole locations and interpreted cross sections illustrating the subsurface conditions encountered in the investigation are provided in **Appendix C**.

The borehole logs provided in Coffey (2022) indicate that the siltstone unit underlies Seal Rocks Road in the area to the west of the caravan park, with the top of the profile reducing from around RL 4.3 to RL 3.2 moving east. Siltstone was not encountered in the boreholes taken at the eastern end of the beach in the vicinity of the caravan park, which is characterised by a sandy subsurface.

Boreholes taken adjacent to Boat Beach indicate that the siltstone unit also underlies Kinka Road. At the western end, the top of the siltstone profile is relatively high (above RL 10), associated with the steep rock bluff in that area. Moving east along the remaining section of the beach where ground levels are lower, the top of the siltstone below the road is inferred to vary between around RL 2 and RL 3.

Geophysical investigations were also undertaken to assess the potential presence of unerodable subsurface materials in the vicinity of the existing roadway and back beach area. This included:

- Multichannel Analysis of Surface Waves (MASW), with seismic profiles undertaken along the back of the sandy beach at both sites. The MASW results for Number One Beach indicated a generally horizontally layered subsurface with an interpreted base of dense sand / top of rock located

Royal HaskoningDHV

around RL -3 to -6. In comparison, the MASW results for Boat Beach were more variable, with an interpreted base of dense sand / top of rock ranging between around RL -7 and RL 2, although Coffey (2022) noted that this is likely the result of loose rock material within the soil layer above the bedrock surface.

- Ground Penetrating Radar (GPR) profiles undertaken along Seal Rocks Road and Kinka Road. The GPR results were interpreted by Coffey (2022) to identify depth to rock and were generally consistent with borehole data.

MASW and GPR locations and results illustrating the subsurface conditions interpreted from the geophysical investigations are provided in **Appendix C**.

Perth Sand Penetrometer (PSP) testing was also undertaken at 40 locations along Number One Beach and Boat Beach. The PSP tests terminated above RL 0 for all test locations, however it is understood that this may not necessarily indicate the presence of unerodable materials.

## 5.3 Interpreted Geotechnical Cross-Shore Profiles

Coffey used existing data on boreholes, PSP testing, MASW testing and survey data to generate six (6) representative cross-shore subsurface profiles across the study area, referred to as CS1 to CS6. This included three (3) sections at Number One Beach (CS1 to CS3) and three (3) sections at Boat Beach (CS4 to CS6) at the locations indicated in Figure 5-1 and Figure 5-2, respectively.

With reference to Figure 2-4, the photogrammetry profiles that each cross-shore subsurface profile were taken to be representative of are summarised in Table 5-1.

*Table 5-1 Representative cross-shore subsurface profiles for DPE photogrammetry profiles*

| Beach | Cross-Shore Subsurface Profile | DPE Photogrammetry Profiles represented by subsurface profile |
|---|---|---|
| Number One Beach | CS1 | Block 3, Profiles 6 to 8 |
| | CS2 | Block 3, Profiles 4 to 5 |
| | CS3 | Block 3, Profiles 1 to 3 |
| Boat Beach | CS4 | Block 2, Profiles 4 to 6 |
| | CS5 | Block 2, Profiles 1 to 3<br>Block 1, Profiles 4 to 6 |
| | CS6 | Block 1, Profiles 1 to 3 |

Each of the interpreted cross-shore subsurface profiles developed by Coffey are reproduced in Figure 5-3 to Figure 5-8. For each profile, the following features are identified:

- fill / loose sand;
- dense sand; and
- inferred top of rock.

For the purpose of the coastal hazard assessment, it was assumed that both the fill / loose sand and dense sand layers would be entirely erodible during a coastal storm event. That is, the ‘inferred top of

Royal HaskoningDHV

rock' layer has been adopted to indicate the presence and geometric profile of unerodable materials within the coastal hazard area of both beaches.


*Figure 5-1: Geotechnical cross-shore profile locations – Number One Beach*


*Figure 5-2: Geotechnical cross-shore profile locations – Boat Beach*

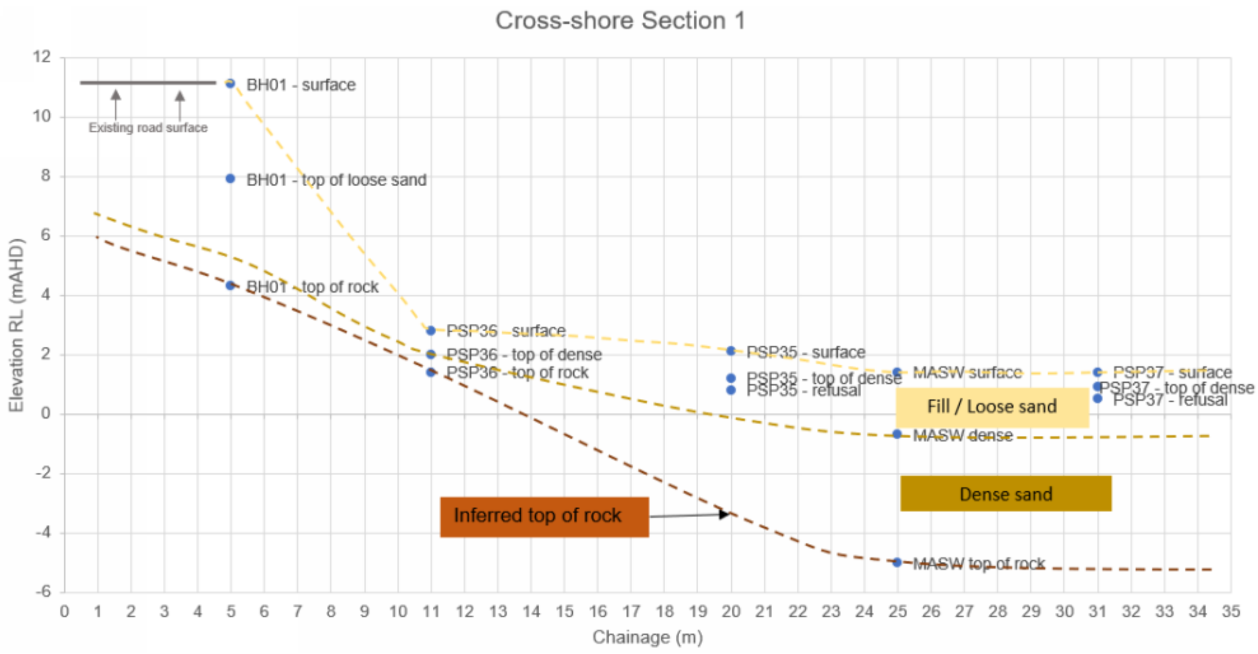



*Figure 5-3: Geotechnical cross-shore profile – Section 1 (Number One Beach)*

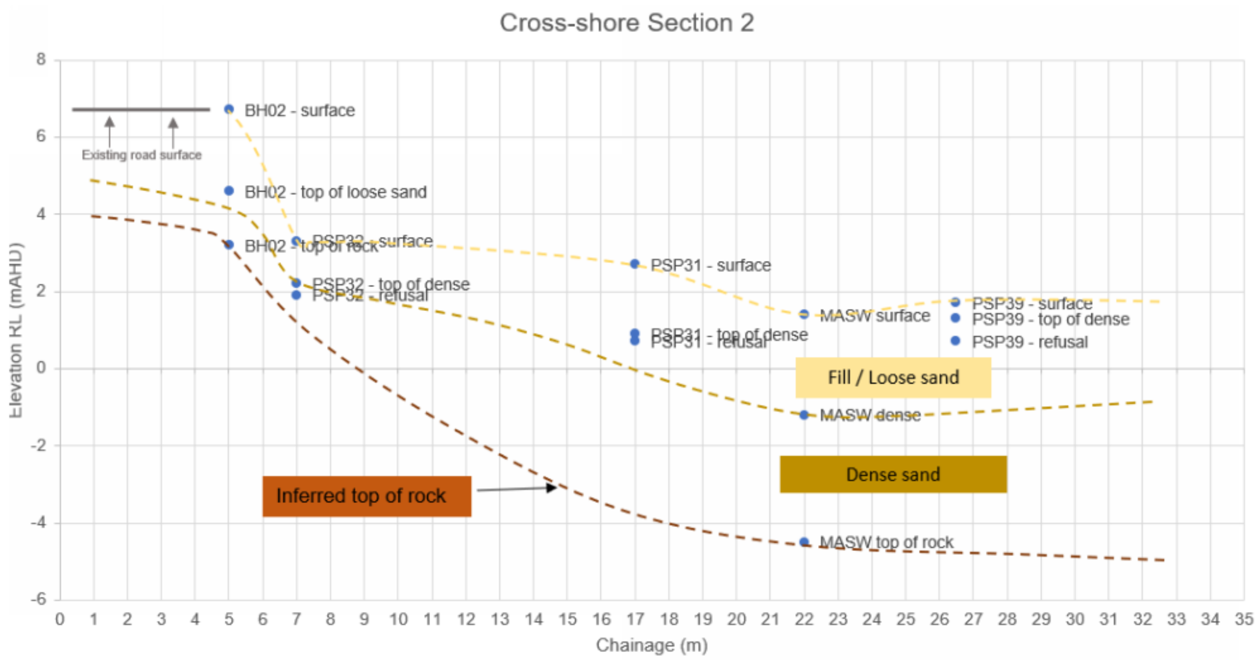



*Figure 5-4: Geotechnical cross-shore profile – Section 2 (Number One Beach)*

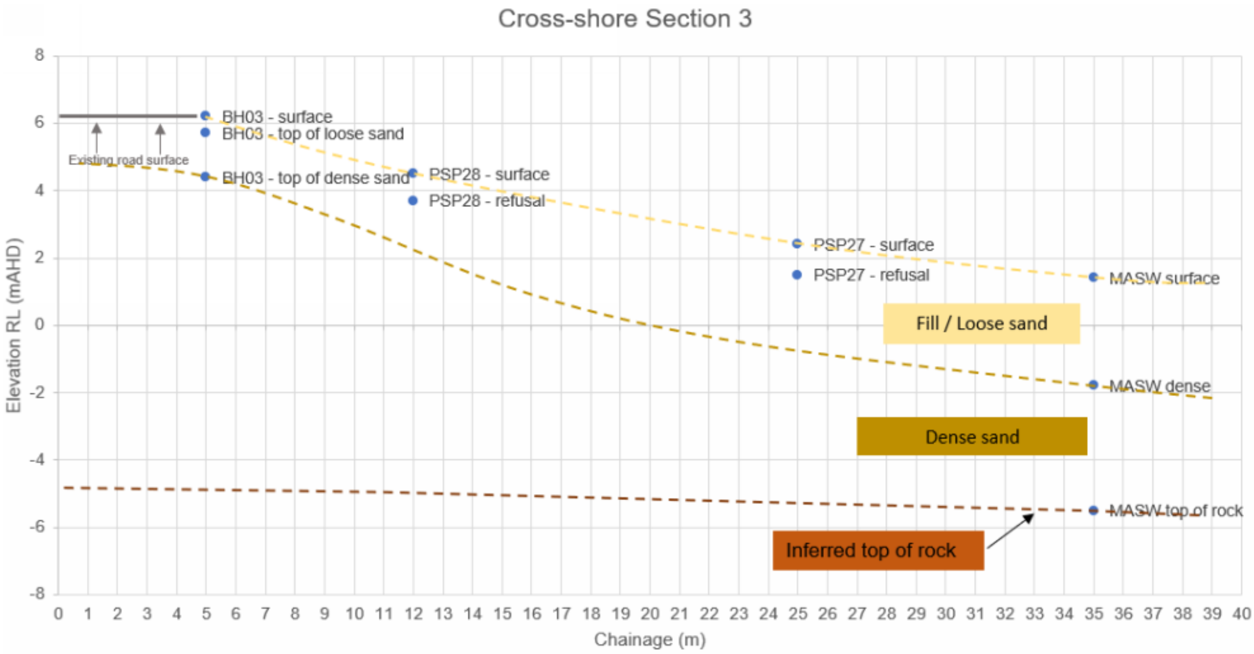



*Figure 5-5: Geotechnical cross-shore profile – Section 3 (Number One Beach)*

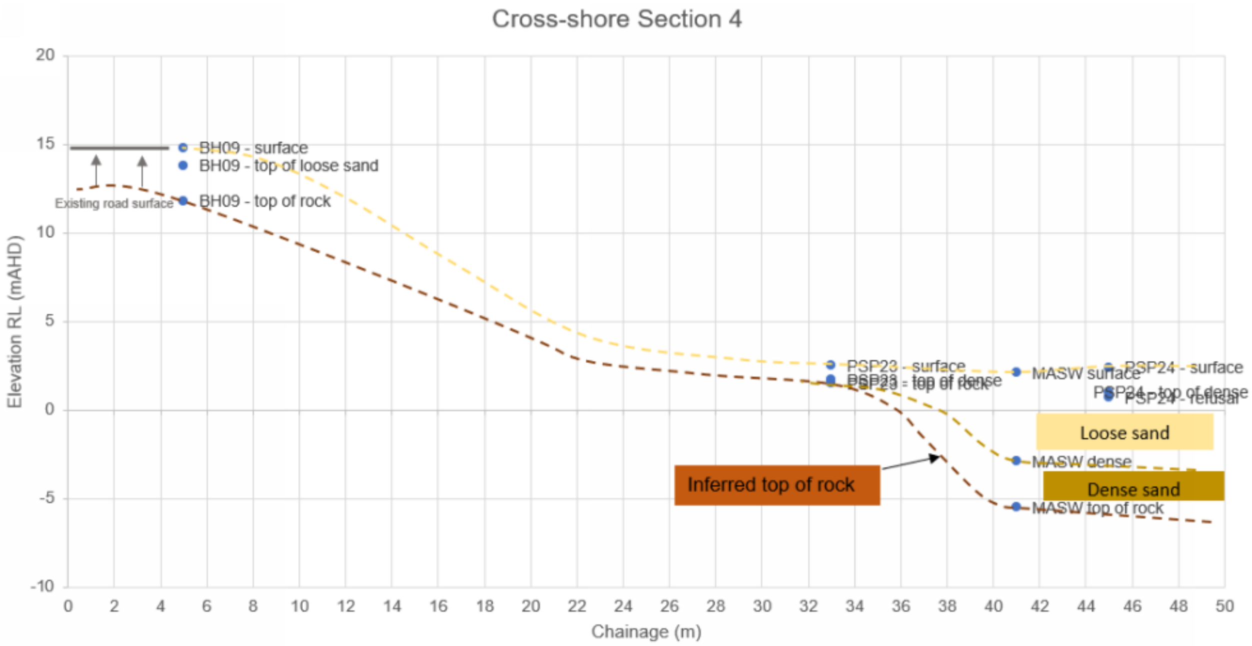



*Figure 5-6: Geotechnical cross-shore profile – Section 4 (Boat Beach)*

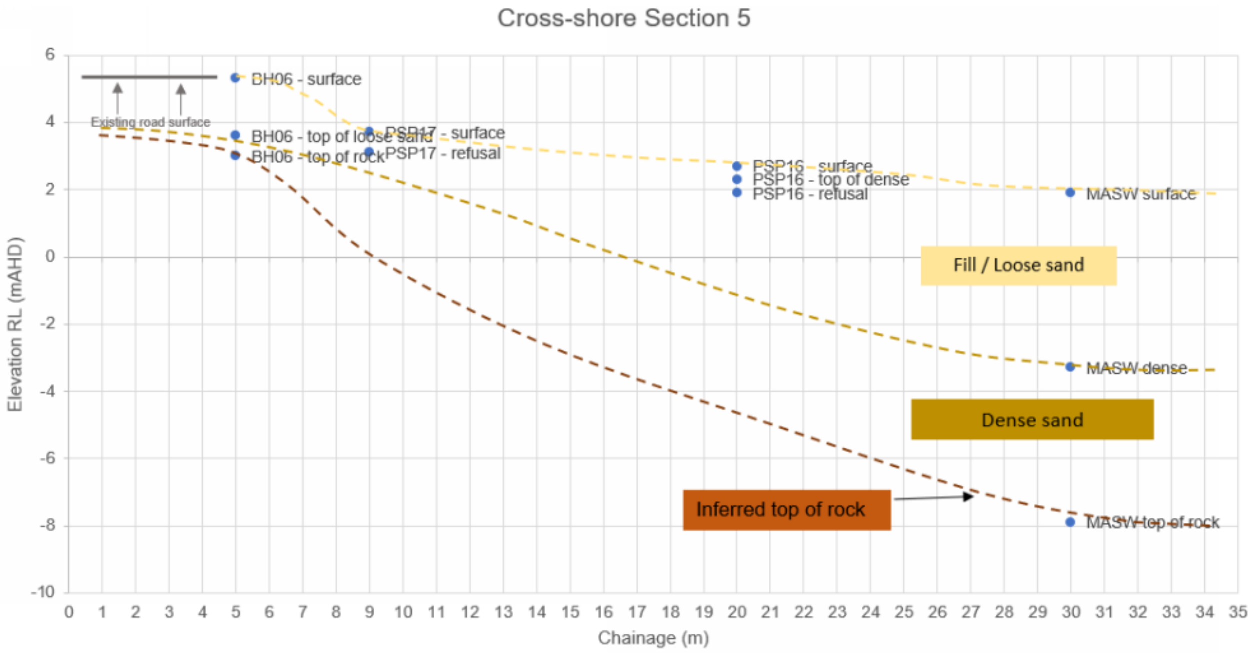



*Figure 5-7: Geotechnical cross-shore profile – Section 5 (Boat Beach)*

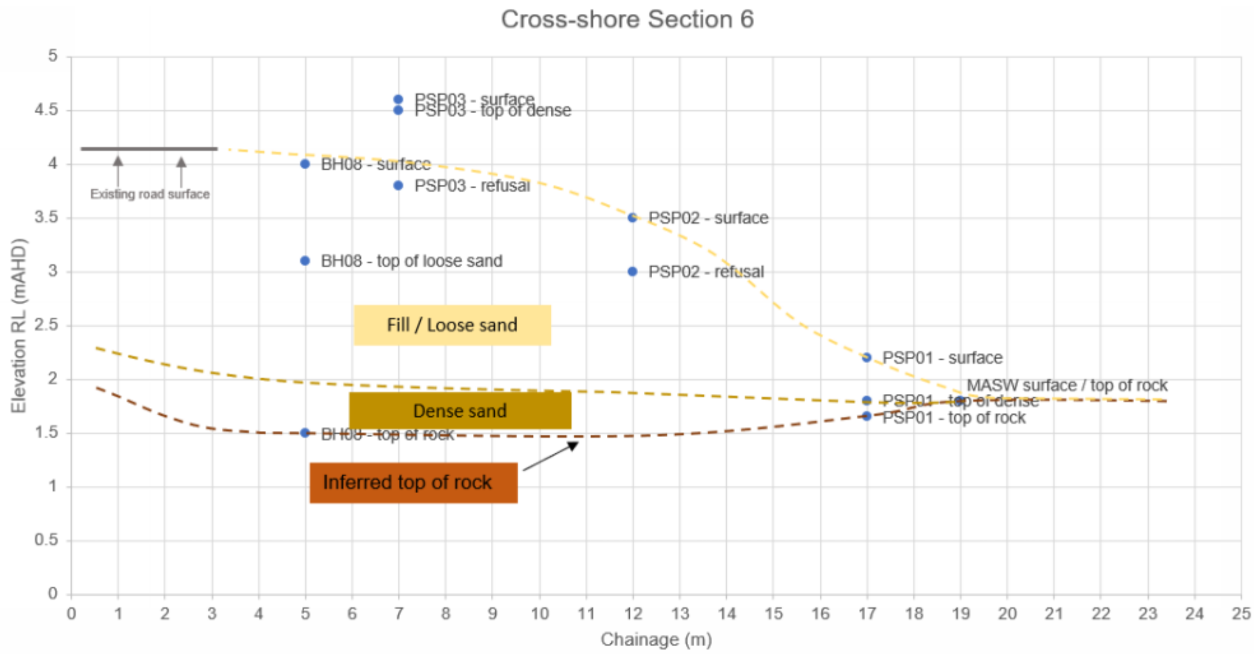



*Figure 5-8: Geotechnical cross-shore profile – Section 6 (Boat Beach)*

## 5.4 Methodology adopted for Coastal Hazard Assessment

### 5.4.1 First-Pass 'Screening' Assessment

While the cross-shore subsurface profiles presented in Figure 5-3 to Figure 5-8 indicate that unerodable material is present throughout the study area, a first-pass 'screening' assessment was undertaken to determine whether this material would be expected to limit the impact of coastal erosion/recession on the key assets being considered as part of this study, i.e. Seal Rocks Road and Kinka Road. As part of this

Royal HaskoningDHV

assessment, it was assumed that the unerodable material would begin to limit the landward extent of potential erosion/recession where the rock profile extends above RL 0.

Two (2) examples of this assessment are indicated in Figure 5-9 and Figure 5-10, undertaken for profiles CS1 and CS4 respectively. The following is noted:

- For profile CS1 (Figure 5-9), it is evident that an erosion/recession scenario that results in exposure of unerodable material above RL 0 would be associated with development of an eroded profile with a ZSA that extends landward of the existing roadway. That is, the rock profile at CS1 would not be expected to reduce the risk of coastal erosion/recession impacts at the roadway.
- Conversely, for profile CS4 (Figure 5-10), it is evident that an erosion/recession scenario that results in exposure of unerodable material above RL 0 would be associated with development of an eroded profile that is entirely seaward of the existing roadway. That is, the rock profile at this location would be expected to reduce the risk of coastal erosion/recession impacts at the roadway.

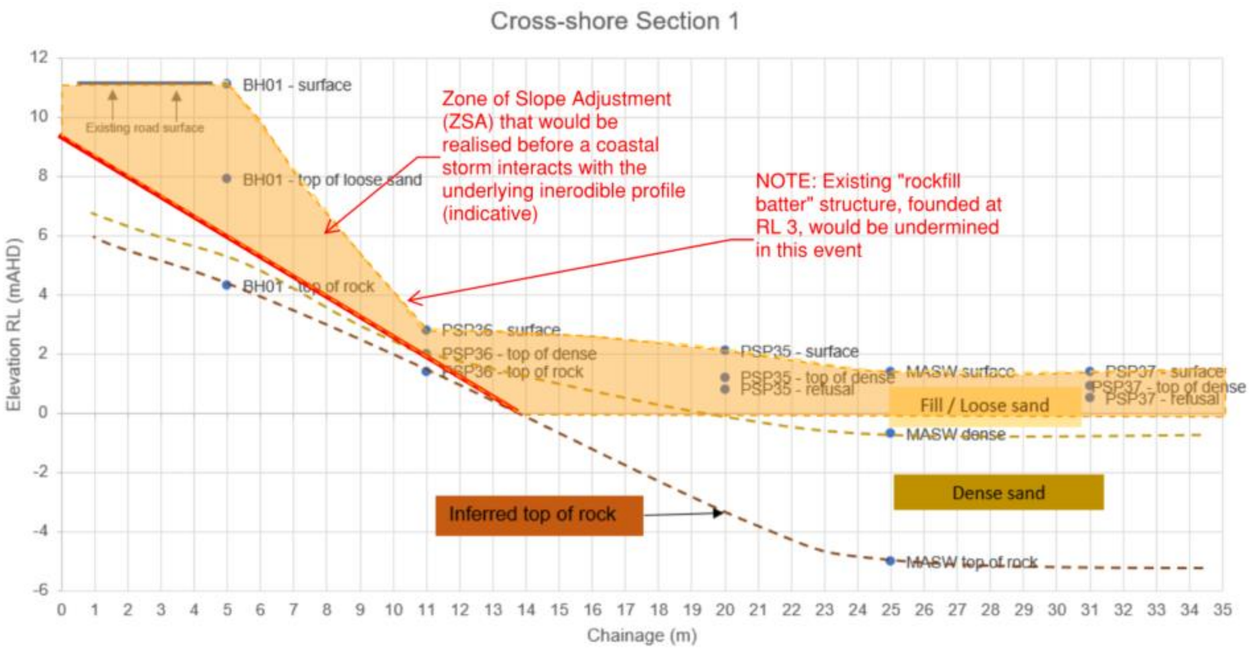



*Figure 5-9: Example first-pass 'screening' assessment – Section 1 (Number One Beach)*

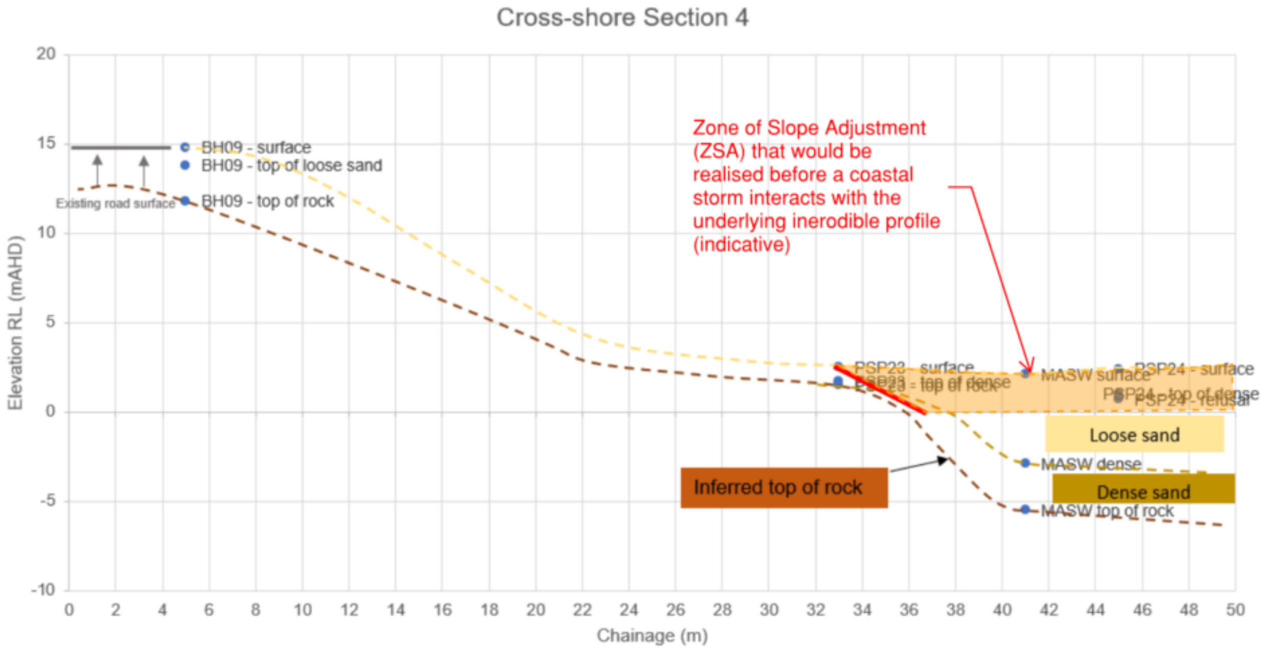



*Figure 5-10: Example first-pass 'screening' assessment – Section 4 (Boat Beach)*

The first-pass 'screening' assessment was undertaken for each representative cross-shore profile and it was determined that the underlying rock material would not be expected to limit coastal erosion/recession at the roadways for the following representative cross-shore profiles:

- Number One Beach – profiles CS1, CS2 and CS3; and,
- Boat Beach – profile CS5.

