

Modelling and response of modal beaches to sea level rise in the Waitpinga, Goolwa and Horseshoe Bay region, South Australia

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Executive Summary

In the report we review the various methods to estimate the response of sandy beaches to sea level rise. We then conduct an analysis of future sea level rise on representative modal beaches in the Coorong, Lower Lakes and Murray Mouth (CLLMM) region and beyond. These beaches are Waitpinga Beach, a modal intermediate beach dominated by large rip systems, Goolwa Beach, a modal longshore-bar-trough beach dominated by a wide multi-bar, largely dissipative system, and Horseshoe Bay, a modal reflective beach dominated by a narrow surfzone and steep, narrow beach. In the worst-case scenarios, the results show that Goolwa Beach could retreat by up to 96 m, Waitpinga Beach by up to 85 m, and Horseshoe Bay by up to 30 m by 2100. The results indicate that there is an order of magnitude difference in degree of shoreline recession between Robin's Rule and the Bruun model, with the XBeach modelling sitting approximately in the middle of the two extremes. This indicates the difficulty that exists when attempting to determine a line or zone of setback for future development, and also a line or zone of coastal land that could be impacted by a future sea level rise of 1 m by ~2100.

Acknowledgements

We acknowledge the cultural connections to the land and connected waters, as well as the cultural significance of waterbirds that exist between people of the Ngarrindjeri and Boandik Nations across the Coorong, Lower Lakes, and Murray Mouth region. We recognise that First Nations peoples' spiritual, social, cultural, and economic practices come from their lands and waters, and they continue to maintain their cultural heritage, economies, languages, and laws which are of ongoing importance. We are committed to fostering and nurturing ongoing relationships with First Nations communities in the CLLMM region as we collectively work toward healthy, resilient and thriving lands, waters, ecosystems and communities across the region.

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1 Introduction

Global mean sea level has risen approximately 21–24 cm since 1880 according to NOAA Climate.gov (<https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level>; sourced Nov., 12th, 2025) (Figure 1). In 2023, global mean sea level was 11 cm above 1993 levels, and thus the highest annual average in the satellite record. The rate of global mean sea level rise in the period 1993–2023 has increased from ~2.1 mm/year in 1993 to ~4.5 mm/year in 2023 (Hamlington et al, 2024). Hamlington et al. (2024) show that the current sea level rise rate recorded from satellite observations is in line with the mid-range sea level projections stated by the IPCC AR6 report (<https://www.ipcc.ch/assessment-report/ar6/>) (Figure 2). The Coast Protection Board (DEW) Policy 1.4 indicates an allowance of 0.3m sea level rise by 2050, and a further 0.7m sl rise by 2100.

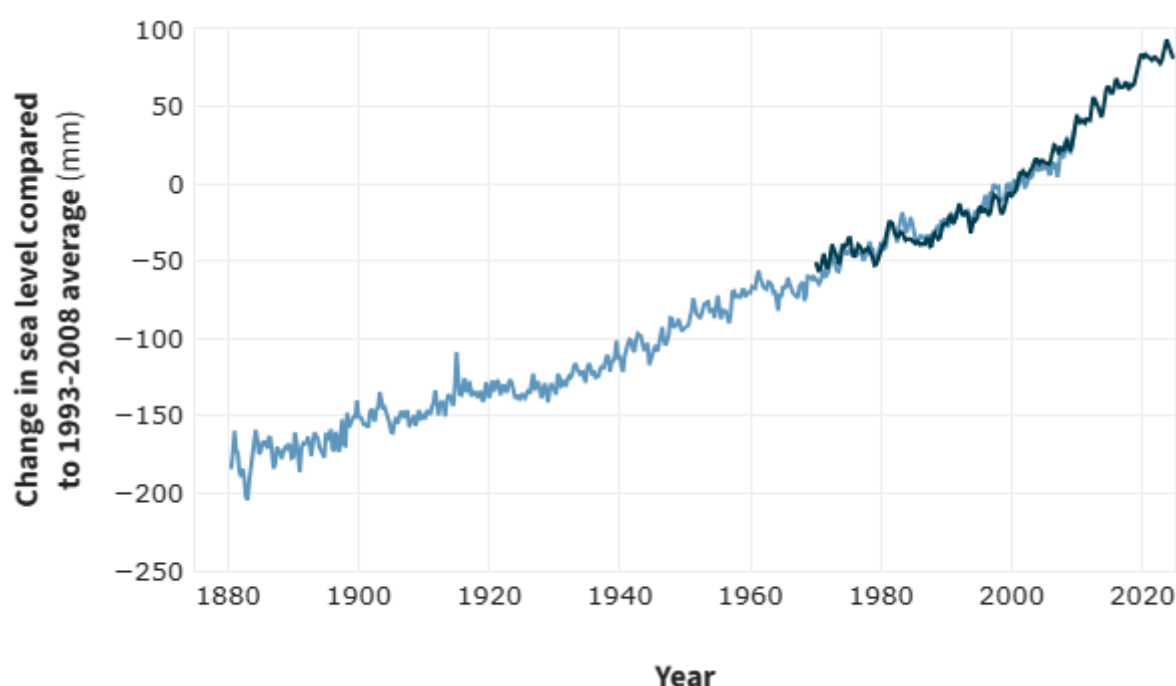


Figure 1. Seasonal (3-month) sea level estimates from Church and White (2011) (light blue line) and University of Hawaii Fast Delivery sea level data (dark blue). The values are shown as change in sea level in millimeters compared to the 1993–2008 average. Source: NOAA Climate.gov.

Sandy beaches are dynamic coastal environments that respond to changes in sea level through complex interactions between wave energy, tides, sediment availability, beach morphology, nearshore bathymetry, and coastal sediment transport processes. As sea levels rise, these interactions may alter the position, profile, width, and sedimentary characteristics of beaches, potentially, and likely resulting in shoreline recession, possibly changes in beach state, increased erosion, and the redistribution of sediment across the beach and nearshore zone, and possibly sediment loss to the local or regional system. However, the magnitude and nature of these responses are unlikely to be uniform across a region, as beaches with different morphological and hydrodynamic characteristics (e.g. a steep narrow reflective beach versus a wide, flat

dissipative beach) respond differently to changing boundary conditions. Consequently, assessing the potential effects of future sea-level rise requires an understanding of both the underlying processes governing beach response and the limitations and applicability of the methods available to predict these changes.