Based on these results, the probabilistic coastal hazard assessment did not include any allowance for the presence of unerodable materials at the photogrammetry profile locations represented by the above cross-shore profiles (refer Table 5-1). However, it should be noted that erosion/recession extents were truncated at obvious geotechnical features such as the escarpment located immediately landward of Seal Rocks Road.

### 5.4.2 Detailed Assessment

Based on the results of the first-pass screening assessment, it was determined that profiles CS4 and CS6 are the only profiles where underlying rock material would be expected to limit coastal erosion/recession at the roadway. For the photogrammetry profiles represented by these profiles (refer Table 5-1), the approach outlined below was adopted to account for the presence of unerodable materials.

It was assumed that the amount of shoreline erosion that occurs above and landward of the rock profile is a function of the wave energy reduction associated with wave transmission across the rock profile. The adopted methodology for implementing this approach is summarised below. This methodology was followed at each relevant profile location for each year in the coastal hazard assessment.

- If the simulated shoreline erosion distance[8] is less than the present-day beach width where rock is below RL 0, it would be assumed that there is no interaction between the rock profile and coastal processes.

- If the simulated shoreline erosion extends a sufficient distance landward to start interacting with the rock profile, wave transmission over the top of the rock profile would be estimated by assuming that depth-limited wave conditions apply both seaward of and above the rock profile as follows:
  - Wave height (H) is estimated both seaward of ($H_{seaward}$) and above the rock profile ($H_{rock}$), where H is the product of water depth at the respective locations and a conservative breaker coefficient of 0.78.
  - Water depth seaward of the rock profile is based on the water level above a nominal scour level of RL -1, as per Nielsen et al (1992). Water depth at the rock profile is based on the water level above an average level for the rock profile.
  - Nearshore water level is the sum of still water level (SWL), SLR and wave setup, where:
    - SWL values for a range of ARIs are provided in Watson (2022) for the 2020 planning period. The Watson (2022) SWL values are applicable to Fort Denison which is representative of mid-north coast NSW. For each Monte Carlo simulation of the probabilistic model, it was assumed that the SWL ARI is the same as the simulated storm demand ARI[9].
    - SLR is simulated in the probabilistic model as described in Section 2.
    - Wave setup at the shoreline is typically assumed to be in the order of 10% to 15% of the offshore wave height ($H_0$), with 15% conservatively adopted for the coastal hazard assessment. $H_0$ values for a range of ARIs are provided in Glatz et al (2017). For each Monte Carlo simulation of the probabilistic model, it was assumed that the $H_0$ ARI is the same as the simulated storm demand ARI[10].
  - Wave transmission at the rock profile ($K_t$) is determined as per Equation 1:

$$K_t = \left(\frac{H_{rock}}{H_{seaward}}\right) \qquad (1)$$

- It is well known that wave erosion at a shoreline correlates closely with rate of delivery of wave energy (c=0.93, Nanson et al 1994). Since wave energy is proportional to the square of the wave height, it follows that the design erosion demand above and landward of the rock profile should reduce by approximately $1 – K_t^2$. For example, a wave transmission coefficient of 0.45 would result in an 80% reduction in the design erosion demand landward of the rock profile.

---

*[8] The simulated shoreline erosion distance is the sum of the erosion due to storm demand, SLR recession and underlying recession. As such, it has been assumed that erosion that results in exposure of the rock profile can occur due to any combination of these components.*

*[9] This implies that there is complete dependence between storm demand and SWL. While complete dependence between these parameters is unlikely, Shand et al (2012) noted that dependence exists between significant wave height and tidal residual based on statistical analysis of corresponding wave and water level data in NSW. In the absence of sufficient data for a full joint probability analysis, the marginal extremes have been conservatively combined assuming complete dependence.*

*[10] This assumption is considered to be reasonable given the strong dependence between storm demand and offshore wave height ($H_0$). In the absence of sufficient data for a full joint probability analysis, the marginal extremes have been conservatively combined assuming complete dependence.*

- For each Monte Carlo simulation, the rock profile would resist a proportion of the horizontal erosion component that would otherwise fully occur landward of the rock profile if a completely sandy subsurface was present.

- The horizontal erosion component landward of the rock profile is calculated based on the thickness of the overlying erodible material inferred from the geotechnical investigations.

- The below example illustrates the application of the above methodology:
  - 90 $m^3$/m of shoreline erosion is simulated at Profile 1, Block 2 (Boat Beach).
  - At this location, 40 $m^3$/m (say) of sand is available in the beach profile (above RL 0) in the area seaward of the rock profile as inferred from the geotechnical investigations.
  - Based on the above, the design erosion demand landward of the rock profile is 50 $m^3$/m.
  - The water level simulated by the model (including SWL, SLR and wave setup) is RL 2.8.
  - Seaward of the rock profile, a scour level or RL -1 applies, resulting in a water depth of 3.8 m and $H_{seaward}$ = 0.78*3.8 = 2.96 m.
  - The top of the rock profile occurs at RL 1.8 at this location. Therefore, water depth is 1 m and $H_{rock}$ = 0.78*1 = 0.78 m.
  - Based on Equation 1, a wave transmission coefficient ($K_t$) of 0.26 is calculated.
  - The design erosion demand above and landward of the rock profile is reduced by 93% (i.e., 1 – $0.26^2$), from 50 $m^3$/m to 3.4 $m^3$/m.
  - A 1.7 m thick layer of erodible material lies above the siltstone profile at this location. Therefore, the horizontal erosion component landward of the rock profile is calculated to be 2 m.

# 6 Recognition of Uncertainty

## 6.1 Future Climate

It is important to recognise that future climate cannot be predicted precisely, and is subject to not only storm variability, but longer term cycles such as the El Nino / La Nina Southern Oscillation, Pacific Decadal Oscillation, and Interdecadal Pacific Oscillation (IPO).

For example, Helman (2007) has postulated that during negative Interdecadal Pacific Oscillation (IPO) phases, the NSW coast experiences wet periods, major floods, sea level above the long-term trend and coastal erosion. Using an 11-year Chebychev filter of annual series from 1871 to 2008 (Folland, 2008), a significant past continuous negative IPO period was from 1945 to 1977, and IPO was positive from 1978 to 2000, returning to negative from 2001 to 2008 (although the nature of the filtering was such that the 2004 to 2008 period should be regarded with caution). A return to negative IPO combined with additional future projected sea level rise could lead to a future period of enhanced erosion compared to the 1978 to 2000 period.

Future climate can also not be predicted precisely due to ongoing climate change caused by the enhanced greenhouse effect. Climate change effects such as sea level rise are projected by researchers based on various scenarios as to how greenhouse gases and aerosols will be emitted anthropogenically in the future, that is so called "Shared Socioeconomic Pathways" as described by the IPCC, for example in IPCC (2021). These scenarios represent a range of 21$^{st}$ century climate policies and cannot be precisely predicted as they largely depend on political decisions and economic growth.

Furthermore, storm events more severe than the adopted design events can occur.

## 6.2 Influence of Existing Protective Structures

As noted in Section 4, it is recognised that the existing rockfill materials at Number One Beach would be likely to at least partially resist shoreline erosion at the structure. However, for the purpose of the coastal hazard assessment it is considered reasonable to conservatively assume that the existing rockfill batter structure would not limit the amount of landward shoreline erosion that occurs during extreme erosion events. This is primarily due to the relatively elevated foundation level of the structure, which is located at around RL 3, which would be undermined during a significant coastal storm event that extends to the structure.

## 6.3 Influence of Unerodable Materials

RHDHV recognise that the assumptions developed to describe the relationships between beach erosion and wave transmission (refer Section 5) are fairly generic and were based on limited guidance from established literature and our coastal engineering experience. However, for the purposes of the coastal hazard assessment they are considered to be valid, i.e. it is a methodology that provides a reasonable means of approximating the partial protective capacity of the rock profile in the study area.

## 6.4 Coastal Hazard Parameters

### 6.4.1 Storm Erosion

As described in Section 2, random storm demand values were applied to the beach profiles for each year in the planning period in a Monte Carlo simulation. Beach recovery was not considered as part of the analysis on the assumption that the beach fully recovers from the preceding storm-driven erosion within one (1) year. In reality, full beach recovery from extreme storm events would be expected to occur over longer timeframes.

### 6.4.2 Bruun Rule

It is noted that the Bruun Rule has been questioned in the scientific literature, for example by Cooper and Pilkey (2004) and Ranasinghe et al. (2007) to name two. While there are other alternatives to the Bruun Rule this model is still considered acceptable for use by industry. The Bruun Rule is based on rational coastal engineering principles and has been applied in this hazard assessment in cognisance of the fundamental assumptions upon which it was based to estimate projected long-term recession due to sea level rise.

# 7 Results

## 7.1 Probability Distributions

Probability distributions for shoreline movement (due to the combined effects of storm erosion and recession) were developed for each beach profile location within the study area. Calculations were performed on a yearly basis, covering the 80-year planning period (i.e., extending from 2020 to 2100) considered by this investigation.

The probability distributions for randomly selected profiles at each beach in the study area are presented in Figure 7-1 (Number One Beach) and Figure 7-2 (Boat Beach). As indicated in Figure 7-1, the erosion/recession extents were truncated at the escarpment located immediately landward of Seal Rocks Road.

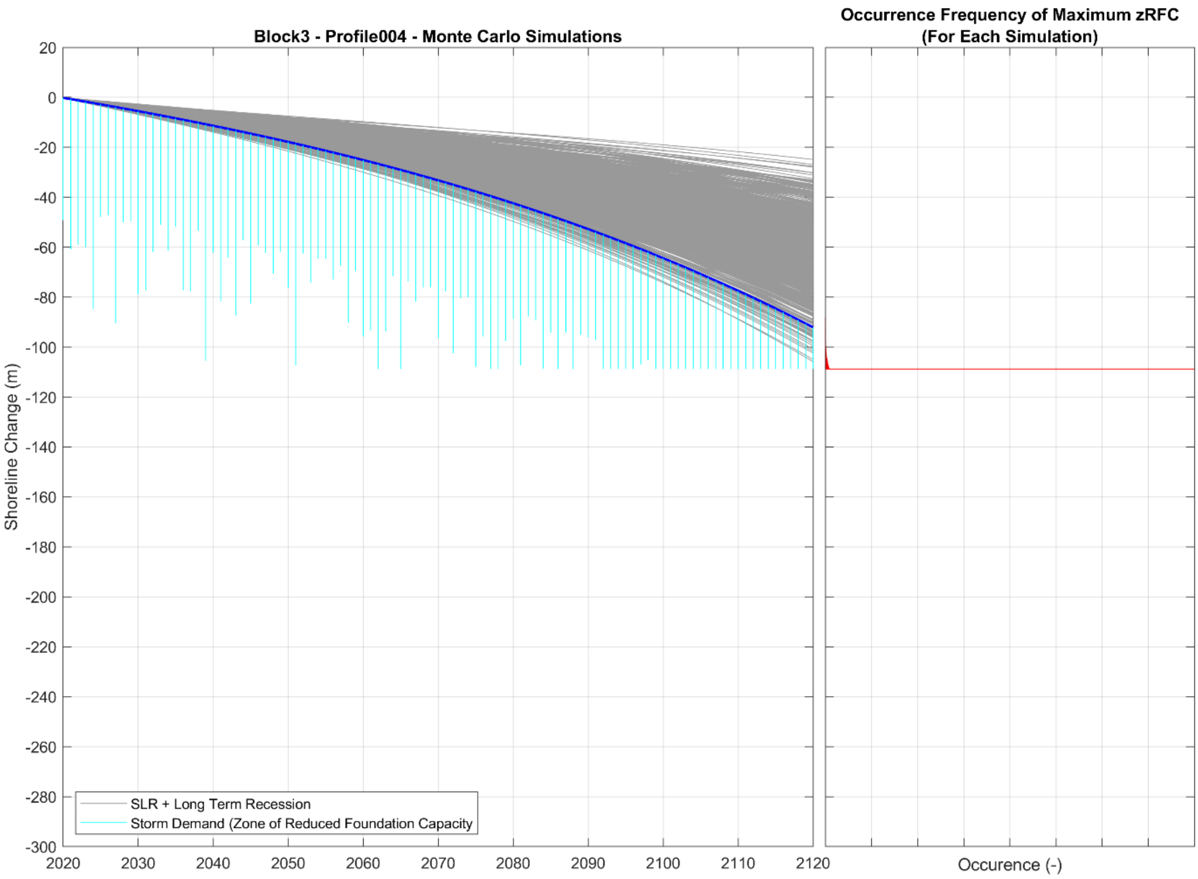



*Figure 7-1: Example of simulated storm demand superimposed on background shoreline movement and corresponding probability distribution, applied over the 2100 planning period – Block 3, Profile 4 (Number One Beach)*[11]

---

[11] *Note 1: The dark blue line represents the recession time series for one of the simulations (106 total simulations, represented by the grey lines), while the vertical light blue lines represent the yearly storm erosion distances for that particular simulation.*
*Note 2: The red probability distribution is the assembled distribution of maximum total shoreline change distances determined from each of the simulations.*

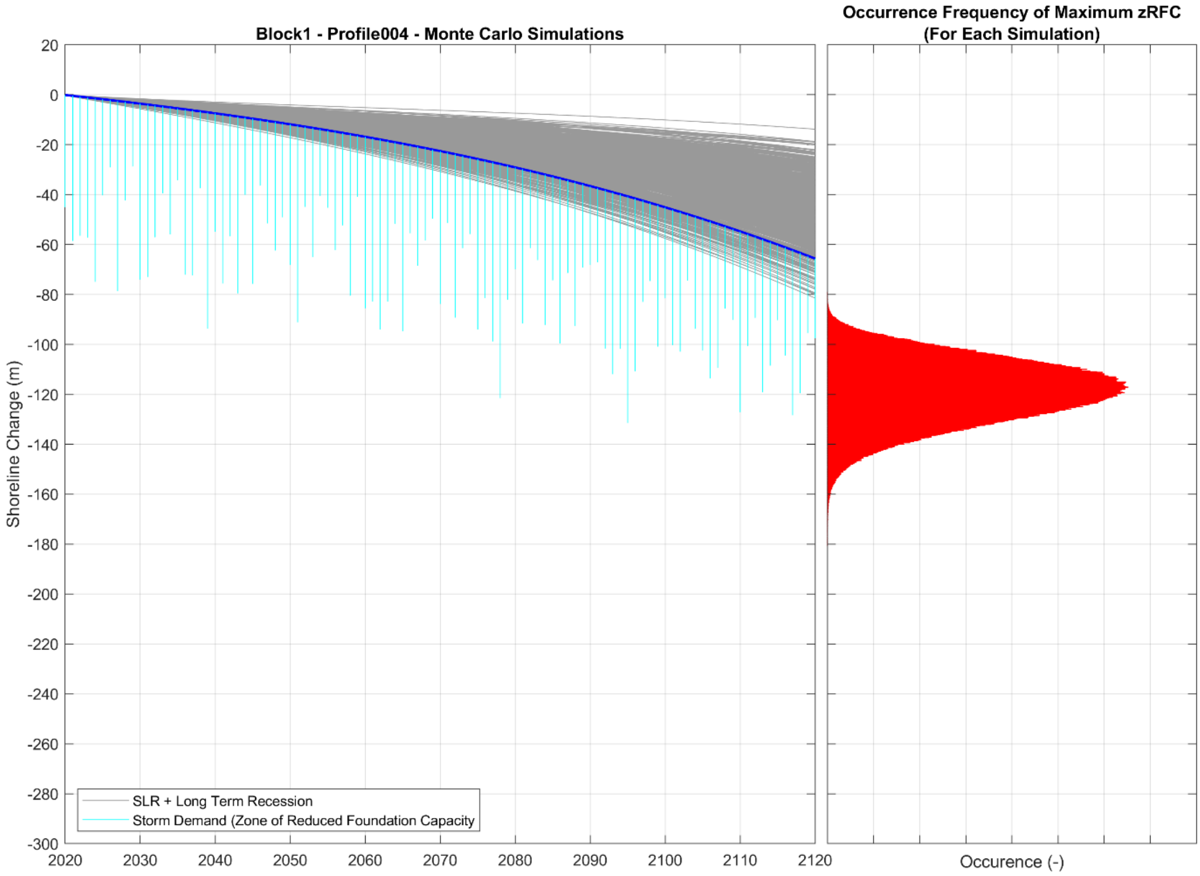



*Figure 7-2: Example of simulated storm demand superimposed on background shoreline movement and corresponding probability distribution, applied over the 2100 planning period – Block 1, Profile 5 (Boat Beach)*

## 7.2 Cumulative Probability Maps

Maps showing the coastal erosion/recession cumulative probability lines (0.1%, 1%, 5%, 20%, 50% and 95% exceedance) were prepared for each planning period considered by the coastal hazard assessment, i.e. 2020 ('present day'), 2060 and 2100. Separate maps were prepared showing coastal hazard lines defined at the landward edge of both the ZSA and ZRFC, respectively[12]. The spatial coverage of the maps spans the study area.

Cumulative probability maps are provided in **Appendix D**.

The maps can be used to provide an indication of the likelihood of specific assets being affected by coastal hazards during the planning periods at each beach in the study area. For example, the mapping indicates that there is an approximately 5% probability that the coastal erosion/recession hazard, defined at the landward edge of the ZRFC, would impact Seal Rocks Road under present day conditions (refer green line on the 2020 ZRFC map in the vicinity of Block 3 Profile 6).

*[12] Application of the ZRFC or ZSA to define the likelihood that an asset is impacted by the coastal erosion/recession hazard should consider the foundation type of the asset. For assets supported by conventional foundations (e.g., slab-on-ground, strip footings, shallow piers), it is common practice to adopt the ZRFC for this purpose, although asset managers may instead choose to adopt the ZSA for this purpose (noting that this is less conservative but not necessarily unreasonable). Although a structure located immediately landward of a slumped escarpment may not be damaged at all, in recognition of the structure being in a ZRFC and hence having a lower factor of safety against settlement or general instability, it is considered that there is the potential for some damage. Assets typically supported by conventional foundations include roadways, sewer infrastructure, shared pathways, etc.*

It should be noted that erosion/recession extents were truncated at obvious geotechnical features such as the escarpment located immediately landward of Seal Rocks Road. Similar truncation was not applied for the probability lines on Boat Beach due to limited information regarding geotechnical conditions landward of the roadway. As such, it should be recognised that the position of these lines may be conservative.

## 7.3 Individual Asset Assessment

The results were supplied to Coffey in electronic format to enable detailed interrogation of the data on an asset by asset basis. The supplied databases can be used to define the risk of coastal impact for individual assets throughout the planning period, including the roadways. Results were supplied for both annualised and cumulative probability data.

The databases are structured according to the DPE photogrammetry profile lines, with results supplied for each of these locations. Therefore, the user is required to identify which of these profile lines the asset is located on (or closest to). If the asset is located across multiple profile lines, or between two lines, results should be extracted for each of these lines. The most conservative set of results should then be adopted to characterise the risk of coastal impact for the asset during the planning period.

Furthermore, the database includes results for each of the coastal hazard zones that may be relevant for characterising coastal impacts to a particular asset. This includes the ZSA and ZRFC. For example, it may be appropriate to adopt the ZRFC for defining coastal impact to assets supported on conventional foundations, such as the roadway. For other assets, it may be appropriate to adopt the ZSA for defining coastal impact (e.g., utilities).

Example outputs from the annual probabilities database are presented below for Seal Rocks Road (Figure 7-3) and Kinka Road (Figure 7-4). For both assets, the landward edge of the ZRFC was conservatively adopted to define the erosion/recession hazard. The following is noted:

- At Block 3, Profile 6, Seal Rocks Road is located approximately 68.5 m from the shoreline as represented by the black dashed line on the maps included in **Appendix D**. It is evident that the annual probability that the coastal erosion/recession hazard (as defined by the ZRFC) extends landward of the seaward edge of Seal Rocks Road, gradually increases from around 16.0% in 2020 to 100% in 2100[13].
- At Block 1, Profile 4, Kinka Road is located approximately 67.0 m from the shoreline. It is evident that the annual probability that the coastal erosion/recession hazard (as defined by the ZRFC) extends landward of the seaward edge of Kinka Road, gradually increases from around 16.0% in 2020 to 77.0% in 2100[14].

It is recommended that Council and other stakeholders make their own detailed assessment of risk to key assets based on the information included in the cumulative probability maps (refer Section 7.2) and the supplied databases.

---

*[13] In comparison, the cumulative probability that the coastal erosion/recession hazard (as defined by the ZRFC) extends landward of the seaward edge of Seal Rocks Road increases from 16.0% in 2020 to 100% by 2044.*

*[14] In comparison, the cumulative probability that the coastal erosion/recession hazard (as defined by the ZRFC) extends landward of the seaward edge of Kinka Road increases from 16.0% in 2020 to 100% by 2039.*

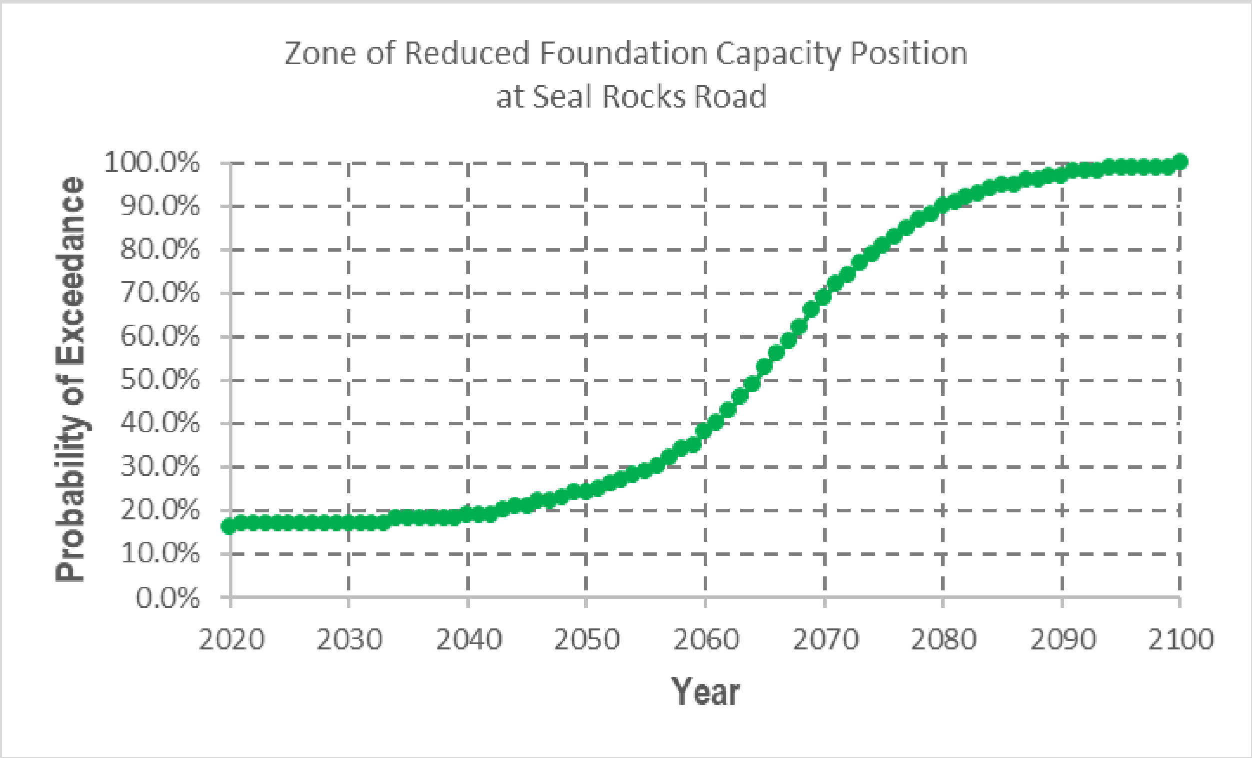



*Figure 7-3: Example output of the database used to generate annualised probability distribution curves of erosion/recession for Seal Rocks Road (representative profile: Block 3, Profile 6)*

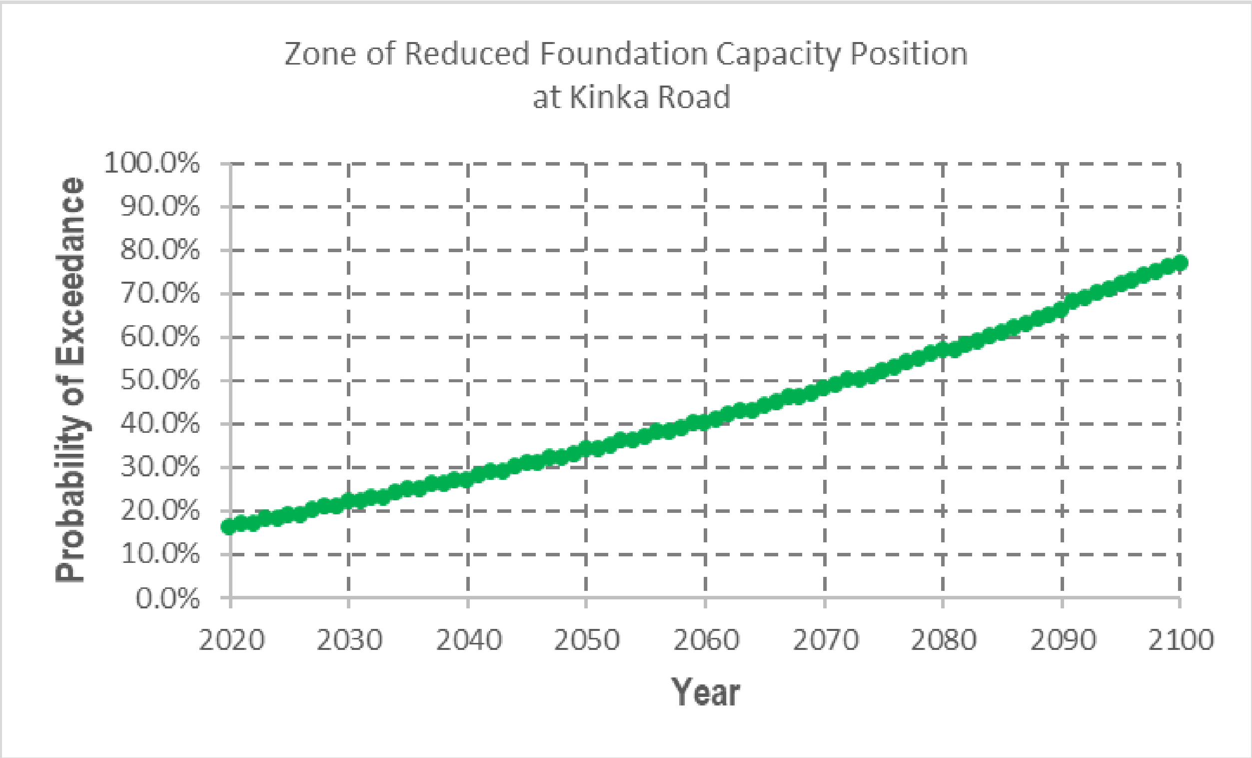



*Figure 7-4: Example output of the database used to generate annualised probability distribution curves of erosion/recession for Kinka Road (representative profile: Block 1, Profile 4)*

Royal HaskoningDHV

# 8 References

Bruun, P. (1962). Sea Level Rise as a Cause of Shore Erosion. Journal of the Waterways and Harbours Division, ASCE, Vol 88 No. WW1, February.

Bruun, P.M. (1983). Review of conditions for uses of the Bruun Rule of erosion, Jnl. Coastal Eng., Vol 7, No. 1, pp 77-89.

Tetra Tech Coffey [Coffey] (2022). Seal Rocks Road Diversion and LAP - Geotechnical & Geophysical Survey. Report reference number: 754-NTLGE284552-AC.Rev1, 9 March 2022.

Cooper, J Andrew G and Orrin H Pilkey (2004), “Sea-level rise and shoreline retreat: time to abandon the Bruun Rule”, Global and Planetary Change, Volume 43, pp. 157-171.

DECCW (2009). NSW Sea Level Rise Policy Statement. Department of Environment, Climate Change and Water, Sydney

Foster, D.N., Gordon, A.D. and Lawson, N.V. (1975), *The Storms of May-June 1974, Sydney, NSW*, Proceedings of the 2nd Australian Conference on Coastal and Ocean Engineering, Gold Coast, Queensland.

Folland, C (2008), “The Interdecadal Pacific Oscillation time series”, Hadley Centre, Met Office, Exeter, UK. Available online at: http://cola.gmu.edu/c20c/

Glatz, M., Fitzhenry, M. & Kulmar, M. (2017), *It’s Time for an Update – Extreme Waves and Directional Distributions along the New South Wales Coastline*, NSW Coastal Conference, 2017.

Gordon, AD (1987). Beach Fluctuations and Shoreline Change – NSW, Preprints of Papers, 8th Australasian Conference on Coastal and Ocean Engineering, Launceston, 30 November to 4 December, Institution of Engineers Australia National Conference Publication No 87/17, pp. 103-167.

Hallermeier, R. J. (1981). A profile zonation for seasonal sand beaches from wave climate. Coastal Eng., Vol. 4, pp 253-277.

Hallermeier, R. J. (1983). Sand Transport limits in coastal structure design, Proc. Coastal Structures ’83, ASCE, pp 703-716.

Helman, Peter (2007), “Two Hundred years of Coastline Change and Future Change, Fraser Island to Coffs Harbour, East Coast, Australia”, *Ph. D Thesis*, Southern Cross University

Helman, P. Thomalla, F. Metusela, C. & Tomlinson, R. (2010), Storm Tides, Coastal Erosion and Inundation, National Climate Change Adaption Research Facility, Gold Coast, 37pp.

Horton, P. Britton, G. Gordon, A. Walker, B. Moratti, M. and Cameron, D. (2014), Drawing a Line in the Sand – Defining Beachfront Setbacks based on Acceptable Risk, NSW Coastal Conference, November 2014, Shoalhaven.

Intergovernmental Panel on Climate Change [IPCC] (2013). Climate Change 2013, The Physical Science Basis, Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, TF; Qin, D; Plattner, G-K; Tignor, M; Allen, SK; Boschung, J; Nauels, A;

Xia, Y;  Bex, V and PM Midgley (editors)], Cambridge University Press, Cambridge, United Kingdom and New York, New York, USA

Intergovernmental Panel on Climate Change [IPCC] (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, edited by V. Masson-Delmotte, et al. Cambridge: Cambridge University Press (in press).

Nanson, G.C., A. Von Krusenstierna and E.A. Bryant. 1994. Experimental measurements of river-bank erosion caused by boat-generated waves on the Gordon River, Tasmania. Regulated Rivers: Research and Management 9: 1-14.

Nielsen, A.F., Lord, D.B. and Poulos, H.G. (1992), *Dune Stability Considerations for Building Foundations*, Australian Civil Engineering Transactions, The Institution of Engineers, Australia, Vol.CE34 No.2, p.167-174.

Nielsen, A. F. (1994) “Subaqueous Beach Fluctuations on the Australian South-Eastern Seaboard”, in Australian Civil Engineering Transactions, Vol. CE36 No.1 January 1994, pp 57-67.

Ranasinghe, Roshanka,, Watson, Phil, Lord, Doug, Hanslow, David and Peter Cowell (2007), “Sea Level Rise, Coastal Recession and the Bruun Rule”, 18$^{th}$ Australasian Conference on Coastal and Ocean Engineering and the 11$^{th}$ Australasian Port and Harbour Conference, Melbourne, 18-20 July

RHDHV (2018). Mollymook Beach Cost Benefit and Distributional Analysis – Coastal Hazard Assessment, for Origin Capital Group, 17 September.

RHDHV (2020a).  North Wollongong Beach Cost Benefit and Distributional Analysis Coastal Hazard Assessment.  Prepared for Origin Capital Group, March 2020.

RHDHV (2020b).  Warilla Beach Cost Benefit and Distributional Analysis Coastal Hazard Assessment. Prepared for Marsden Jacob, April 2020.

Regional Geotechnical Solutions [RGS] (2014). Segment 100, Seal Rocks Road, Seal Rocks – Design of Remedial Measures. Report No. RGS00510.1-AF, March 2014.

Rijkswaterstaat (1987).  Manual on Artificial Beach Nourishment, document prepared by the Netherlands Department of Public Works (Rijkswaterstaat), August, ISBN 9021260786.

SMEC (2013). Great Lakes Coastal Hazards Study. Prepared for Great Lakes Council, October 2013.

Vellinga, P. (1983).  Predictive Computational Model for Beach and Dune Erosion during Storm Events, Delft Hydraulics Laboratory Publication Number 294, February 1983.

Watson, P.J. Determining Extreme Still Water Levels for Design and Planning Purposes Incorporating Sea Level Rise: Sydney, Australia. *Atmosphere* 2022, 13, 95.

# Appendix A: Probabilistic Coastal Hazard Assessment - Technical Note

**Note / Memo**

**HaskoningDHV Nederland B.V.**
**Maritime & Aviation**

**Subject:** **Probabilistic Coastal Hazard Assessment - Technical Note**
**October, 2019**

---

# 1 Introduction

Traditionally, coastal hazard assessments (CHAs) have been undertaken under a deterministic approach, whereby each input parameter is assigned a single value (e.g. 'design' storm demand, sea level rise (SLR) projection, etc.) with generally conservative estimates applied. A probabilistic approach allows each input parameter to vary randomly according to appropriate probability distribution functions. The randomly sampled parameters are repeatedly combined in a process known as Monte Carlo simulation. All outputs from the Monte Carlo simulation are collated to develop a probability curve for the shoreline position at the end of a planning period.

This technical note outlines in detail the methodology followed in the probabilistic approach incorporating a Monte Carlo analysis.

# 2 Probabilistic Input Parameters

The key input parameters in a probabilistic CHA typically comprise:

1. Shoreline movement due to sediment budget differentials – 'Underlying/Long-Term Recession';
2. Sea level rise and the shoreline recession in response to sea level rise – 'SLR Recession; and
3. Event-based erosion due to storm activity – 'Storm Demand'.

These key parameters and their assumed distributions are discussed below.

## 2.1 Long-Term Shoreline Recession

Underlying or long-term shoreline recession rates are typically estimated by analysis of a photogrammetry dataset for a particular beach spanning a sufficiently long time period. Rates of shoreline movement (for each beach profile) of an appropriate elevation contour position(s) are derived by linear regression. Alternatively, or in addition, rates of shoreline movement may be determined by assessment of volumetric change (for each beach profile) above 0m AHD derived by linear regression. Underlying shoreline recession rates typically vary spatially (i.e. within a beach compartment) and temporally (i.e. depending on the analysis period considered). In all cases the interpretation of underlying recession needs to be developed in the framework of a strong coastal processes understanding.

A triangular probability distribution, as a rough approximation of a random variable with unknown distribution, is used to generate a set of random long-term recession values (refer **Figure 1**). The triangular distribution is defined by a minimum (a), maximum (b) and peak/modal (most likely) value (c).

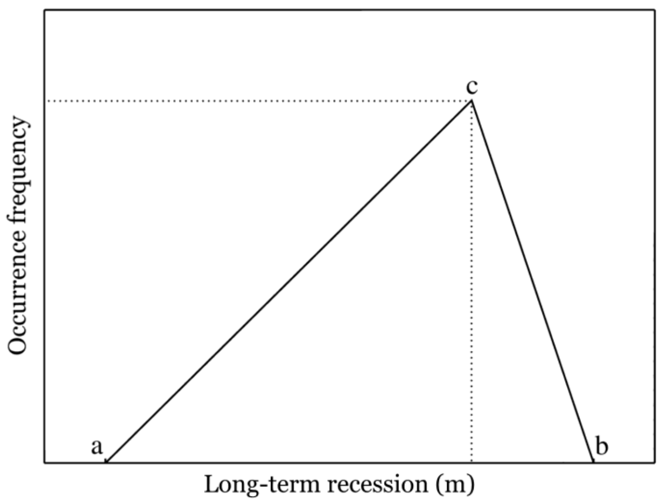



*Figure 1 Triangular distribution - example probability density function*

## 2.2 Shoreline Recession due to Sea Level Rise

SLR may result in shoreline recession due to re-adjustment of the beach profile to the new coastal water levels. Bruun (1962; 1983) proposed a methodology to estimate shoreline recession due to SLR, the so-called *Bruun Rule*. The Bruun Rule is based on the concept that SLR will lead to erosion of the upper shoreface, followed by re-establishment of the original equilibrium profile. This profile is re-established by shifting it landward and upward. The Bruun Rule is illustrated in **Figure 2**, where:

R is horizontal recession

B is width of the active beach profile (cross-shore distance from the initial dune height to the depth of closure
S is Sea Level Rise
h is active dune/berm height
$d_c$ is depth of closure

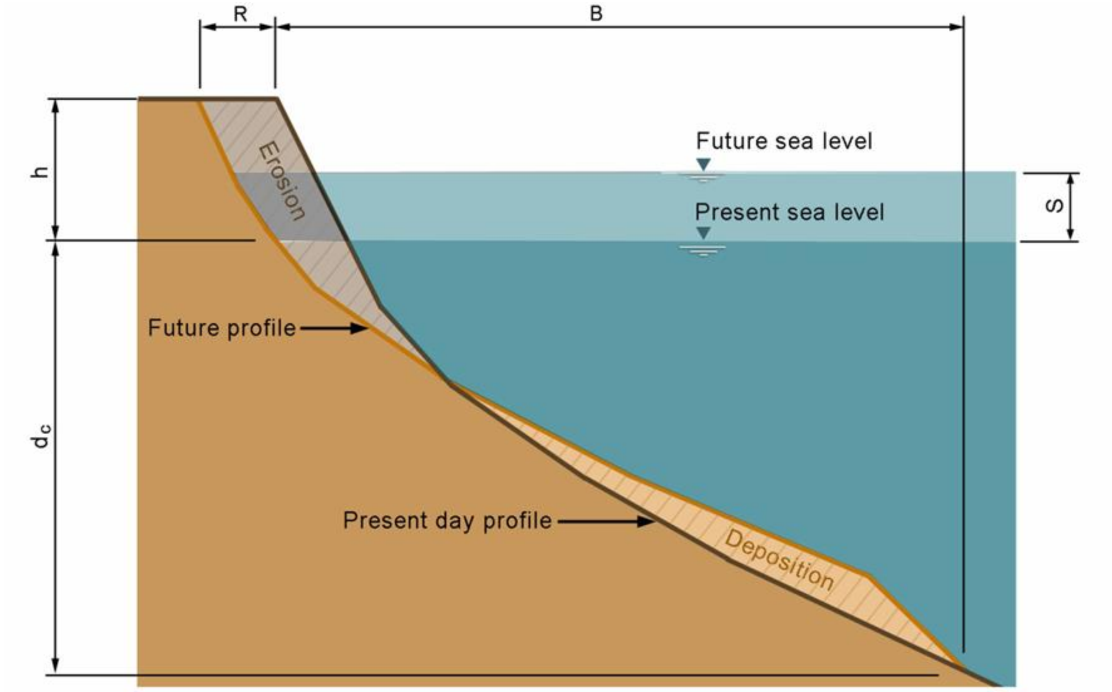



*Figure 2 Illustration of the Bruun Rule*

A recession rate can be estimated using the Bruun Rule equation, which divides sea level rise by the average slope of the active beach profile extending to the depth of closure (the outer limit for the nearshore littoral drift and exchange zone of littoral material between the shore and the offshore bottom area. Bruun, 1962):

$$R = \frac{S}{(h + d_c)/B}$$

The inverse beach slope is also referred to as the 'Bruun factor':

$$Bf = \frac{1}{(h + d_c)/B} = \frac{B}{h + d_c}$$

Shoreline recession due to SLR is therefore a function of both SLR and the Bruun factor:

$$R = S * Bf$$

Similar to long-term recession (refer **Section 2.1**), there is uncertainty around the distribution of both of these parameters, i.e. the values for SLR and for the Bruun factor.  As such, for the Monte Carlo simulations, both of these parameters are defined by separate triangular probability distributions and minimum, maximum and peak/modal SLR and Bruun factor values are required.

## 2.3 Combined Long-Term Recession and Recession due to Sea Level Rise

Random values for SLR and the Bruun factor and long-term recession, are simulated using triangular distributions (refer **Section 2.1** and **Section 2.2**). The values for these variables are then combined in a Monte Carlo process to give a total shoreline movement (recession) along the beach for the given planning period (refer **Figure 3**).

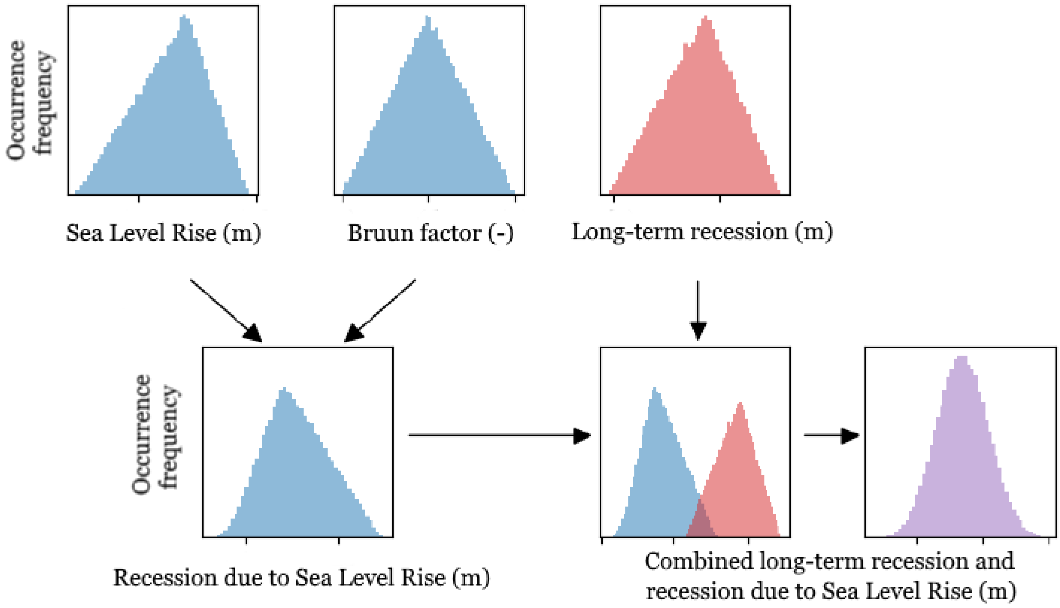



*Figure 3 Methodology for combining random values to estimate shoreline movement (based on: WRL, 2017)*

## 2.4 Storm Demand

Storm demand represents the volume of sand removed from a beach in a severe storm or a series of closely spaced storms. It is typically measured above a level of 0m AHD and expressed as cubic metres for metre run of beach ($m^3/m$).

Storm demand modelling using SBEACH is typically undertaken to determine storm erosion resulting under certain (average recurrence interval - ARI) storm conditions. Analysis of historical beach profiles is also used to estimate storm demand for particular ARIs. In addition, there are generally accepted values for storm demand for open coast beaches in NSW contained in the literature.

Storm demand probabilities for each year of the planning period in the Monte Carlo simulations are determined by random selection from a uniform distribution of annual exceedance probability (AEP) /ARI values (refer **Figure 4**).

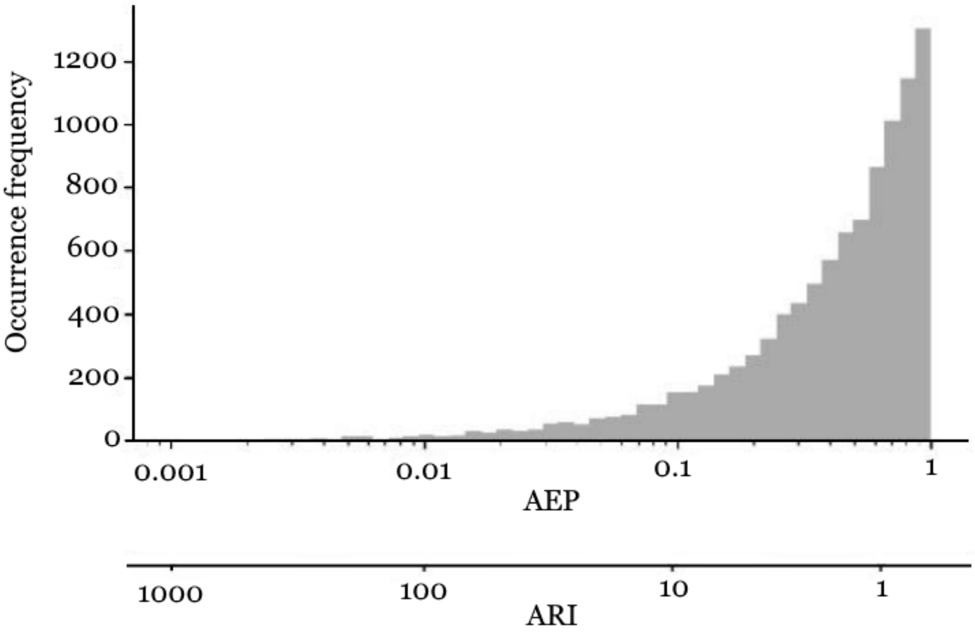



*Figure 4 Uniform distribution of AEP values for generating storm demand volumes*

The randomly generated AEP values are then converted to storm erosion volumes using empirical relationships. For beaches in NSW, it is reasonable to use the distribution of storm erosion volumes based on beach erosion data described in Gordon (1987), using the reference 100-year ARI storm demand volume for the beach in question. Gordon (1987) derived relationships between storm demand and ARI, in both "high demand" (at rip heads) and "low demand" (away from rip heads) areas (refer **Figure 5**). The "high demand" (rip head) values are adopted in the methodology.

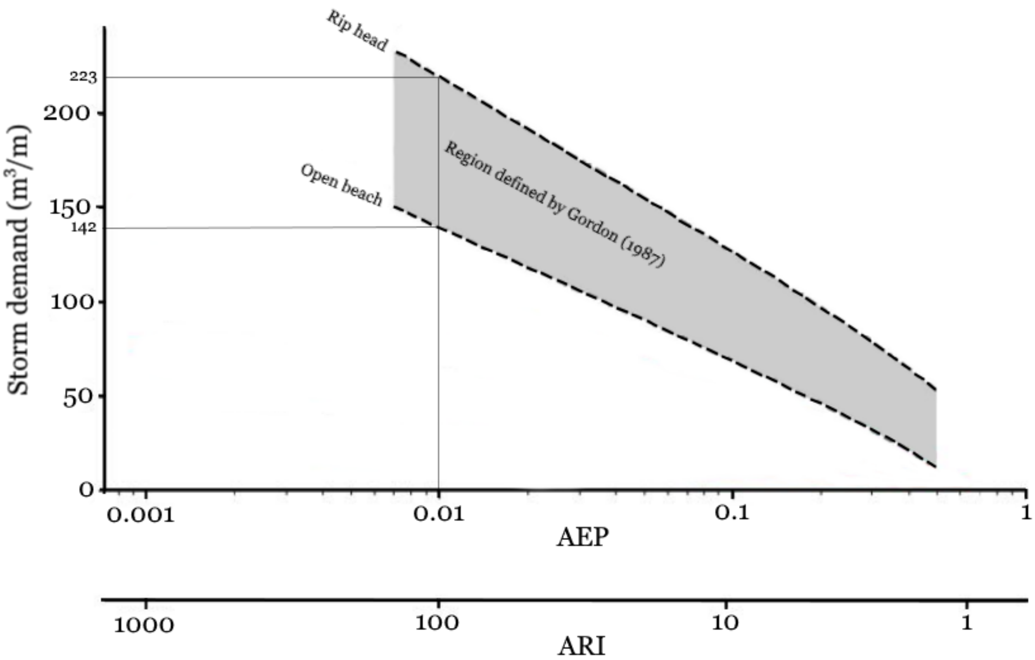



*Figure 5 Storm demand volumes for exposed beaches in NSW (based on: Gordon, 1987)*

In the following example, 100-year ARI storm demand values were estimated for a range of profiles based on SBEACH model results. The relationship between storm demand and ARI was then determined for each profile in accordance with the following methodology:

- Determine the ratio of the estimated 100-year ARI storm demand value to the appropriate ('low' or 'high' demand) Gordon (1987) 100-year ARI values (refer **Figure 5**); and
- Determine storm demand values for a range of ARIs by multiplying the appropriate Gordon (1987) storm demand values (describing 'low' or 'high' demand) by the storm demand scale factor (ratio) of that profile (re-interpolate to a range of nominated ARIs if applicable).

Example results of this exercise are presented in **Figure 6**.

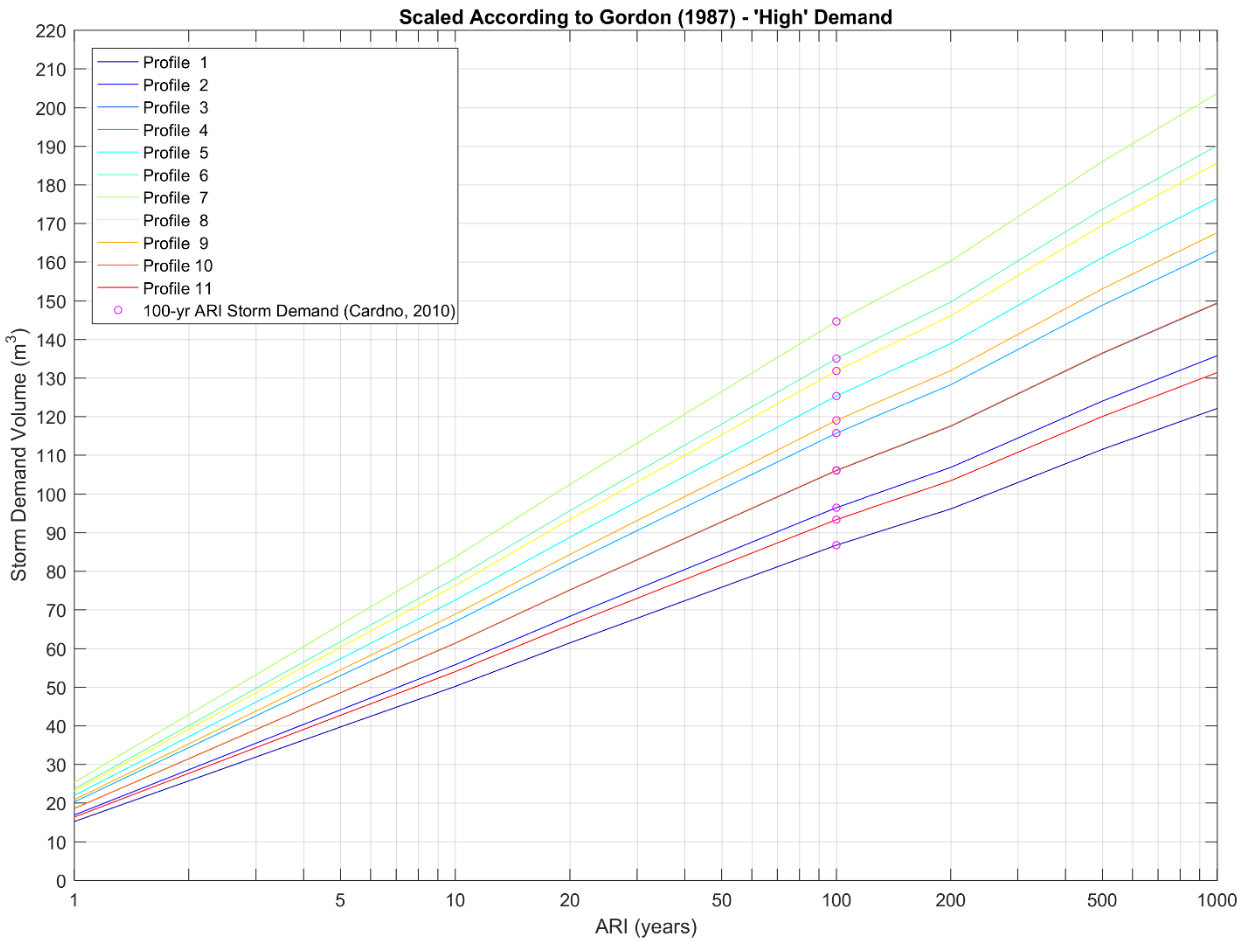



*Figure 6 Example storm demand scaled according to Gordon (1987)*

# 3 Monte Carlo Analysis Methodology

This section outlines the methodology followed in a CHA Monte Carlo analysis

## 3.1 Underlying Shoreline Recession

Further to **Section 2.1**, minimum, modal and maximum underlying shoreline recession values serve as input parameters for the triangular distribution of the long-term shoreline recession. One set of one million randomly-generated values of the long-term shoreline recession rate (m/year) is generated from the specified triangular distribution. These are essentially *annual* long-term shoreline recession values. The methodology to calculate *cumulative* long-term shoreline recession for each year is as follows:

- For each year in the planning period, for each of the one million randomly-generated values of *annual* long-term shoreline recession, calculate the *cumulative* long-term shoreline recession by multiplying the annual long-term shoreline recession value by the number of years passed in the planning period (subtract base year from the year under consideration)

Consequently, the above results in a matrix of one million (Monte Carlo simulations) by *n* (number of years in the planning period) of randomly-generated cumulative long-term shoreline recession values based on annual long-term shoreline recession values and its associated distribution (refer **Figure 7** for an example Monte Carlo results matrix).

Year in planning period

Monte Carlo simulation number

| | 1 | 2 | 3 | 4 | 5 | 6 | 96 | 97 | 98 | 99 | 100 | 101 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.1051 | 0.2102 | 0.3153 | 0.4204 | 0.5255 | 0.6306 | 10.0888 | 10.1939 | 10.2990 | 10.4041 | 10.5092 | 10.6143 |
| 2 | 0.0830 | 0.1660 | 0.2490 | 0.3321 | 0.4151 | 0.4981 | 7.9694 | 8.0524 | 8.1354 | 8.2185 | 8.3015 | 8.3845 |
| 3 | 0.0433 | 0.0865 | 0.1298 | 0.1731 | 0.2163 | 0.2596 | 4.1536 | 4.1969 | 4.2401 | 4.2834 | 4.3267 | 4.3699 |
| 4 | 0.0766 | 0.1531 | 0.2297 | 0.3062 | 0.3828 | 0.4593 | 7.3488 | 7.4254 | 7.5019 | 7.5785 | 7.6550 | 7.7316 |
| 5 | 0.0950 | 0.1900 | 0.2850 | 0.3800 | 0.4750 | 0.5700 | 9.1199 | 9.2149 | 9.3099 | 9.4049 | 9.4999 | 9.5949 |
| 6 | 0.0167 | 0.0335 | 0.0502 | 0.0669 | 0.0837 | 0.1004 | 1.6065 | 1.6232 | 1.6400 | 1.6567 | 1.6734 | 1.6902 |
| 7 | 0.0750 | 0.1500 | 0.2250 | 0.3000 | 0.3749 | 0.4499 | 7.1989 | 7.2739 | 7.3489 | 7.4238 | 7.4988 | 7.5738 |
| 8 | 0.0992 | 0.1984 | 0.2975 | 0.3967 | 0.4959 | 0.5951 | 9.5210 | 9.6201 | 9.7193 | 9.8185 | 9.9177 | 10.0169 |
| 9 | 0.0978 | 0.1955 | 0.2933 | 0.3911 | 0.4889 | 0.5866 | 9.3859 | 9.4837 | 9.5815 | 9.6792 | 9.7770 | 9.8748 |
| 10 | 0.0282 | 0.0565 | 0.0847 | 0.1130 | 0.1412 | 0.1695 | 2.7118 | 2.7401 | 2.7683 | 2.7966 | 2.8248 | 2.8531 |
| 11 | 0.0405 | 0.0811 | 0.1216 | 0.1622 | 0.2027 | 0.2433 | 3.8928 | 3.9333 | 3.9739 | 4.0144 | 4.0550 | 4.0955 |
| 999989 | 0.0429 | 0.0857 | 0.1286 | 0.1714 | 0.2143 | 0.2572 | 4.1145 | 4.1574 | 4.2002 | 4.2431 | 4.2860 | 4.3288 |
| 999990 | 0.0301 | 0.0602 | 0.0903 | 0.1203 | 0.1504 | 0.1805 | 2.8883 | 2.9184 | 2.9485 | 2.9786 | 3.0087 | 3.0388 |
| 999991 | 0.0814 | 0.1627 | 0.2441 | 0.3254 | 0.4068 | 0.4882 | 7.8105 | 7.8918 | 7.9732 | 8.0545 | 8.1359 | 8.2173 |
| 999992 | 0.0092 | 0.0185 | 0.0277 | 0.0369 | 0.0461 | 0.0554 | 0.8860 | 0.8952 | 0.9044 | 0.9136 | 0.9229 | 0.9321 |
| 999993 | 0.0111 | 0.0223 | 0.0334 | 0.0446 | 0.0557 | 0.0669 | 1.0699 | 1.0811 | 1.0922 | 1.1033 | 1.1145 | 1.1256 |
| 999994 | 0.1355 | 0.2710 | 0.4065 | 0.5420 | 0.6775 | 0.8130 | 13.0076 | 13.1431 | 13.2786 | 13.4141 | 13.5496 | 13.6851 |
| 999995 | 0.0793 | 0.1586 | 0.2379 | 0.3172 | 0.3965 | 0.4757 | 7.6119 | 7.6912 | 7.7705 | 7.8498 | 7.9291 | 8.0084 |
| 999996 | 0.0198 | 0.0395 | 0.0593 | 0.0790 | 0.0988 | 0.1186 | 1.8969 | 1.9167 | 1.9365 | 1.9562 | 1.9760 | 1.9957 |
| 999997 | 0.0319 | 0.0638 | 0.0958 | 0.1277 | 0.1596 | 0.1915 | 3.0645 | 3.0964 | 3.1284 | 3.1603 | 3.1922 | 3.2241 |
| 999998 | 0.0849 | 0.1697 | 0.2546 | 0.3394 | 0.4243 | 0.5091 | 8.1459 | 8.2308 | 8.3156 | 8.4005 | 8.4853 | 8.5702 |
| 999999 | 0.0400 | 0.0800 | 0.1200 | 0.1600 | 0.2000 | 0.2400 | 3.8397 | 3.8796 | 3.9196 | 3.9596 | 3.9996 | 4.0396 |
| 1000000 | 0.0655 | 0.1310 | 0.1964 | 0.2619 | 0.3274 | 0.3929 | 6.2863 | 6.3518 | 6.4172 | 6.4827 | 6.5482 | 6.6137 |

*Figure 7 Example Monte Carlo results matrix for long-term recession*

## 3.2 Shoreline Recession due to Sea Level Rise

As outlined in **Section 2.2**, shoreline recession due to SLR is a function of both SLR and the Bruun factor.

In regard to SLR, Monte Carlo simulations are assumed to be based on proposed minimum, modal and maximum SLR projections. Where the adopted projections or trajectories are available at discrete points in time (e.g. IPCC concentration pathways), a polynomial fit through these points is estimated (refer example in **Figure 8**).

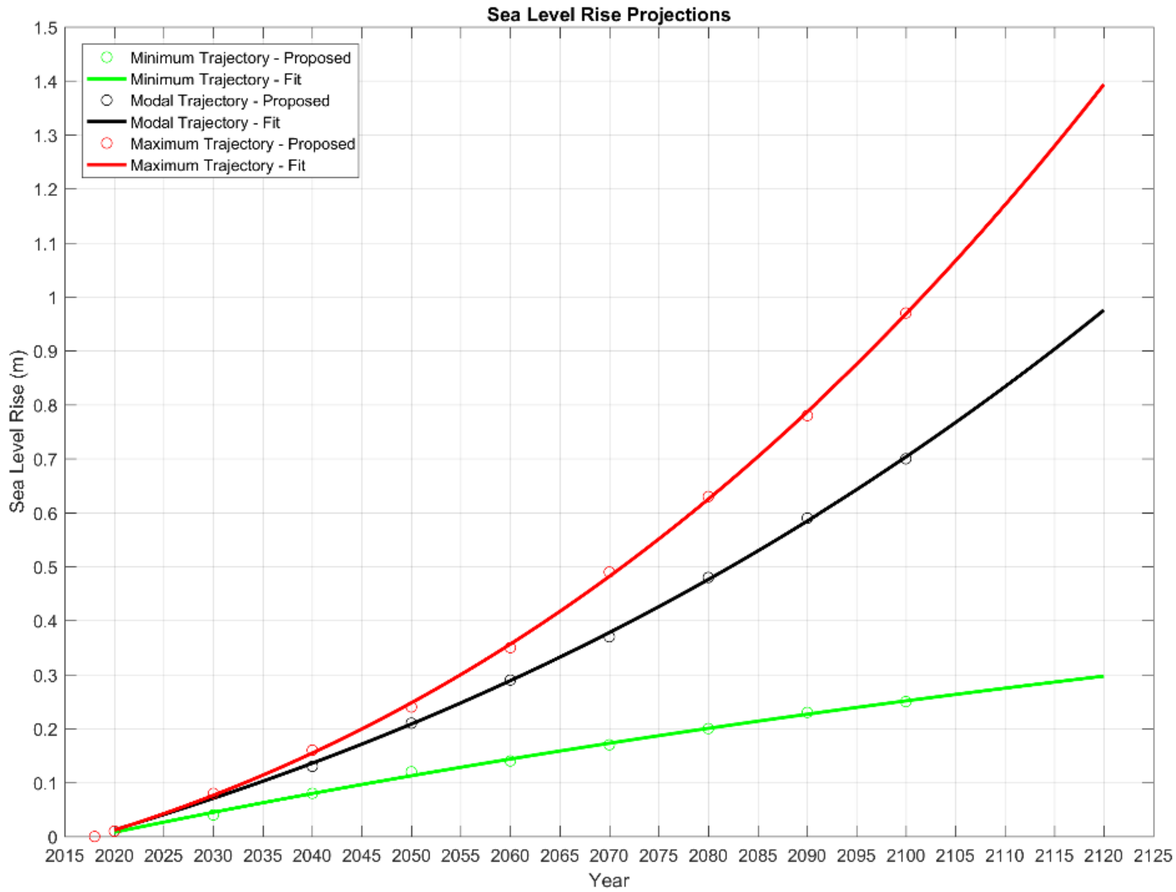



*Figure 8 Example Sea Level Rise projections*

A set of one million randomly-generated values of SLR for each year in the planning period is generated. The methodology is as follows:

- For each year in the planning period, the minimum, modal and maximum projected SLR is determined based on the above polynomial trajectory fits - these serve as input parameters for the triangular distribution of that year;
- Then, for each year in the planning period, one million random SLR values are generated from the specified triangular distribution of that year.

Note that in the case of SLR, relevant input parameters to the Monte Carlo simulation are set such that the algorithm (or 'set of rules') used to generate random SLR values is the same each year. In combination with a triangular distribution that changes from year to year (increasing minimum, maximum and modal values), basically one million random SLR *trajectories* are generated in the Monte Carlo simulations (refer **Figure 9** and **Figure 10**).

Year in planning period

Monte Carlo simulation number

| | 1 | 2 | 3 | 4 | 5 | 6 | 96 | 97 | 98 | 99 | 100 | 101 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.0127 | 0.0184 | 0.0228 | 0.0285 | 0.0343 | 0.0401 | 1.0160 | 1.0329 | 1.0500 | 1.0672 | 1.0846 | 1.1021 |
| 2 | 0.0127 | 0.0185 | 0.0232 | 0.0290 | 0.0349 | 0.0409 | 1.0915 | 1.1100 | 1.1287 | 1.1475 | 1.1665 | 1.1857 |
| 3 | 0.0123 | 0.0179 | 0.0184 | 0.0229 | 0.0274 | 0.0320 | 0.5650 | 0.5728 | 0.5806 | 0.5885 | 0.5965 | 0.6045 |
| 4 | 0.0128 | 0.0185 | 0.0233 | 0.0291 | 0.0350 | 0.0409 | 1.0992 | 1.1179 | 1.1367 | 1.1557 | 1.1749 | 1.1943 |
| 5 | 0.0125 | 0.0182 | 0.0219 | 0.0274 | 0.0329 | 0.0385 | 0.9085 | 0.9232 | 0.9379 | 0.9528 | 0.9679 | 0.9830 |
| 6 | 0.0123 | 0.0179 | 0.0180 | 0.0224 | 0.0269 | 0.0313 | 0.5306 | 0.5377 | 0.5448 | 0.5520 | 0.5592 | 0.5665 |
| 7 | 0.0124 | 0.0180 | 0.0198 | 0.0246 | 0.0296 | 0.0345 | 0.6991 | 0.7096 | 0.7201 | 0.7308 | 0.7415 | 0.7523 |
| 8 | 0.0125 | 0.0181 | 0.0215 | 0.0268 | 0.0322 | 0.0377 | 0.8649 | 0.8786 | 0.8925 | 0.9065 | 0.9206 | 0.9349 |
| 9 | 0.0128 | 0.0186 | 0.0234 | 0.0293 | 0.0353 | 0.0414 | 1.1531 | 1.1729 | 1.1929 | 1.2131 | 1.2334 | 1.2540 |
| 10 | 0.0128 | 0.0186 | 0.0235 | 0.0294 | 0.0354 | 0.0415 | 1.1646 | 1.1846 | 1.2048 | 1.2253 | 1.2459 | 1.2667 |
| 11 | 0.0123 | 0.0179 | 0.0187 | 0.0233 | 0.0279 | 0.0326 | 0.5968 | 0.6053 | 0.6137 | 0.6223 | 0.6309 | 0.6395 |
| 999989 | 0.0128 | 0.0186 | 0.0235 | 0.0294 | 0.0354 | 0.0416 | 1.1785 | 1.1989 | 1.2194 | 1.2401 | 1.2610 | 1.2821 |
| 999990 | 0.0125 | 0.0182 | 0.0217 | 0.0271 | 0.0326 | 0.0381 | 0.8874 | 0.9016 | 0.9159 | 0.9304 | 0.9449 | 0.9597 |
| 999991 | 0.0123 | 0.0178 | 0.0170 | 0.0212 | 0.0253 | 0.0295 | 0.4358 | 0.4410 | 0.4462 | 0.4515 | 0.4568 | 0.4621 |
| 999992 | 0.0126 | 0.0182 | 0.0221 | 0.0276 | 0.0332 | 0.0388 | 0.9232 | 0.9382 | 0.9532 | 0.9685 | 0.9838 | 0.9993 |
| 999993 | 0.0125 | 0.0181 | 0.0214 | 0.0267 | 0.0320 | 0.0374 | 0.8517 | 0.8652 | 0.8788 | 0.8925 | 0.9064 | 0.9203 |
| 999994 | 0.0127 | 0.0184 | 0.0229 | 0.0286 | 0.0344 | 0.0403 | 1.0293 | 1.0464 | 1.0638 | 1.0813 | 1.0989 | 1.1168 |
| 999995 | 0.0129 | 0.0187 | 0.0236 | 0.0295 | 0.0357 | 0.0419 | 1.2117 | 1.2328 | 1.2540 | 1.2754 | 1.2971 | 1.3189 |
| 999996 | 0.0127 | 0.0185 | 0.0232 | 0.0289 | 0.0348 | 0.0407 | 1.0761 | 1.0942 | 1.1126 | 1.1311 | 1.1498 | 1.1686 |
| 999997 | 0.0124 | 0.0179 | 0.0193 | 0.0240 | 0.0288 | 0.0336 | 0.6507 | 0.6602 | 0.6698 | 0.6794 | 0.6891 | 0.6989 |
| 999998 | 0.0125 | 0.0181 | 0.0213 | 0.0266 | 0.0320 | 0.0374 | 0.8511 | 0.8646 | 0.8782 | 0.8920 | 0.9058 | 0.9198 |
| 999999 | 0.0126 | 0.0183 | 0.0223 | 0.0278 | 0.0334 | 0.0391 | 0.9427 | 0.9580 | 0.9735 | 0.9892 | 1.0050 | 1.0209 |
| 1000000 | 0.0126 | 0.0182 | 0.0222 | 0.0277 | 0.0333 | 0.0390 | 0.9367 | 0.9520 | 0.9673 | 0.9828 | 0.9985 | 1.0143 |

*Figure 9 Monte Carlo results matrix for SLR*

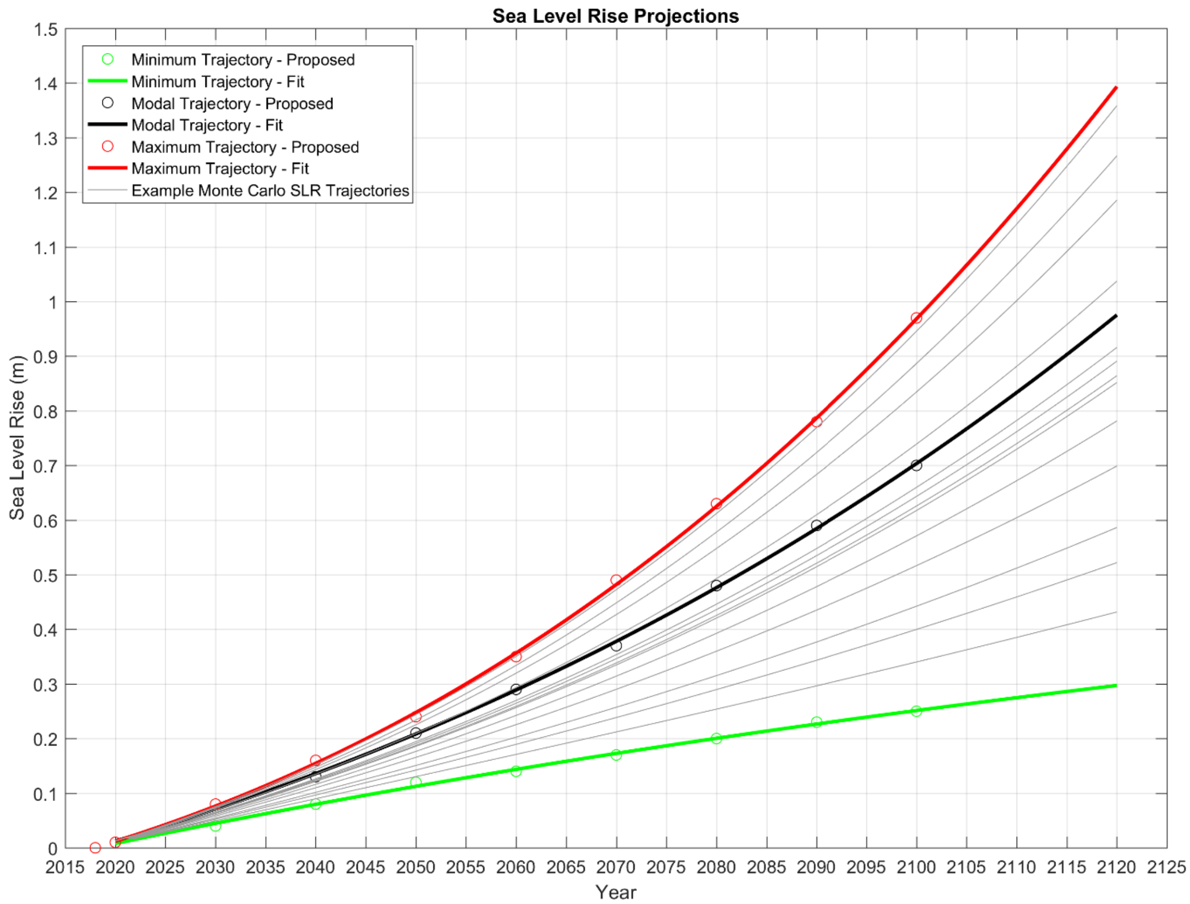



*Figure 10 Example Monte Carlo Sea Level Rise trajectories*

Similarly, minimum, modal and maximum values for the Bruun factor (which result from a separate assessment of dune height and local closure depth) serve as input parameters for the triangular distribution of the Bruun factor. One set of one million randomly-generated values of the Bruun factor is generated from the specified triangular Bruun factor distribution.

Monte Carlo simulation number

| | 1 |
|---|---|
| 1 | 46.9396 |
| 2 | 36.4402 |
| 3 | 38.7887 |
| 4 | 43.0681 |
| 5 | 45.2201 |
| 6 | 38.4200 |
| 7 | 40.4453 |
| 8 | 43.0260 |
| 9 | 40.0742 |
| 10 | 38.3600 |
| 11 | 32.4870 |
| ⋮ | |
| 999989 | 41.1772 |
| 999990 | 38.1521 |
| 999991 | 40.9444 |
| 999992 | 46.7384 |
| 999993 | 43.6584 |
| 999994 | 40.5733 |
| 999995 | 45.4701 |
| 999996 | 38.0921 |
| 999997 | 38.2370 |
| 999998 | 39.9227 |
| 999999 | 41.8228 |
| 1000000 | 36.3170 |

*Figure 11 Example Monte Carlo result values for the Bruun Factor*

Randomly-generated values for shoreline recession due to SLR (one million for each year in the planning period) are then calculated using the probabilistic information of SLR and the Bruun factor. The methodology is as follows:

- For each year in the planning period, for each of the one million randomly-generated values of both SLR (for a particular year) and the Bruun factor, calculate the shoreline recession using the Bruun Rule equation (SLR multiplied by the Bruun factor - refer **Section 2.2**).

Consequently, the above procedure results in a matrix of one million (Monte Carlo simulations) by *n* (number of years in the planning period) of randomly-generated shoreline recession values based on SLR and the Bruun factor and their associated distributions (refer **Figure 12**).

Year in planning period

Monte Carlo simulation number

| | 1 | 2 | 3 | 4 | 5 | 6 | 96 | 97 | 98 | 99 | 100 | 101 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5345 | 0.7756 | 0.9635 | 1.2036 | 1.4472 | 1.6943 | 42.8915 | 43.6051 | 44.3253 | 45.0521 | 45.7855 | 46.5256 |
| 2 | 0.5506 | 0.7990 | 1.0034 | 1.2537 | 1.5078 | 1.7659 | 47.1571 | 47.9561 | 48.7627 | 49.5769 | 50.3986 | 51.2281 |
| 3 | 0.5297 | 0.7687 | 0.7893 | 0.9835 | 1.1786 | 1.3745 | 24.2979 | 24.6327 | 24.9698 | 25.3092 | 25.6508 | 25.9947 |
| 4 | 0.4558 | 0.6615 | 0.8314 | 1.0388 | 1.2494 | 1.4634 | 39.2932 | 39.9602 | 40.6334 | 41.3130 | 41.9989 | 42.6912 |
| 5 | 0.5480 | 0.7952 | 0.9588 | 1.1973 | 1.4388 | 1.6834 | 39.6950 | 40.3345 | 40.9798 | 41.6306 | 42.2873 | 42.9496 |
| 6 | 0.3993 | 0.5794 | 0.5839 | 0.7274 | 0.8713 | 1.0157 | 17.2159 | 17.4463 | 17.6781 | 17.9114 | 18.1461 | 18.3823 |
| 7 | 0.4967 | 0.7208 | 0.7928 | 0.9888 | 1.1864 | 1.3855 | 28.0558 | 28.4755 | 28.8985 | 29.3248 | 29.7545 | 30.1875 |
| 8 | 0.4895 | 0.7104 | 0.8418 | 1.0510 | 1.2626 | 1.4767 | 33.8812 | 34.4204 | 34.9641 | 35.5126 | 36.0658 | 36.6237 |
| 9 | 0.5218 | 0.7573 | 0.9549 | 1.1935 | 1.4374 | 1.6861 | 46.9685 | 47.7747 | 48.5886 | 49.4103 | 50.2398 | 51.0771 |
| 10 | 0.4632 | 0.6721 | 0.8478 | 1.0600 | 1.2771 | 1.4985 | 42.0602 | 42.7838 | 43.5143 | 44.2519 | 44.9964 | 45.7480 |
| 11 | 0.5229 | 0.7587 | 0.7924 | 0.9876 | 1.1838 | 1.3810 | 25.3068 | 25.6639 | 26.0234 | 26.3855 | 26.7501 | 27.1173 |
| 999989 | 0.6094 | 0.8843 | 1.1157 | 1.3958 | 1.6825 | 1.9749 | 55.9356 | 56.9005 | 57.8746 | 58.8581 | 59.8510 | 60.8533 |
| 999990 | 0.4033 | 0.5853 | 0.6999 | 0.8739 | 1.0500 | 1.2283 | 28.5895 | 29.0473 | 29.5091 | 29.9749 | 30.4448 | 30.9188 |
| 999991 | 0.5121 | 0.7431 | 0.7097 | 0.8834 | 1.0571 | 1.2309 | 18.1887 | 18.4063 | 18.6247 | 18.8442 | 19.0646 | 19.2861 |
| 999992 | 0.5720 | 0.8300 | 1.0061 | 1.2565 | 1.5101 | 1.7670 | 42.0495 | 42.7303 | 43.4172 | 44.1102 | 44.8093 | 45.5145 |
| 999993 | 0.5893 | 0.8552 | 1.0079 | 1.2582 | 1.5114 | 1.7675 | 40.2043 | 40.8415 | 41.4842 | 42.1325 | 42.7862 | 43.4456 |
| 999994 | 0.5174 | 0.7508 | 0.9350 | 1.1681 | 1.4046 | 1.6445 | 42.0157 | 42.7171 | 43.4250 | 44.1394 | 44.8604 | 45.5880 |
| 999995 | 0.4726 | 0.6858 | 0.8653 | 1.0844 | 1.3086 | 1.5373 | 44.4702 | 45.2419 | 46.0212 | 46.8079 | 47.6023 | 48.4042 |
| 999996 | 0.4660 | 0.6763 | 0.8479 | 1.0594 | 1.2741 | 1.4920 | 39.4045 | 40.0699 | 40.7414 | 41.4193 | 42.1035 | 42.7940 |
| 999997 | 0.5059 | 0.7341 | 0.7883 | 0.9829 | 1.1788 | 1.3759 | 26.6472 | 27.0360 | 27.4277 | 27.8224 | 28.2200 | 28.6205 |
| 999998 | 0.5245 | 0.7612 | 0.8969 | 1.1196 | 1.3449 | 1.5728 | 35.7632 | 36.3299 | 36.9015 | 37.4780 | 38.0595 | 38.6459 |
| 999999 | 0.5291 | 0.7679 | 0.9367 | 1.1699 | 1.4062 | 1.6456 | 39.6536 | 40.2996 | 40.9515 | 41.6091 | 42.2726 | 42.9420 |
| 1000000 | 0.4211 | 0.6111 | 0.7442 | 0.9294 | 1.1170 | 1.3072 | 31.3772 | 31.8874 | 32.4022 | 32.9216 | 33.4456 | 33.9743 |

*Figure 12 Example Monte Carlo results matrix for recession due to SLR*

## 3.3 Combined Underlying Recession and Recession due to Sea Level Rise

Following from **Section 3.1** and **Section 3.2**, the combined long-term recession (refer **Figure 7**) and recession due to SLR (refer **Figure 12**) is simply calculated by summing the separate results (of each combination of Monte Carlo simulation number and year in the planning period) - refer **Figure 13**.

Year in planning period

Monte Carlo simulation number

| | 1 | 2 | 3 | 4 | 5 | 6 | 96 | 97 | 98 | 99 | 100 | 101 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.6396 | 0.9858 | 1.2788 | 1.6240 | 1.9727 | 2.3249 | 52.9803 | 53.7990 | 54.6243 | 55.4562 | 56.2947 | 57.1399 |
| 2 | 0.6336 | 0.9650 | 1.2524 | 1.5858 | 1.9229 | 2.2640 | 55.1265 | 56.0085 | 56.8981 | 57.7954 | 58.7001 | 59.6126 |
| 3 | 0.5730 | 0.8552 | 0.9191 | 1.1566 | 1.3949 | 1.6341 | 28.4515 | 28.8296 | 29.2099 | 29.5926 | 29.9775 | 30.3646 |
| 4 | 0.5324 | 0.8146 | 1.0611 | 1.3450 | 1.6322 | 1.9227 | 46.6420 | 47.3856 | 48.1353 | 48.8915 | 49.6539 | 50.4228 |
| 5 | 0.6430 | 0.9852 | 1.2438 | 1.5773 | 1.9138 | 2.2534 | 48.8149 | 49.5494 | 50.2897 | 51.0355 | 51.7872 | 52.5445 |
| 6 | 0.4160 | 0.6129 | 0.6341 | 0.7943 | 0.9550 | 1.1161 | 18.8224 | 19.0695 | 19.3181 | 19.5681 | 19.8204 | 20.0725 |
| 7 | 0.5717 | 0.8708 | 1.0178 | 1.2888 | 1.5613 | 1.8354 | 35.2547 | 35.7494 | 36.2474 | 36.7486 | 37.2533 | 37.7613 |
| 8 | 0.5887 | 0.9088 | 1.1393 | 1.4477 | 1.7585 | 2.0718 | 43.4022 | 44.0405 | 44.6834 | 45.3311 | 45.9835 | 46.6406 |
| 9 | 0.6196 | 0.9528 | 1.2482 | 1.5846 | 1.9263 | 2.2727 | 56.3544 | 57.2584 | 58.1701 | 50.0895 | 60.0168 | 60.9519 |
| 10 | 0.4914 | 0.7286 | 0.9325 | 1.1730 | 1.4183 | 1.6680 | 44.7720 | 45.5239 | 46.2826 | 47.0485 | 47.8212 | 48.6011 |
| 11 | 0.5634 | 0.8398 | 0.9140 | 1.1498 | 1.3865 | 1.6243 | 29.1996 | 29.5972 | 29.9973 | 26.3999 | 26.8051 | 27.2128 |
| 999989 | 0.6523 | 0.9700 | 1.2443 | 1.5672 | 1.8968 | 2.2321 | 60.0501 | 61.0579 | 62.0748 | 63.1012 | 64.1370 | 65.1821 |
| 999990 | 0.4334 | 0.6455 | 0.7902 | 0.9942 | 1.2004 | 1.4088 | 31.4778 | 31.9657 | 32.4576 | 32.9535 | 33.4535 | 33.9576 |
| 999991 | 0.5935 | 0.9058 | 0.9538 | 1.2088 | 1.4639 | 1.7191 | 25.9992 | 26.2981 | 26.5979 | 26.8987 | 27.2005 | 27.5034 |
| 999992 | 0.5812 | 0.8485 | 1.0338 | 1.2934 | 1.5563 | 1.8224 | 42.9355 | 43.6255 | 44.3216 | 45.0238 | 45.7322 | 46.4466 |
| 999993 | 0.6004 | 0.8775 | 1.0413 | 1.3028 | 1.5671 | 1.8344 | 41.2742 | 41.9226 | 42.5764 | 43.2358 | 43.9007 | 44.5712 |
| 999994 | 0.6529 | 1.0218 | 1.3415 | 1.7101 | 2.0821 | 2.4575 | 55.0233 | 55.8602 | 56.7036 | 57.5535 | 58.4100 | 59.2731 |
| 999995 | 0.5519 | 0.8444 | 1.1032 | 1.4016 | 1.7051 | 2.0130 | 52.0821 | 52.9331 | 53.7917 | 54.6577 | 55.5314 | 56.4126 |
| 999996 | 0.4858 | 0.7158 | 0.9072 | 1.1384 | 1.3729 | 1.6106 | 41.3014 | 41.9866 | 42.6779 | 43.3755 | 44.0795 | 44.7897 |
| 999997 | 0.5378 | 0.7979 | 0.8841 | 1.1106 | 1.3384 | 1.5674 | 29.7117 | 30.1324 | 30.5561 | 30.9827 | 31.4122 | 31.8446 |
| 999998 | 0.6094 | 0.9309 | 1.1515 | 1.4590 | 1.7692 | 2.0819 | 43.9091 | 44.5607 | 45.2171 | 45.8785 | 46.5448 | 47.2161 |
| 999999 | 0.5691 | 0.8479 | 1.0567 | 1.3299 | 1.6062 | 1.8856 | 43.4933 | 44.1792 | 44.8711 | 45.5687 | 46.2722 | 46.9816 |
| 1000000 | 0.4866 | 0.7421 | 0.9406 | 1.1913 | 1.4444 | 1.7001 | 37.6635 | 38.2392 | 38.8194 | 39.4043 | 39.9938 | 40.5880 |

*Figure 13 Example Monte Carlo results matrix for combined long-term recession and recession due to SLR*

An example overview of the statistical distribution of SLR as well as the recession parameters discussed above, is presented in **Figure 14**.

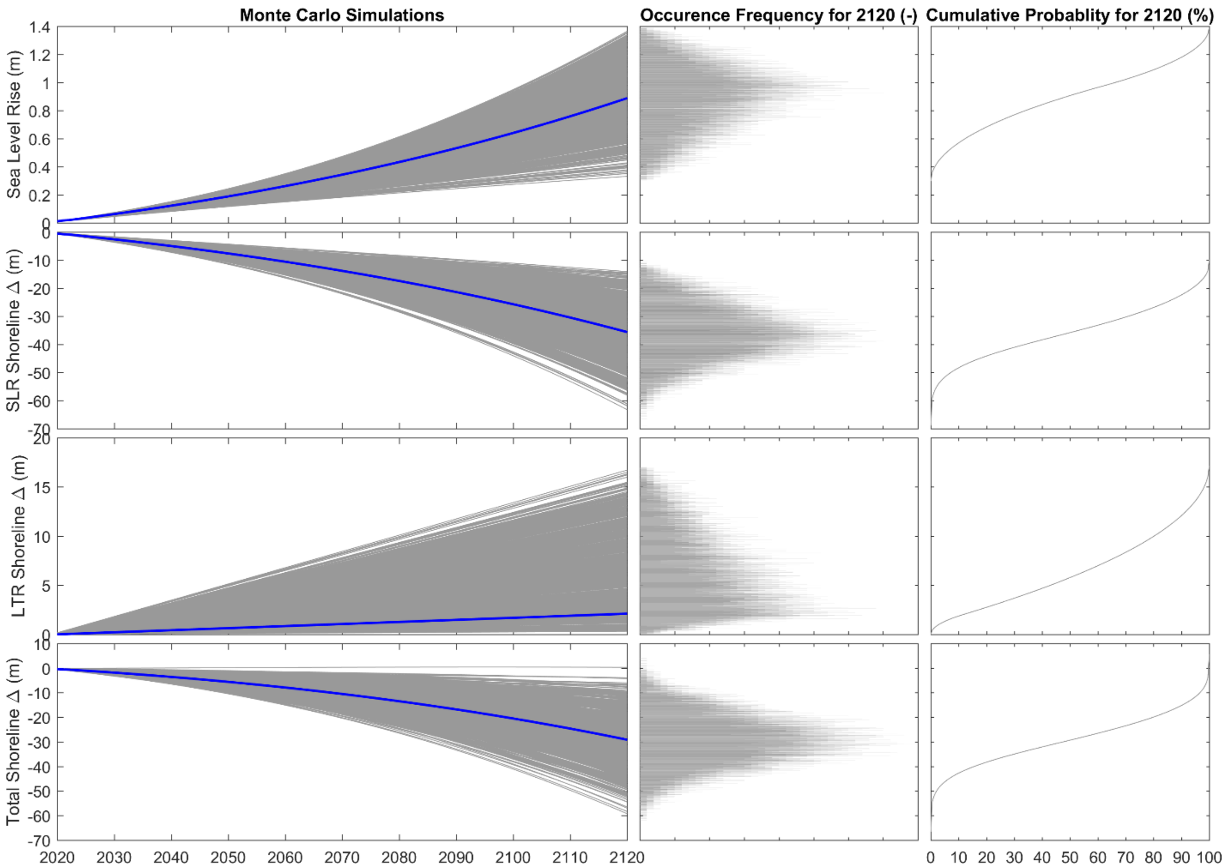



*Figure 14 Example statistical distribution of SLR and recession input parameters*

## 3.4 Storm Demand

As outlined in **Section 2.4**, storm demand probabilities for each year are calculated using a uniform distribution of AEP values, which vary between zero and one (inclusive). To this end, a random number generator, which generates numbers between zero and one (inclusive), is used to generate a matrix of one million (Monte Carlo simulations) by *n* (number of years in the planning period) of uniformly-distributed AEP values for storm demand (refer **Figure 15**).

Year in planning period

Monte Carlo simulation number

| | 1 | 2 | 3 | 4 | 5 | 6 | ---------> | 96 | 97 | 98 | 99 | 100 | 101 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.5211 | 0.1433 | 0.1681 | 0.5705 | 0.1985 | 0.0676 | | 0.0143 | 0.4133 | 0.5005 | 0.4970 | 0.4689 | 0.6261 |
| 2 | 0.8149 | 0.7980 | 0.4172 | 0.7914 | 0.8939 | 0.0206 | | 0.6072 | 0.8694 | 0.8399 | 0.1100 | 0.2615 | 0.4325 |
| 3 | 0.5458 | 0.5477 | 0.3296 | 0.2688 | 0.2379 | 0.0655 | | 0.3834 | 0.0830 | 0.8493 | 0.5362 | 0.0073 | 0.1695 |
| 4 | 0.5087 | 0.4707 | 0.0038 | 0.1373 | 0.3797 | 0.9081 | | 0.7995 | 0.9138 | 0.9794 | 0.5510 | 0.9034 | 0.5027 |
| 5 | 0.9881 | 0.6417 | 0.3252 | 0.6651 | 0.7316 | 0.7733 | | 0.9320 | 0.5714 | 0.6254 | 0.7152 | 0.4875 | 0.4066 |
| 6 | 0.4740 | 0.2762 | 0.1815 | 0.3050 | 0.8444 | 0.8813 | | 0.9521 | 0.1355 | 0.4809 | 0.0581 | 0.1155 | 0.3953 |
| 7 | 0.4222 | 0.3398 | 0.9737 | 0.3651 | 0.8694 | 0.3812 | | 0.6662 | 0.1313 | 0.5621 | 0.8765 | 0.4046 | 0.5181 |
| 8 | 0.7992 | 0.6367 | 0.9084 | 0.3498 | 0.3013 | 0.4366 | | 0.9541 | 0.6667 | 0.8798 | 0.7209 | 0.2139 | 0.8878 |
| 9 | 0.7240 | 0.1421 | 0.1627 | 0.6812 | 0.4241 | 0.1054 | | 0.0642 | 0.4773 | 0.9751 | 0.1608 | 0.8695 | 0.7144 |
| 10 | 0.4086 | 0.6729 | 0.9885 | 0.8283 | 0.6452 | 0.6493 | | 0.8380 | 0.4518 | 0.7750 | 0.1011 | 0.7526 | 0.6143 |
| 11 | 0.9980 | 0.9046 | 0.7173 | 0.2221 | 0.3897 | 0.1093 | | 0.3159 | 0.6629 | 0.6563 | 0.4835 | 0.2639 | 0.4399 |
| ↓ | | | | | | | | | | | | | |
| 999989 | 0.1365 | 0.5059 | 0.3831 | 0.5096 | 0.4849 | 0.7014 | | 0.8971 | 0.8647 | 0.5013 | 0.5413 | 0.7999 | 0.6870 |
| 999990 | 0.5131 | 0.0999 | 0.9039 | 0.9366 | 0.5538 | 0.8772 | | 0.5771 | 0.6315 | 0.3175 | 0.6496 | 0.4016 | 0.7901 |
| 999991 | 0.8088 | 0.7322 | 0.5738 | 0.0762 | 0.5157 | 0.9757 | | 0.2237 | 0.6372 | 0.9301 | 0.0782 | 0.1860 | 0.8296 |
| 999992 | 0.8508 | 0.2440 | 0.4792 | 0.6550 | 0.5626 | 0.3994 | | 0.7192 | 0.8316 | 0.0713 | 0.9394 | 0.8676 | 0.4612 |
| 999993 | 0.1214 | 0.2502 | 0.1058 | 0.5404 | 0.3929 | 0.2730 | | 0.5313 | 0.5783 | 0.5392 | 0.7318 | 0.8102 | 0.7756 |
| 999994 | 0.0767 | 0.6440 | 0.3050 | 0.2651 | 0.5803 | 0.5584 | | 0.6843 | 0.1969 | 0.9896 | 0.2547 | 0.7687 | 0.3575 |
| 999995 | 0.7449 | 0.5510 | 0.6578 | 0.9384 | 0.4688 | 0.5548 | | 0.4908 | 0.2624 | 0.1648 | 0.7591 | 0.1004 | 0.9544 |
| 999996 | 0.2394 | 0.7564 | 0.5075 | 0.1577 | 0.7687 | 0.7278 | | 0.0607 | 0.4223 | 0.5405 | 0.5732 | 0.8295 | 0.8812 |
| 999997 | 0.5580 | 0.2587 | 0.7511 | 0.0143 | 0.0549 | 0.1603 | | 0.6783 | 0.4446 | 0.0175 | 0.9656 | 0.6234 | 0.5631 |
| 999998 | 0.2848 | 0.2011 | 0.8650 | 0.0453 | 0.8744 | 0.4970 | | 0.0159 | 0.3791 | 0.9553 | 0.1719 | 0.3230 | 0.7761 |
| 999999 | 0.3229 | 0.5324 | 0.6930 | 0.3870 | 0.7697 | 0.4690 | | 0.5372 | 0.0206 | 0.1524 | 0.6518 | 0.6741 | 0.2335 |
| 1000000 | 0.1346 | 0.5810 | 0.3792 | 0.4773 | 0.8346 | 0.0326 | | 0.5292 | 0.1483 | 0.3098 | 0.6524 | 0.1953 | 0.8941 |

*Figure 15 Example Monte Carlo results matrix for the storm demand AEP*

These AEP values are translated to actual storm demand values on a per-profile basis. The methodology (applicable to each profile) is as follows:

- For each storm demand AEP value (converted from ARI values), post-storm setback distance from the zero-elevation (0m AHD) crossing are calculated for the following hazard 'zones' (refer Nielsen, 1992, and **Figure 16**):
    - Zone of Wave Impact (ZWI);
    - Zone of Slope Adjustment (ZSA); and
    - Zone of Reduced Foundation Capacity (ZRFC).

  This is an iterative process whereby the area below the beach profile (or volume per metre run of beach) is matched against the relevant storm demand value, while obeying the geometrical constraints of the above zones outlined in Nielsen (1992). Example results are presented in **Figure 17** and **Figure 18**.
- For each of the above zones, a matrix of one million (Monte Carlo simulations) by *n* (number of years in the planning period) of post-storm setback distance values is calculated by interpolating the AEP values and associated setback distance values onto the uniformly-distributed AEP values for storm demand (refer **Figure 15**).

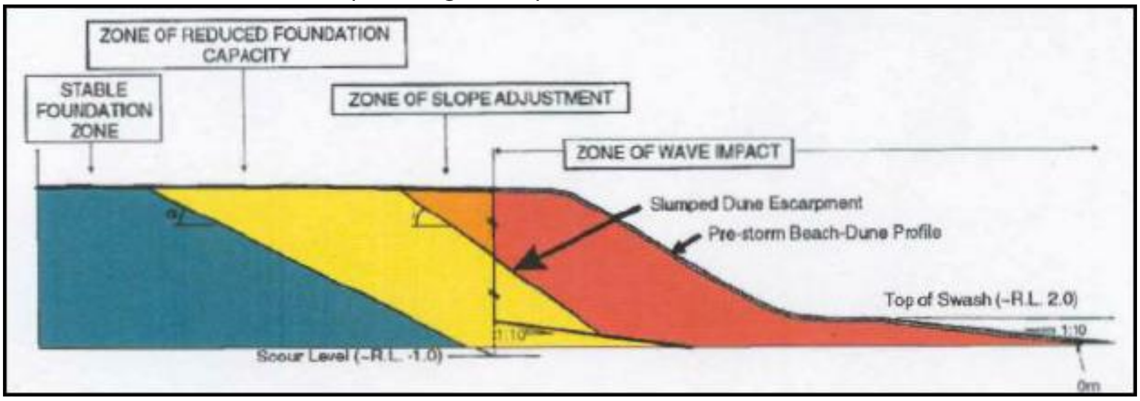



*Figure 16 Schematic representation of coastline hazard zones (after Nielsen, 1992)*

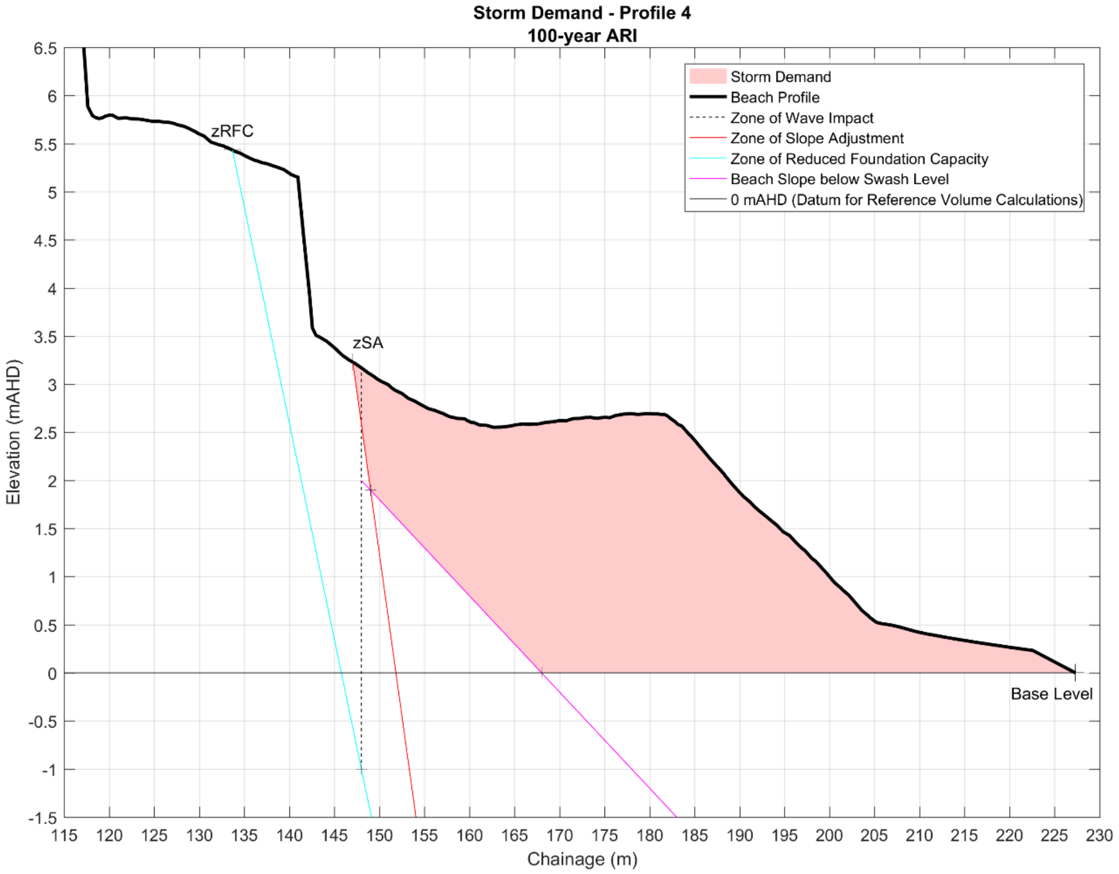



*Figure 17 Example profile storm demand*

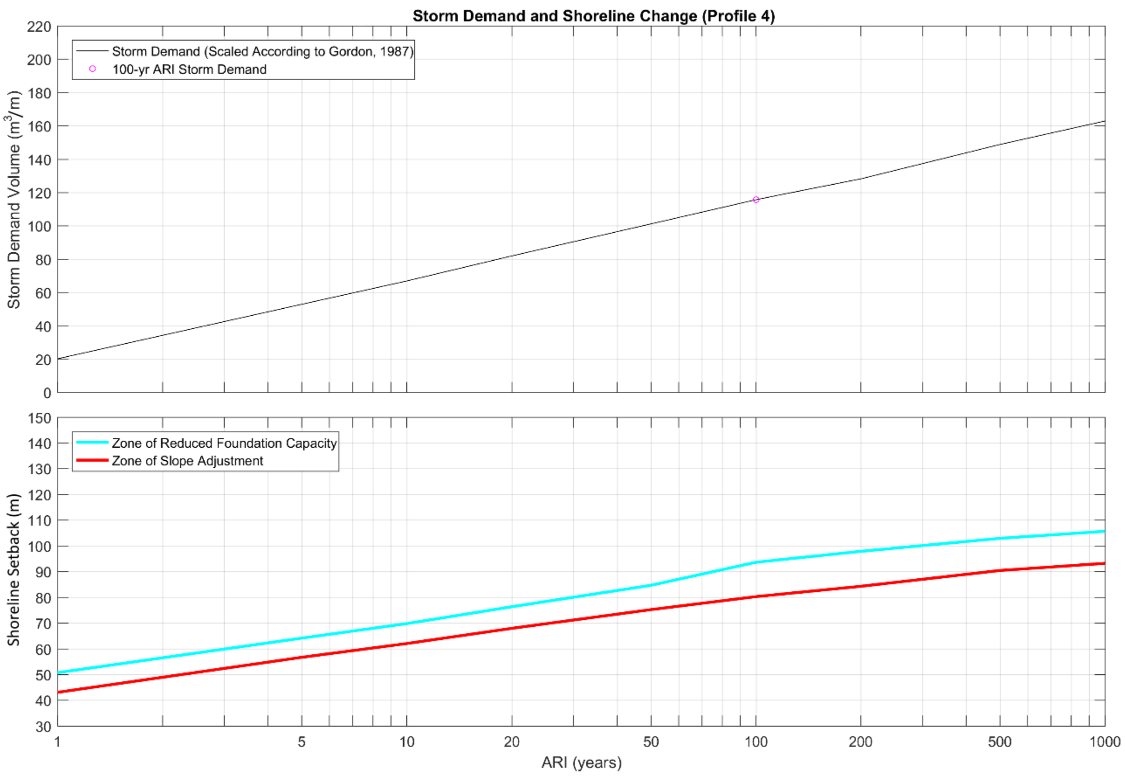



*Figure 18 Example storm demand and shoreline setback distance*

## 3.5 Combined Shoreline Position due to Underlying Recession, Sea Level Rise and Storm Demand

Total shoreline change for each of the hazard zones (ZWI, ZSA and ZRFC) outlined in **Section 3.4** is calculated by combining storm setback distances (cyan lines in **Figure 19**, presenting one example set of storm demand distances out of one million) with the 'combined recession' trajectories (grey lines and blue line, the latter representing one example trajectory out of one million) for each year in the planning period. The total shoreline change in each year (one million values in total – refer **Figure 19** for example distribution (in red) of the ZRFC setback distance in the final year of the planning period) is subsequently utilised to calculate probabilities of exceedance of each of the hazard zones and produce hazard lines on a map.

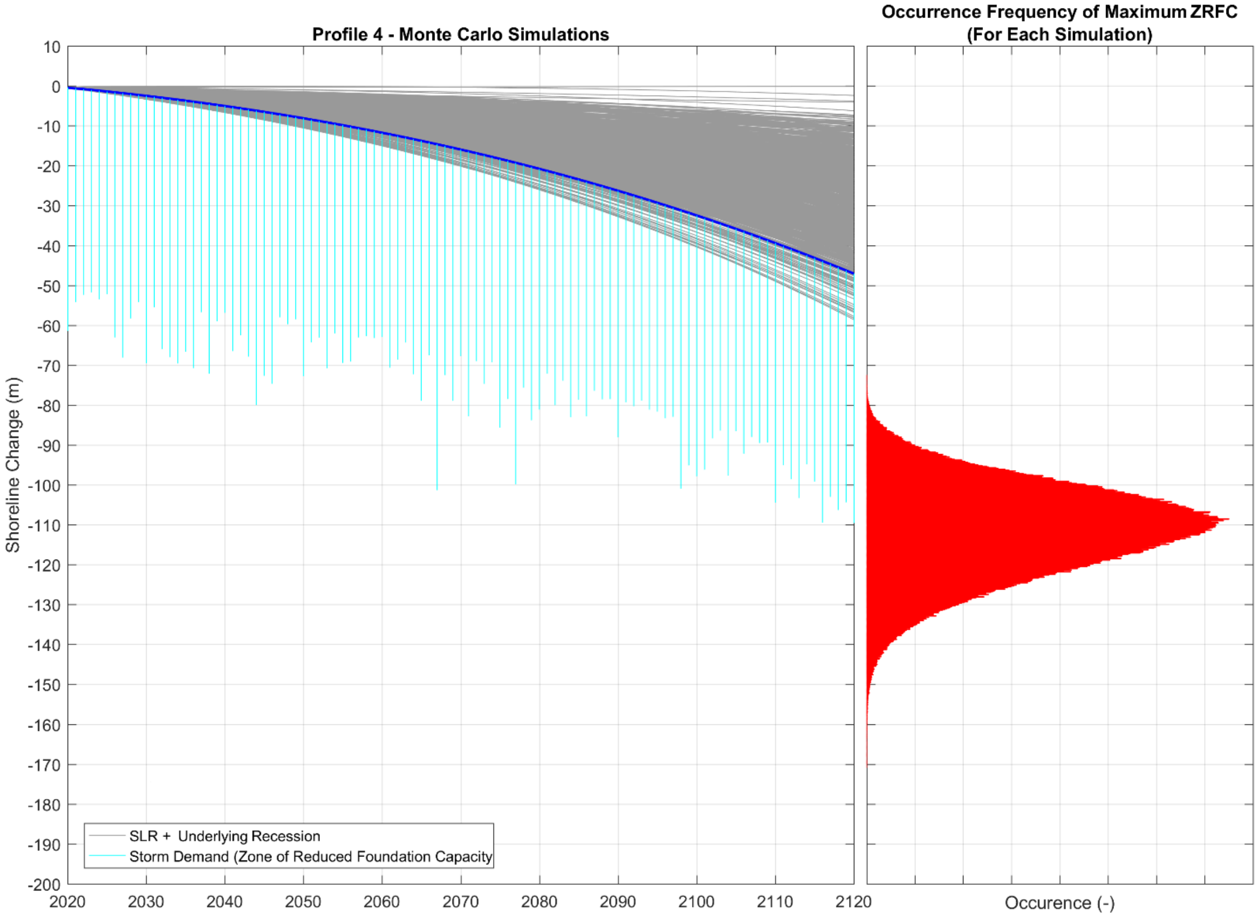



*Figure 19 Example of simulated storm demand superimposed on background shoreline change due to combined recession*

# 4 References

Bruun, P.M. (1962). Sea-Level rise as a cause of shore erosion, Jnl. Waterways, Harbour & Coastal Eng. Div., ASCE, Vol. 88, No. WW1, pp 117-130.

Bruun, P.M. (1983). Review of conditions for uses of the Bruun Rule of erosion, Jnl. Coastal Eng., Vol 7, No. 1, pp 77-89.

Gordon, A.D. (1987). Beach fluctuations and shoreline change - NSW, 8th Australasian Conference on Coastal and Ocean Engineering, Launceston, p. 5.

Nielsen, A.F., D. B. Lord, H. G. Poulos (1992). Dune Stability Considerations for Building Foundations, Vol. CE34 No. 2 June 1992.

WRL (2017). Eurobodalla Coastal Hazard Assessment, WRL Technical Report 2017/09, October 2017.

# Appendix B: Assessment of Closure Depths and Bruun Factors

Royal HaskoningDHV

## B.1 Preamble

There are numerous methods available to estimate the closure depth, including:

- analytical methods based on wave characteristics and sediment grain size characteristics;
- field methods based on survey data; and,
- field methods based on sedimentological data.

A synthesis and discussion of the available methods is provided below.

References are included in **Section 4** of the main report.

## B.2 Methods based on Wave Characteristics

For methods based on wave characteristics, Hallermeier (1981, 1983) defined three profile zones, namely the littoral zone, shoal or buffer zone[15], and offshore zone. This thus defined two closure depths (defined to be relative to the mean low water level), namely:

- an "inner" (closer to shore) closure depth at the seaward limit of the littoral zone, termed $d_l$ by Hallermeier (1981) and $d_s$ by Hallermeier (1983), and $d_{inner}$ herein; and
- an "outer" or "lower" (further from shore) closure depth at the seaward limit of the shoal/buffer zone, termed $d_i$ by Hallermeier (1981) and $d_o$ by Hallermeier (1983), and $d_{outer}$ herein.

From Hallermeier (1981):

$$d_{inner} = 2.28H_e - 68.5\left(\frac{{H_e}^2}{g{T_e}^2}\right) \qquad (2)$$

where $H_e$ is the effective significant wave height exceeded for 12 hours per year (that is, the significant wave height with a probability of exceedance of 0.137%), and $T_e$ is the corresponding significant wave period or "typical period of measured high waves" (Hallermeier, 1978). Based on measured Crowdy Head offshore wave data as analysed by Shand et al (2011), $H_e$ is 5.3 m and the equivalent $T_e$ is about 12 s[16]. When applied to Equation 1, this results in an inner closure depth of about RL -11.2 (10.7 m depth below Mean Low Water at RL -0.5).

Rijkswaterstaat (1987) approximates the work of Hallermeier to estimate the effective depth of closure as 1.75 x $H_e$, which results in a predicted inner closure depth of 9.3 m below Mean Low Water or about RL -9.8.

For practical purposes it is assumed by Rijkswaterstaat (1987) that the $d_{outer}$ can be calculated as follows:

$$d_{outer} = 2d_{inner}$$

The outer closure depth is then equal to approximately 22.4 m.

---

[15] *Shoal zone in Hallermeier (1981) and buffer zone in Hallermeier (1983).*

[16] *In Shand et al (2011), $T_p$ varies between about 9 s and 15 s at the Crowdy Head offshore Waverider buoy at an $H_s$ value of 5.3 m, with an approximate graphical central estimate of 13 s. $T_p$ is about 1.1 times $T_e$ (Takahashi et al, 1979; Lawson et al, 1987) thus giving a $T_e$ value of about 12s.*

## B.3 Field Methods based on Survey Data

Closure depths can also be determined from examination of bathymetry, generally coinciding with changes in slope of the offshore seabed profile.

SMEC (2013) assessed closure depths in the study area based on a review of available admiralty charts, bathymetric survey data and topographic data, including consideration of significant shoreline features such as nearshore rock which may form an offshore barrier to sediment movement.

SMEC (2013) determined closure depths of 4.5 m for Number One Beach, and 16.3 m for Boat Beach. A Bruun factor of 50 was adopted for both beaches. However, SMEC (2013) noted that the depth of nearshore rock extent was not known precisely at most locations. It is possible that the active beach profile widths were overestimated, which would result in steeper equilibrium profile slopes due to the presence of rock at relatively shallow depths.

Marine LiDAR data collected in 2018 was downloaded from the ELVIS website[17] to enable further assessment of closure depths for the probabilistic coastal hazard assessment. Example offshore profiles were extracted from the LiDAR dataset and are provided in **Figure B1** (Number One Beach) and **Figure B2** (Boat Beach).

The presence of rocky reefs at a depth of around RL -29 can be inferred from the LiDAR data for Number One Beach (**Figure B1**). However, this is below the closure depths estimated based on wave characteristics (see Section B2) and is therefore not considered to be relevant for the present assessment. However, comparison of the nearshore profiles with an idealised equilibrium profile based on the power relationship given in Bruun (1954) indicated closure depths of around RL -20 and RL-24 for profiles 3 and 7, with associated Bruun Factors of around 50 to 67.

The nearshore profile at Boat Beach varies as follows:

- The eastern end is dominated by the rocky reef system that is also visible in aerial photographs (refer profile plot for Block 1 Profile 3, **Figure B2**).
- The middle section of the beach indicates a more conventional sandy profile (refer profile plot for Block 2 Profile 4, **Figure B2**). Comparison of the nearshore profile with an idealised equilibrium profile based on the power relationship given in Bruun (1954) indicated a closure depth of around RL -10 with an associated Bruun Factor of around 34.

[17] *Available online: https://elevation.fsdf.org.au/.*

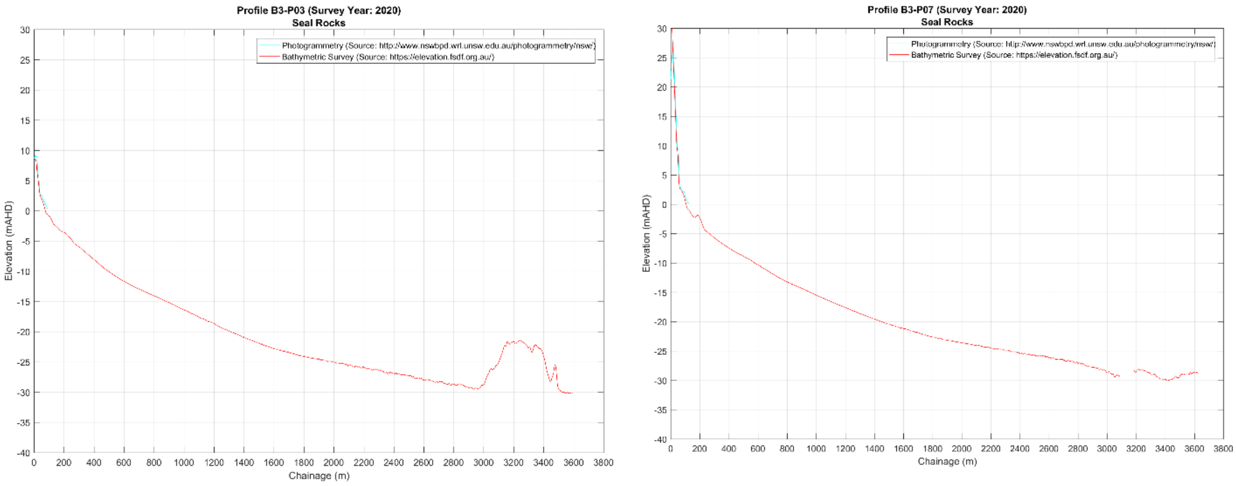



*Figure B1: Nearshore bed profiles at Number One Beach*
*(coinciding with photogrammetry profile locations 3 and 7, Block 3)*

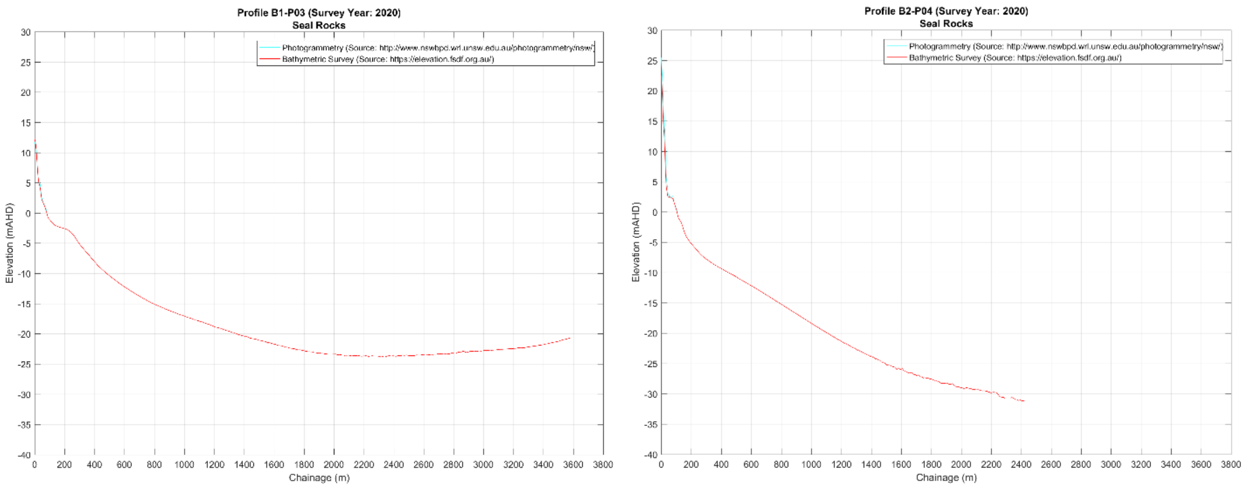



*Figure B1: Nearshore bed profiles at Boat Beach*
*(coinciding with photogrammetry profile locations: Block 1 Profile 3 and Block 2 Profile 4)*

## B.4 Field Methods based on Sedimentological Data

For methods based on sedimentological data, it can be noted that sedimentological data consistently shows distinct changes in the characteristics of sediments with water depth offshore of NSW (Nielsen, 1994). These changes include variations in grain size, sorting, carbonate content and colour.

There are two distinctive sediment units immediately offshore of the NSW shoreline, namely Nearshore Sand, and (further offshore and coarser) Inner Shelf Sand (also known as Shelf Plain Relict or Palimpsest Sand). Nearshore Sand is further subdivided into Inner and Outer Nearshore Sand units.

For beaches fully exposed to the offshore wave climate, the boundary between Inner and Outer Nearshore Sands is typically found at about 11 m to 15 m depth (relative to AHD), while the boundary to the nearshore edge of Inner Shelf Sand is usually at 18 m to 26 m depth. The boundary between Nearshore Sands and Inner Shelf Sands corresponds to those parts of the seabed considered to be active and relict respectively. That is, there is no significant exchange of Nearshore Sands with those of the Inner Shelf.

Royal HaskoningDHV

In relation to field measurements, Nielsen (1994) found that, based on a synthesis of field and laboratory data and analytical studies (particularly offshore of SE Australia), there were consistent limits of subaqueous beach fluctuations, namely water depths (relative to AHD) of:

- 12 m ± 4 m being the limit of significant wave breaking and beach fluctuations (consistent with the Inner/Outer Nearshore Sand Boundary and inner Hallermeier depth);
- 22 m ± 4 m being the absolute limit of sand transport under cyclonic or extreme storm events (consistent with the inshore Inner Shelf Sand boundary); and
- 30 m ± 5 m being the limit of reworking and onshore transport of beach sized sand under wave action (consistent with the outer Hallermeier depth).

## B.5 Synthesis and Discussion

The Bruun factors corresponding to each of the estimated closure depths are summarised in **Table B1**. It is noted that the closure depths estimated based on bathymetric survey data vary widely across the study area, which is reflective of the variable nearshore profiles that are influenced by rocky reef outcrops.

*Table B1: Summary of Closure Depths and Bruun Factors for the study area*

| Parameter | Bathymetry Features | | Inner Hallermeier | | Outer Hallermeier | |
|---|---|---|---|---|---|---|
| | Number One Beach | Boat Beach | Number One Beach | Boat Beach | Number One Beach | Boat Beach |
| Closure Depth (m AHD) | -4.5 to -24 | -10 to -16 | -11.2 | | -22.4 | |
| Bruun Factor | 50 to 67 | 34 to 50 | 32 to 38 | 31 | 56 to 63 | 50 |

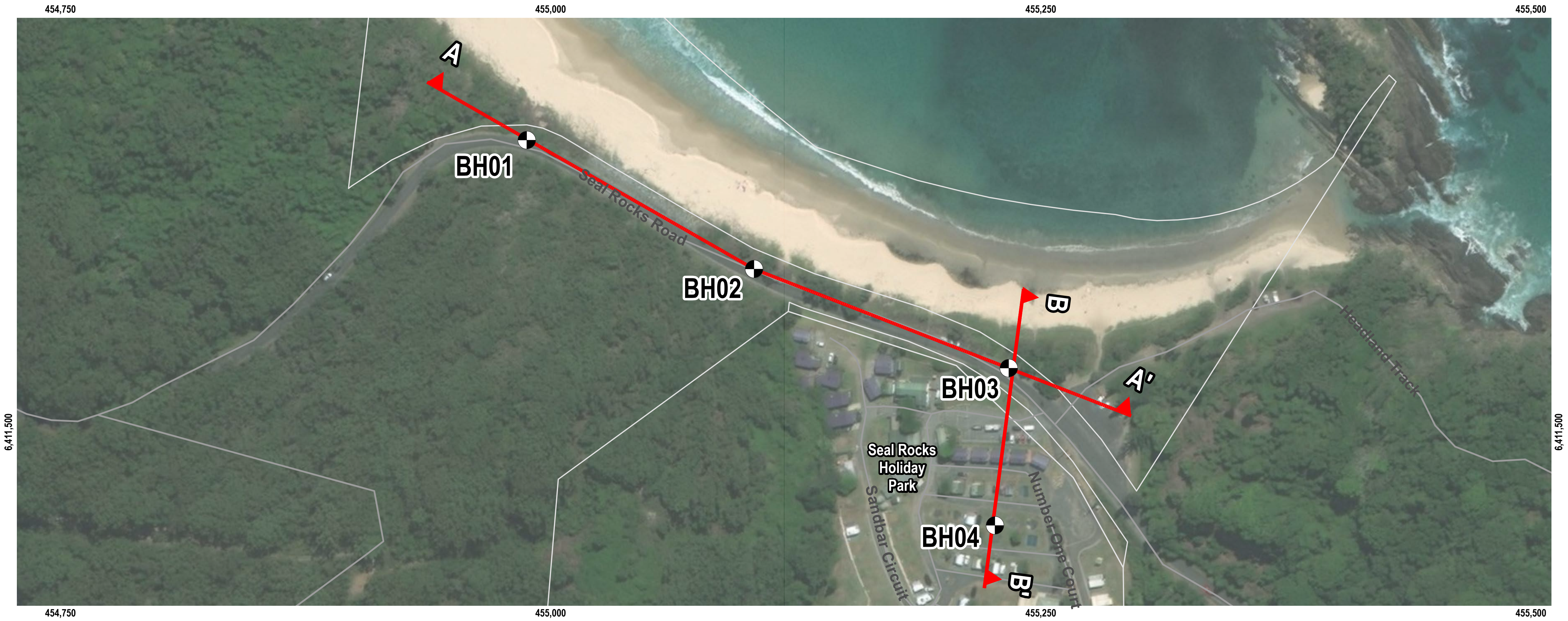
For the range of closure depths reported above, the corresponding Bruun factors range between around 30 and 70. Based on these results, the Bruun factors presented in **Table B2** are proposed for the probabilistic assessment. It can be seen that slightly lower Bruun factors are proposed for Boat Beach due to the steeper nearshore profile that occurs along the middle section of the beach.

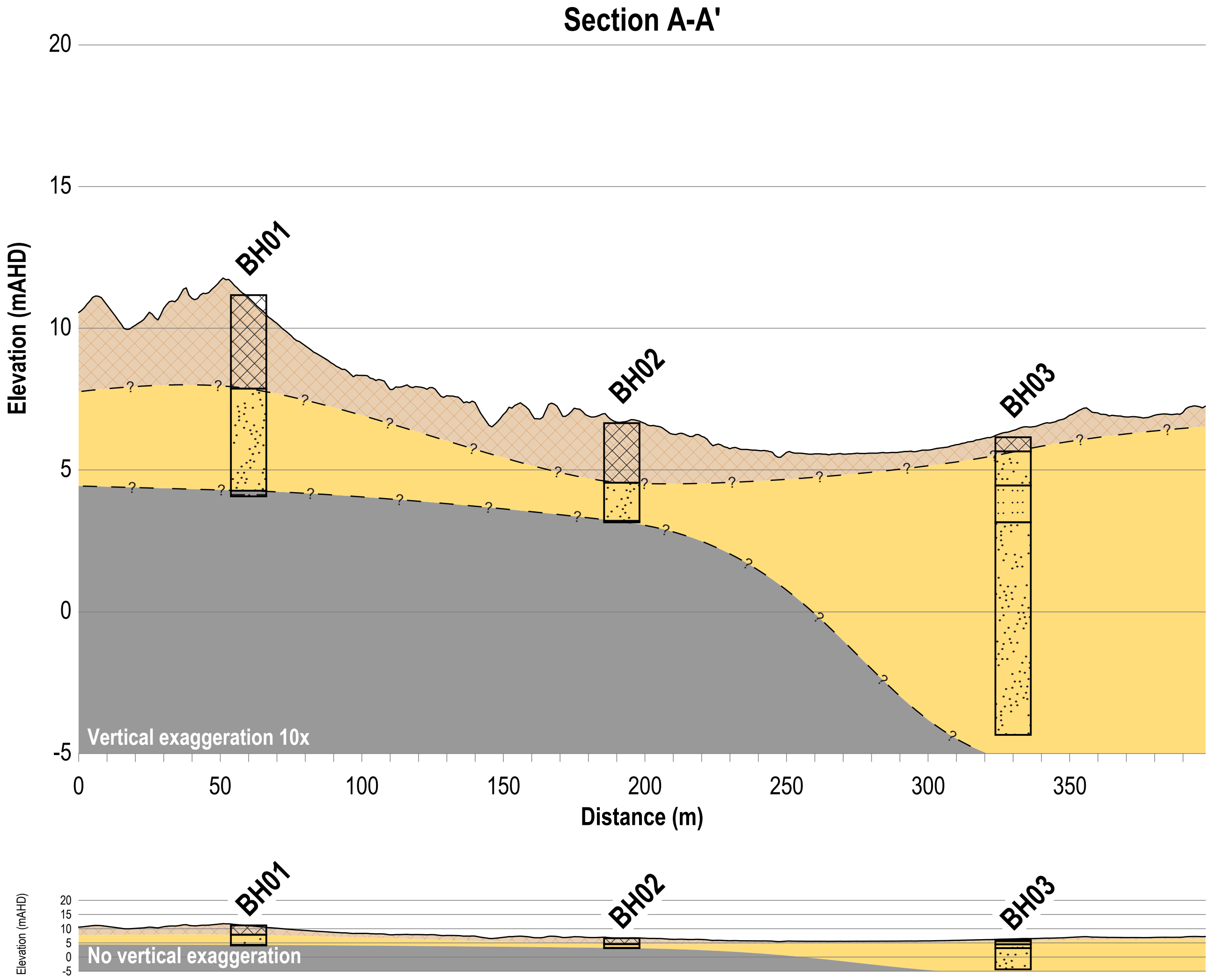
*Table B2: Bruun Factor – Proposed Inputs for Probabilistic Analysis*

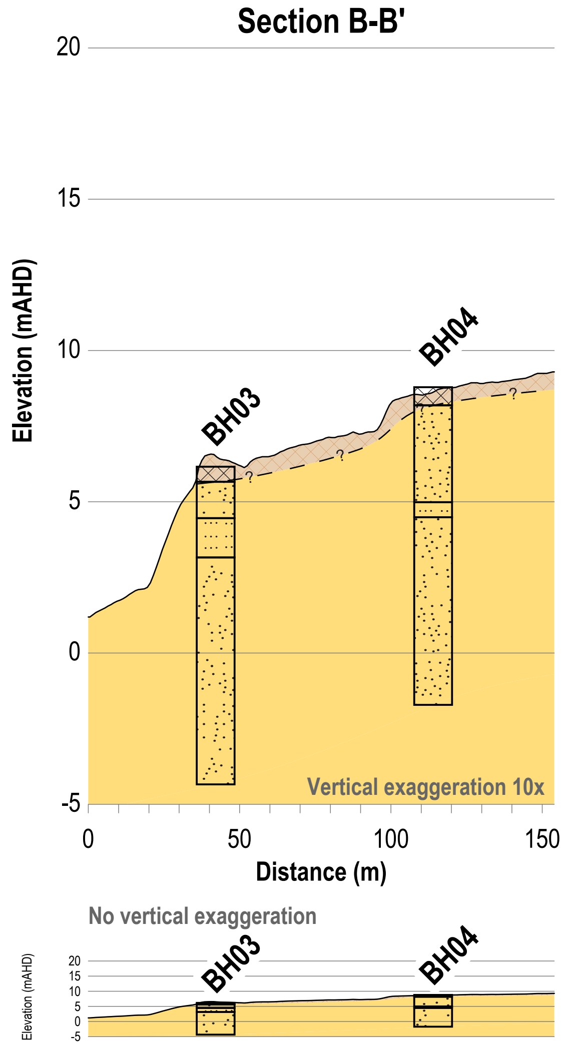
| Statistic | Bruun Factor | |
|---|---|---|
| | Number One Beach | Boat Beach |
| Minimum | 35 | 30 |
| Mode | 50 | 40 |
| Maximum | 65 | 50 |

Royal HaskoningDHV

# Appendix C: Subsurface cross sections from the geotechnical investigations (Coffey, 2022)




MIDCOAST council

## LEGEND

- Surveyed borehole location
- Cross-section
- Road
- Cadastre

### Material

- Fill
- Sand
- Coffee rock
- Clayey gravel
- Siltstone

### Geology

- Fill (Units 1a, 1b, 1c)
- Aeolian sand / Coffee Rock (Unit 2)
- Extremely Weathered Material (Unit 3)
- Siltstone (Unit 4a, 4b)

SOURCE
Boreholes from TtCOF (2021).
Road segment from MCC (2021).
Roads and place names from SIX Maps (2021).
Aerial imagery from ArcGIS Online (capture date 2016).

SCALE 1:2,500
PAGE SIZE: A3
PROJECTION: GDA 1994 MGA Zone 56

MID COAST COUNCIL

SEAL ROCKS ROAD DIVERSION AND LAP GEOTECHNICAL SURVEY

**FIGURE 3**

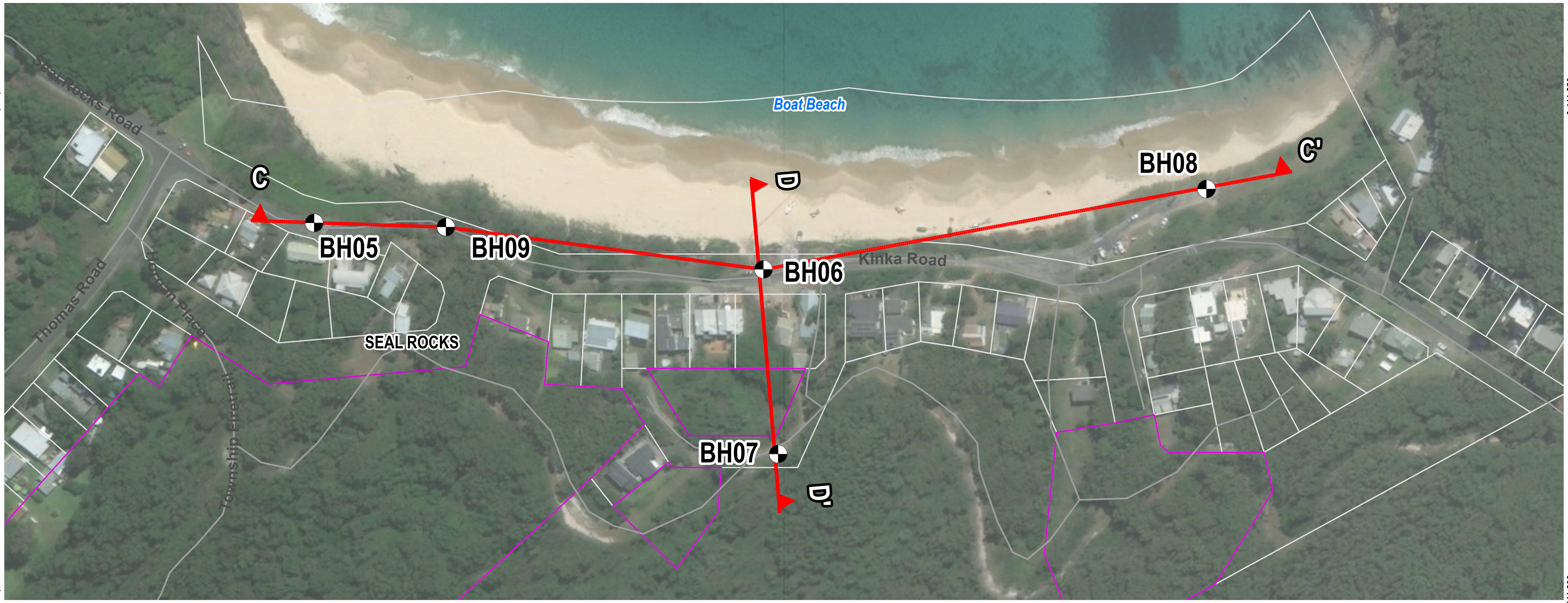
**Geotechnical cross sections: Section A-A' and B-B'**

TETRA TECH COFFEY

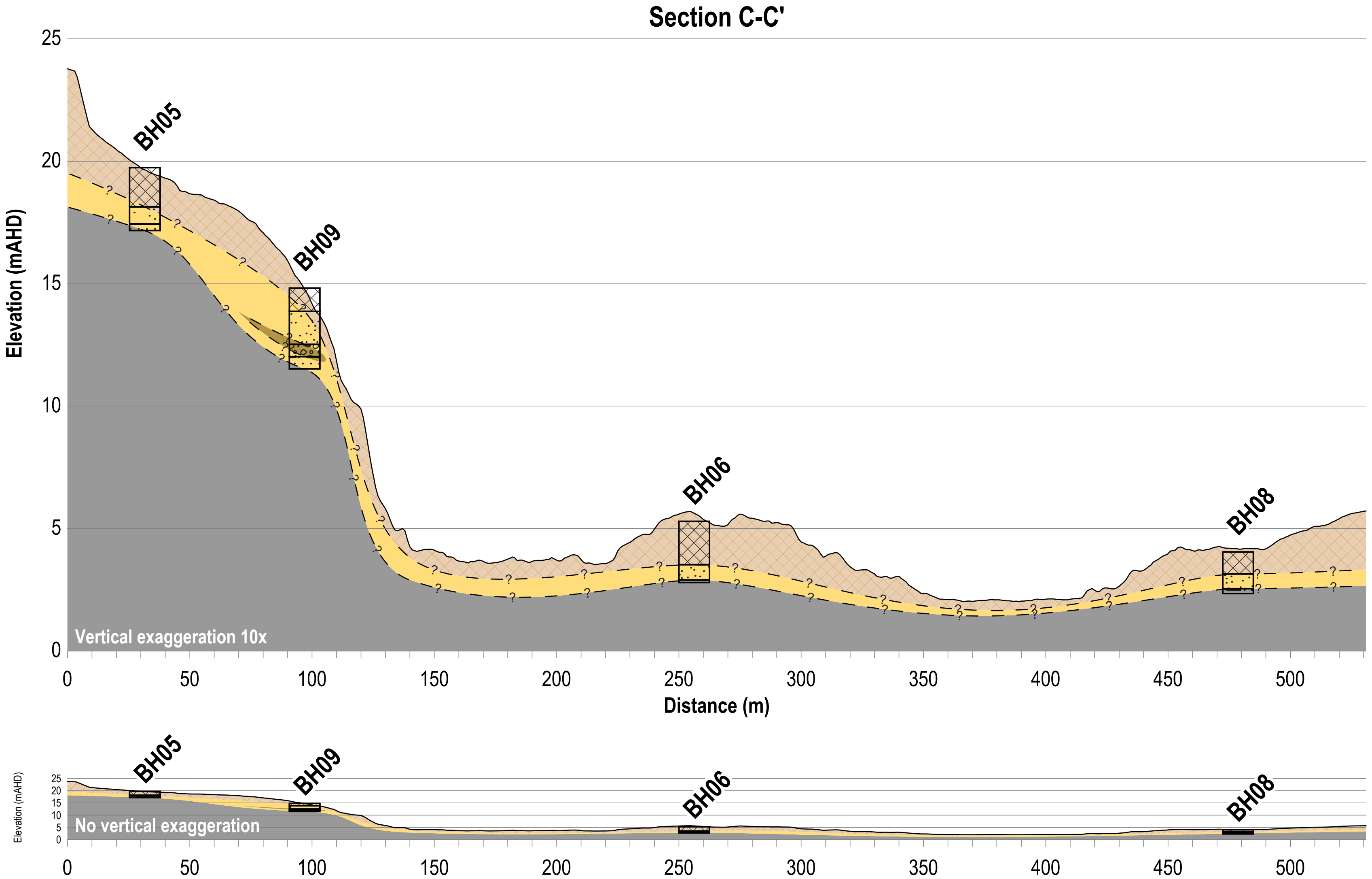
DATE: 28.10.21 PROJECT: 754-NTLGE284552 FILE: 284552_01_F003_GRA_RevA-4

SAVED BY: RICHARD.HEATH 25.08.21 10:18 AM

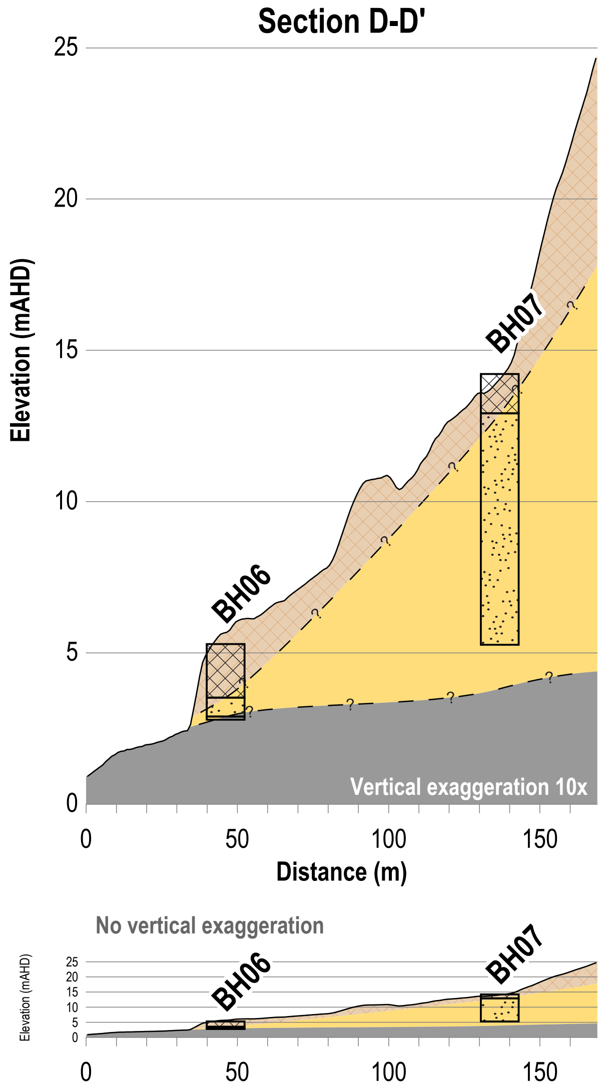
SAVED BY: RICHARD.HEATH 25.08.21 10:18 AM
DOC REFERENCE: \\ETSS772GISFS1\DATA$\GIS\283787_NTLPR_MCC_SEALROCKSROAD\MCC_SEALROCKS_GIS\APRX283787_MCC_SEALROCKSROAD_CROSSSECTIONS.APRX283787_MCC_SEALROCKSROAD_CROSSSECTIONS_1_284552_01_GRA002.ai_4




## Section C-C'




## Section D-D'




MIDCOAST council

**LEGEND**

- Surveyed borehole location
- Cross-section
- Road
- Cadastre

**Lithology**

- Fill
- Sand
- Coffee rock
- Clayey gravel
- Siltstone

**Geological units**

- Fill (Units 1a, 1b, 1c)
- Aeolian sand / Coffee Rock (Unit 2)
- Extremely Weathered Material (Unit 3)
- Siltstone (Unit 4a, 4b)

SOURCE
Boreholes from TtCOF (2021).
Road segment from MCC (2021).
Roads and place names from SIX Maps (2021).
Aerial imagery from ArcGIS Online (capture date 2016).

0 50 100 m
N
**SCALE 1:2,500**
PAGE SIZE: **A3**
PROJECTION: **GDA 1994 MGA Zone 56**

MID COAST COUNCIL

SEAL ROCKS ROAD DIVERSION AND LAP GEOTECHNICAL SURVEY

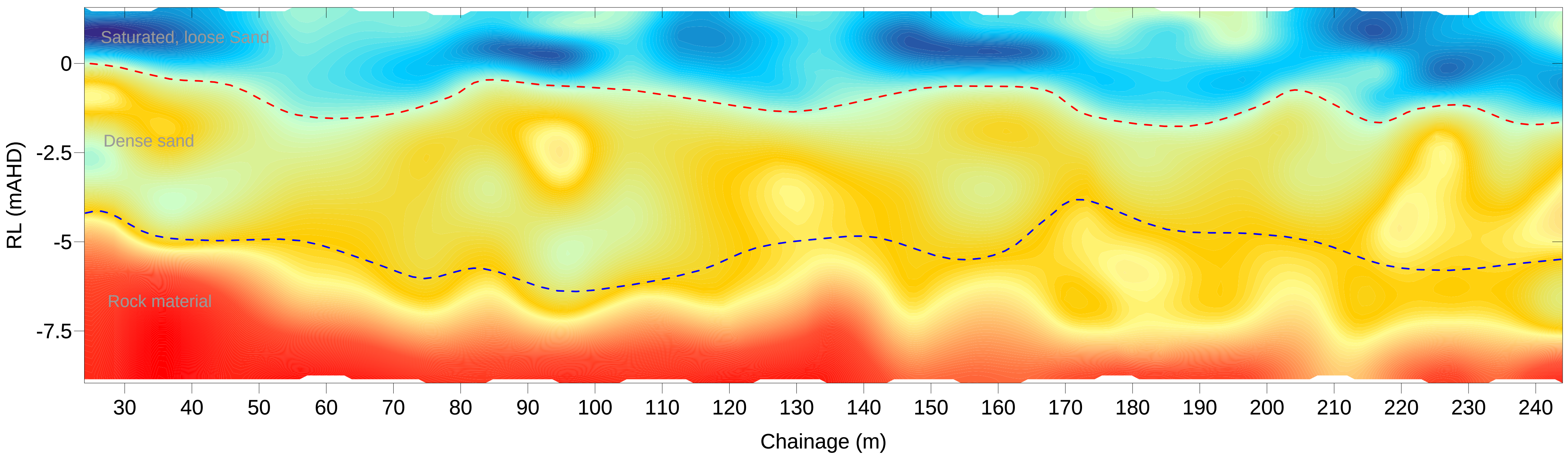
**FIGURE 4**

**Geotechnical cross sections: Section C-C' and D-D'**

TETRA TECH COFFEY

DATE: 28.10.21 PROJECT: 754-NTLGE284552 FILE: 284552_01_F004_GRA_RevA-4

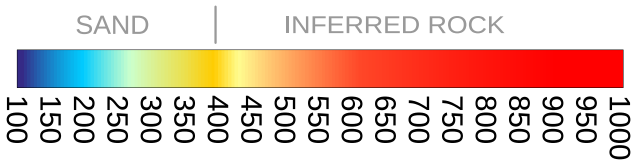

West — MASW 1 - NUMBER ONE BEACH — East




INTERPRETED BASE OF LOOSE SATURATED SAND / TOP OF DENSE SAND (approx 250 m.s$^{-1}$)

INTERPRETED BASE OF DENSE SAND / TOP OF ROCK (approx 400 m.s$^{-1}$)

Seismic S-wave Velocity ($V_s$) m.s$^{-1}$




GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |

0 10 20 30 40
Horizontal Scale (m)

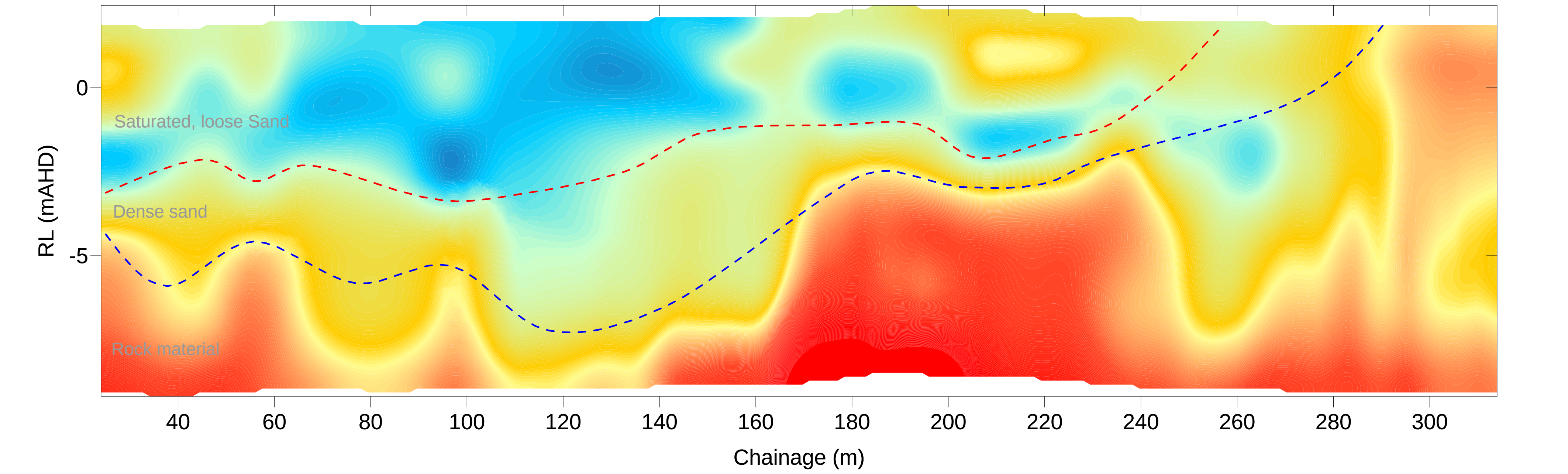
0 2.5 5
Vertical Scale (m)

| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

| | |
|---|---|
| client: | MIDCOAST COUNCIL |
| project: | ADDITIONAL GEOTECHNICAL INVESTIGATION |
| title: | GEOPHYSICAL SURVEY - MASW 1 |
| project no: 754-NTLGE284552-AC. | figure no: GEOP-02 |
| rev: | |

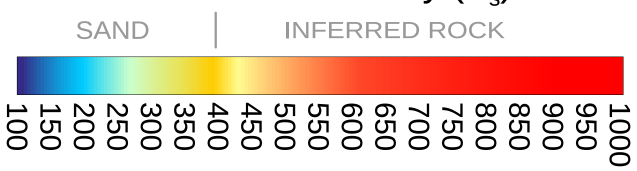

# MASW 3 - BOAT BEACH




INTERPRETED BASE OF LOOSE SATURATED SAND / TOP OF DENSE SAND (approx 250 m.s$^{-1}$)

INTERPRETED BASE OF DENSE SAND / TOP OF ROCK (approx 400 m.s$^{-1}$)

Seismic S-wave Velocity ($V_s$) m.s$^{-1}$




GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |

0 10 20 30 40
Horizontal Scale (m)

0 2.5 5
Vertical Scale (m)

| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

| | |
|---|---|
| client: | MIDCOAST COUNCIL |
| project: | ADDITIONAL GEOTECHNICAL INVESTIGATION |
| title: | GEOPHYSICAL SURVEY - MASW 3 |
| project no: 754-NTLGE284552-AC. | figure no: GEOP-03 |
| rev: | |

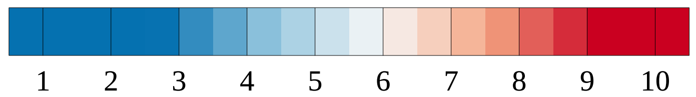
# GPR 2 - NUMBER ONE BEACH



LEGEND

- GROUND PENETRATING RADAR (GPR) LINE
- TETRA TECH COFFEY BOREHOLE
- AREA OF GPR SIGNAL ATTENUATION

Interpreted Depth to Rock (m)




GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |

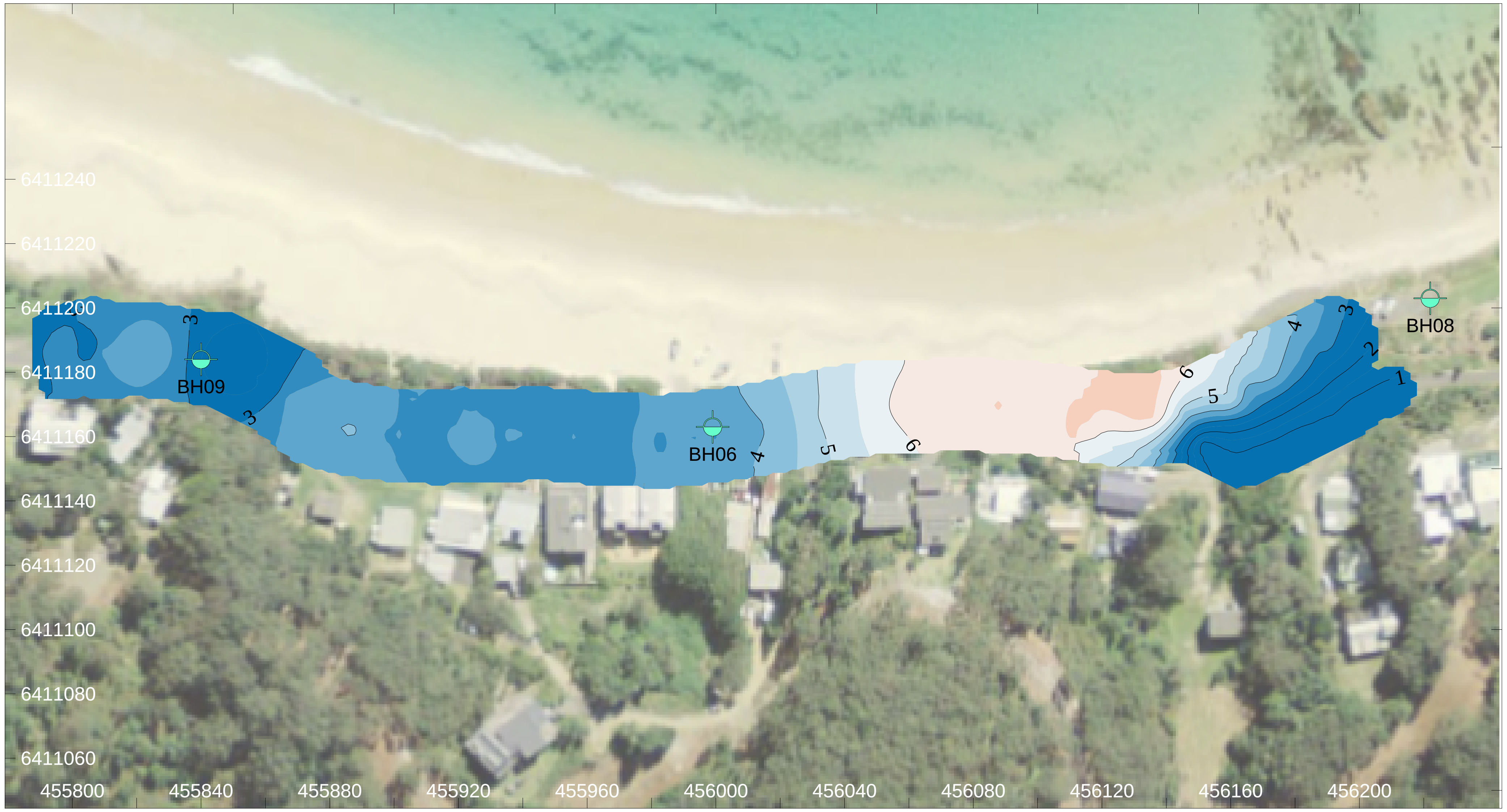
0 10 20 30 40 50
Scale (m)

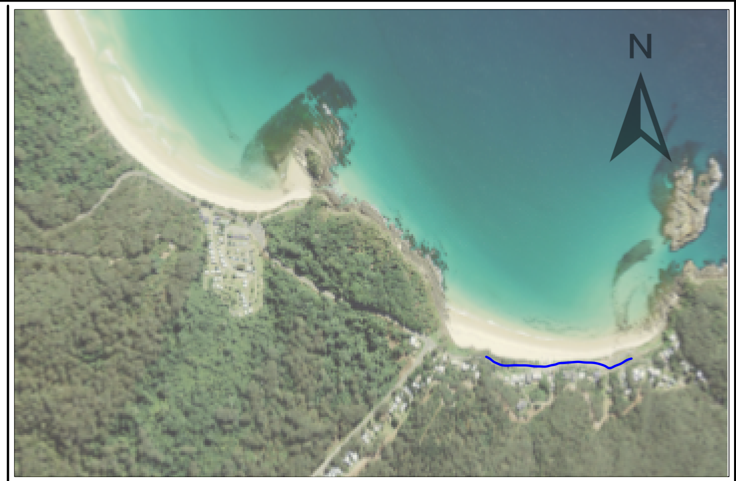
| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

| | |
|---|---|
| client: | MIDCOAST COUNCIL |
| project: | ADDITIONAL GEOTECHNICAL INVESTIGATION |
| title: | GEOPHYSICAL SURVEY - GPR 2 |
| project no: 754-NTLGE284552-AC | figure no: GEOP-04 |
| rev: | |

# GPR 4 - BOAT BEACH




LEGEND

GROUND PENETRATING RADAR (GPR) LINE

TETRA TECH COFFEY BOREHOLE

Interpreted Depth to Rock (m)

1 2 3 4 5 6 7 8 9 10

GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |

0 25 50 75 100

Scale (m)

| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

client: MIDCOAST COUNCIL

project: ADDITIONAL GEOTECHNICAL INVESTIGATION

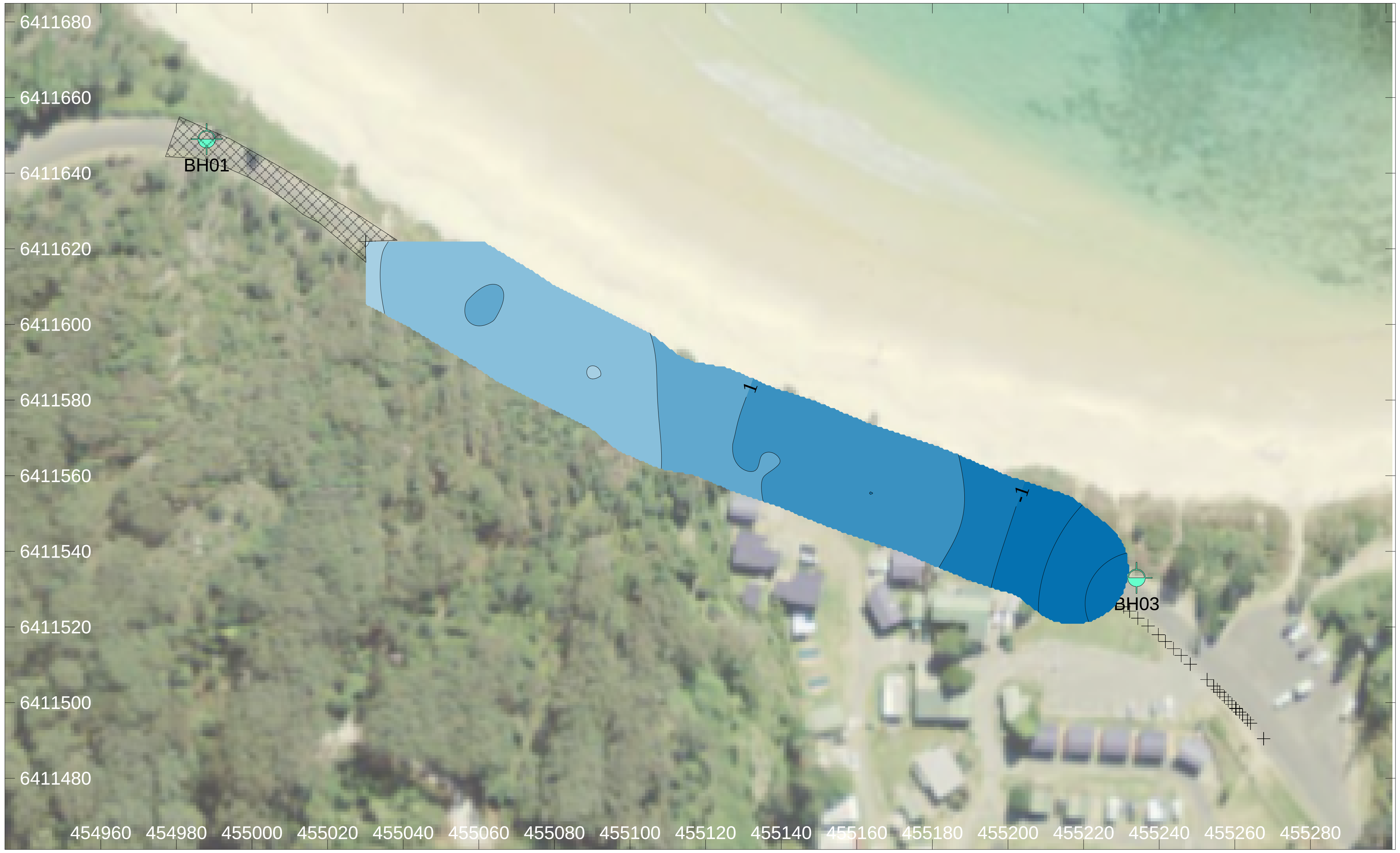
title: GEOPHYSICAL SURVEY - GPR 4

project no: 754-NTLGE284552-AC

figure no: GEOP-05

rev:

# GPR 2 - NUMBER ONE BEACH




Northing

Easting


LEGEND

- GROUND PENETRATING RADAR (GPR) LINE
- TETRA TECH COFFEY BOREHOLE
- AREA OF GPR SIGNAL ATTENUATION

Interpreted Rock RL (mAHD)

-3 -1 1 3 5 7 9 11 13 15

GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |

0 10 20 30 40 50
Scale (m)

| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

client: MIDCOAST COUNCIL

project: ADDITIONAL GEOTECHNICAL INVESTIGATION

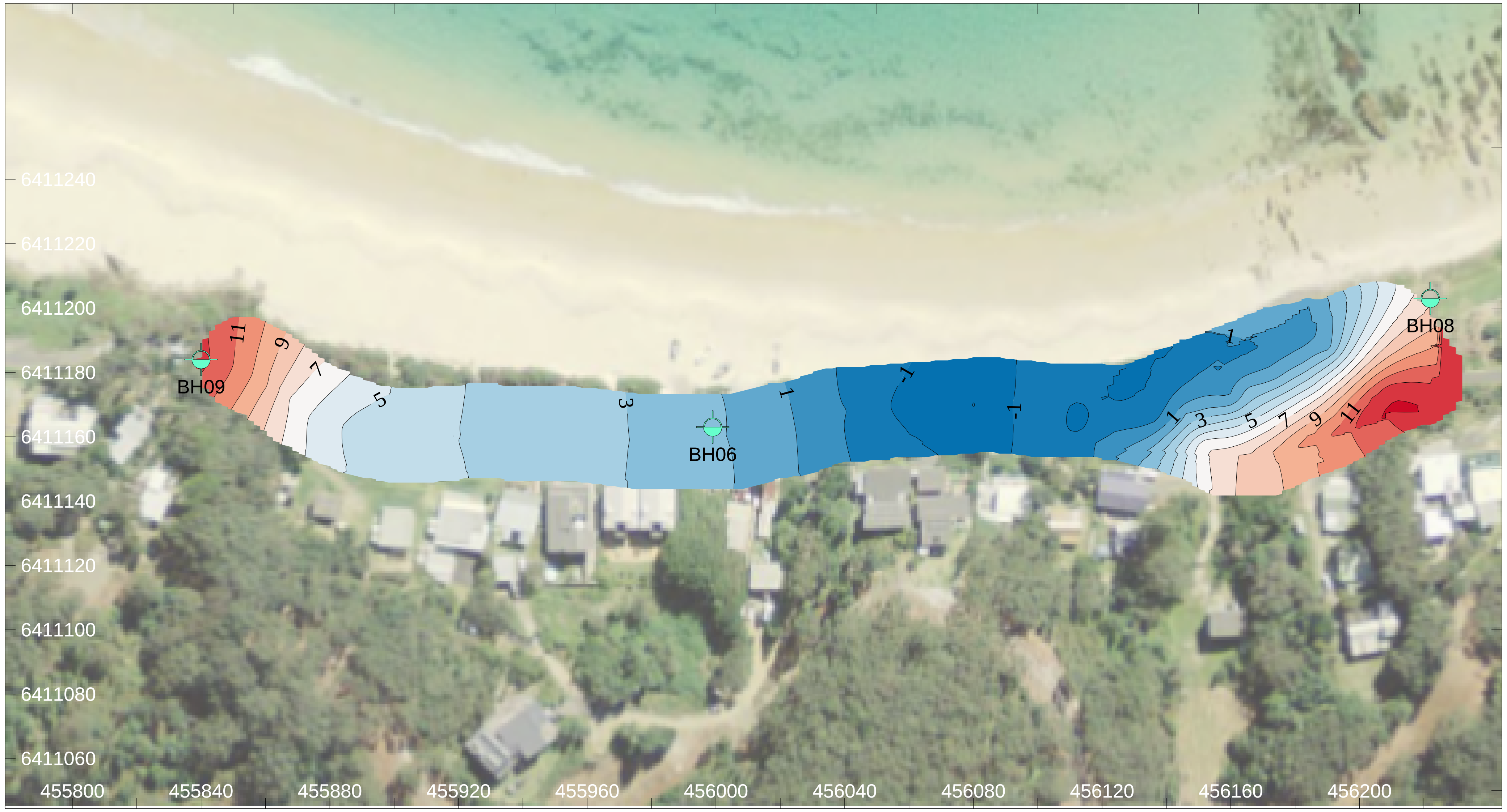
title: GEOPHYSICAL SURVEY - GPR 2 - INTERPRETED ROCK RL

project no: 754-NTLGE284552-AC

figure no: GEOP-06

rev:

# GPR 4 - BOAT BEACH




Northing

Easting


LEGEND

GROUND PENETRATING RADAR (GPR) LINE

TETRA TECH COFFEY BOREHOLE

Interpreted Rock RL (mAHD)

-1 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

GEODETIC PARAMETERS

| | |
|---|---|
| Geodetic Datum: | GDA2020 |
| Coordinate System: | MAP GRID of AUSTRALIA 2020 |
| Projection: | Universal Transverse Mercator (UTM) Zone 56 |
| Semi Major Axis: | 6378137.0m |
| Inverse Flattening (1/f): | 298.257222101 |
| Central Meridian: | 153°00'00 East |
| Reference Latitude: | 00°00'00 North |
| Scale Factor at CM: | 0.9996 |
| False Easting: | 500,000m |
| False Northing: | 10,000,000m |

revision

| no. | description | drawn | approved | date |
|---|---|---|---|---|
| 01 | ORIGINAL ISSUE | BS | SS | 28-02-2022 |

0 25 50 75 100

Scale (m)

| | |
|---|---|
| drawn | BS |
| approved | SS |
| date | 28-02-2022 |
| scale | As Shown |
| original size | A3 |

TETRA TECH COFFEY

client: MIDCOAST COUNCIL

project: ADDITIONAL GEOTECHNICAL INVESTIGATION

title: GEOPHYSICAL SURVEY - GPR 4 - INTERPRETED ROCK RL

project no: 754-NTLGE284552-AC

figure no: GEOP-07

rev:

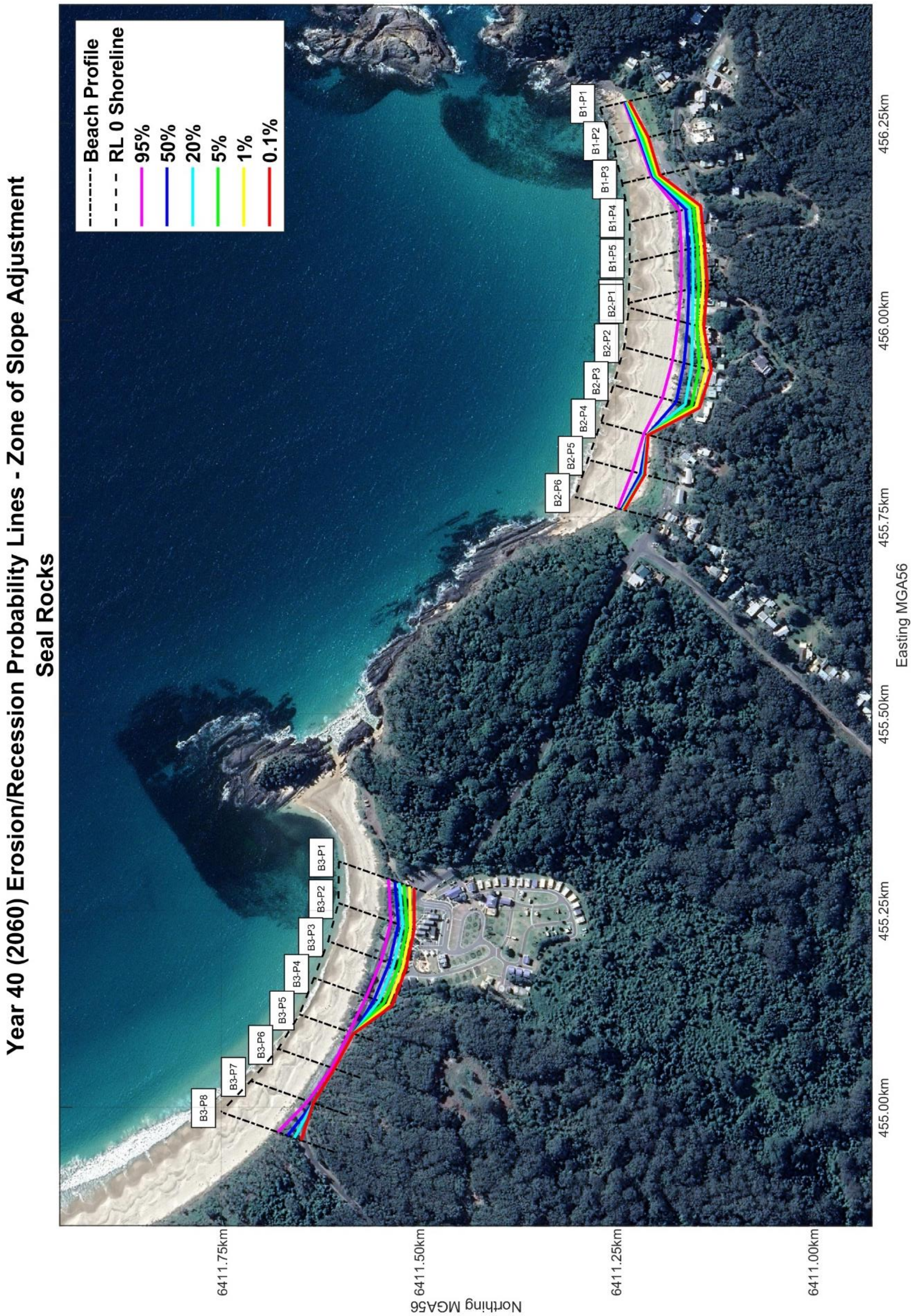
# Appendix D: Coastal Erosion/Recession Cumulative Probability Maps

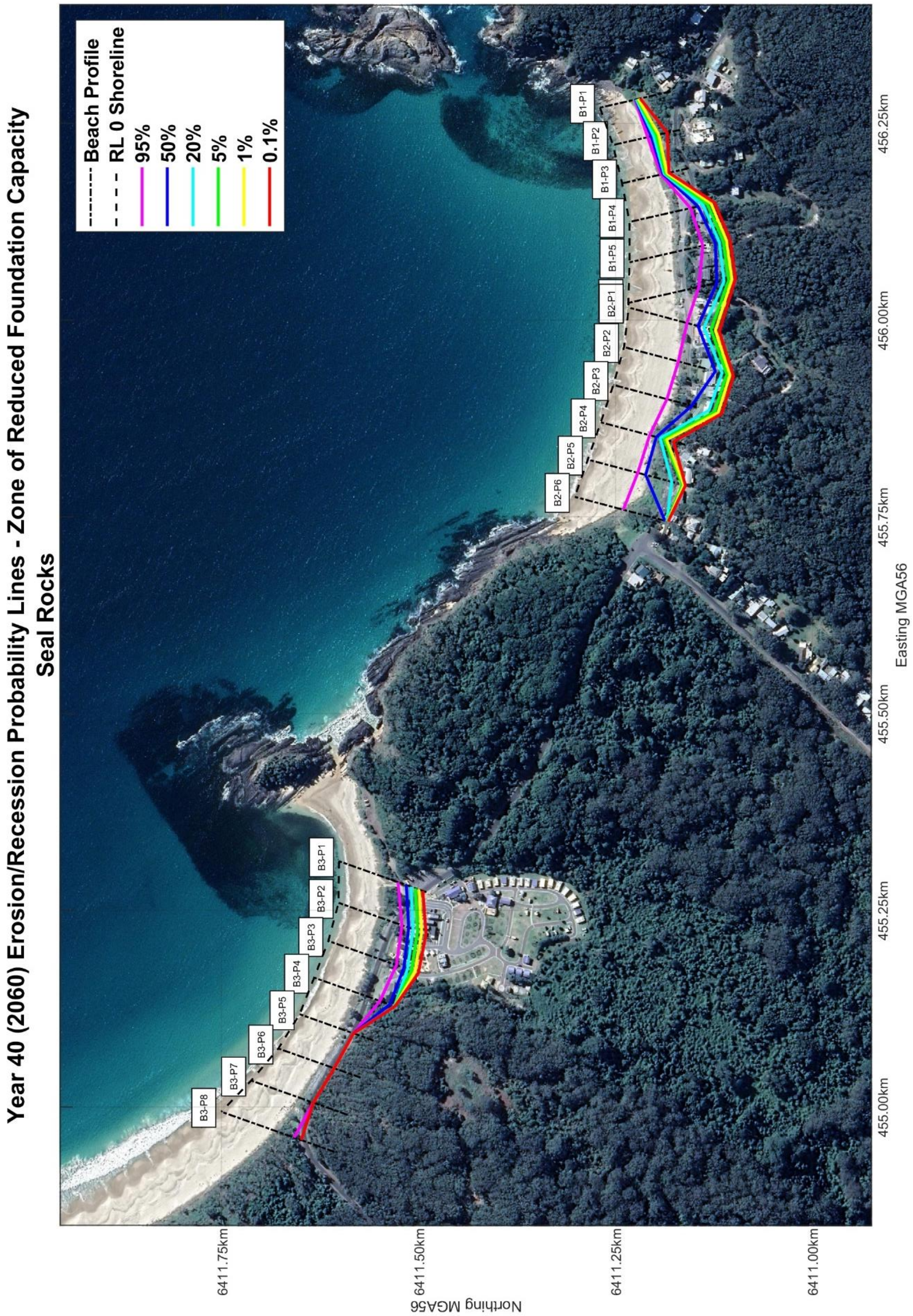
Year 0 (2020) Erosion/Recession Probability Lines - Zone of Slope Adjustment
Seal Rocks

Royal HaskoningDHV

**Year 0 (2020) Erosion/Recession Probability Lines - Zone of Reduced Foundation Capacity**
**Seal Rocks**

Royal HaskoningDHV




Year 40 (2060) Erosion/Recession Probability Lines - Zone of Reduced Foundation Capacity
Seal Rocks
Beach Profile
RL 0 Shoreline
95%
50%
20%
5%
1%
0.1%
B1-P1
B1-P2
B1-P3
B1-P4
B1-P5
B2-P1
B2-P2
B2-P3
B2-P4
B2-P5
B2-P6
B3-P1
B3-P2
B3-P3
B3-P4
B3-P5
B3-P6
B3-P7
B3-P8
456.25km
456.00km
455.75km
455.50km
455.25km
455.00km
Easting MGA56
6411.75km
6411.50km
6411.25km
6411.00km
Northing MGA56

**Year 80 (2100) Erosion/Recession Probability Lines - Zone of Slope Adjustment**
**Seal Rocks**

Year 80 (2100) Erosion/Recession Probability Lines - Zone of Reduced Foundation Capacity
Seal Rocks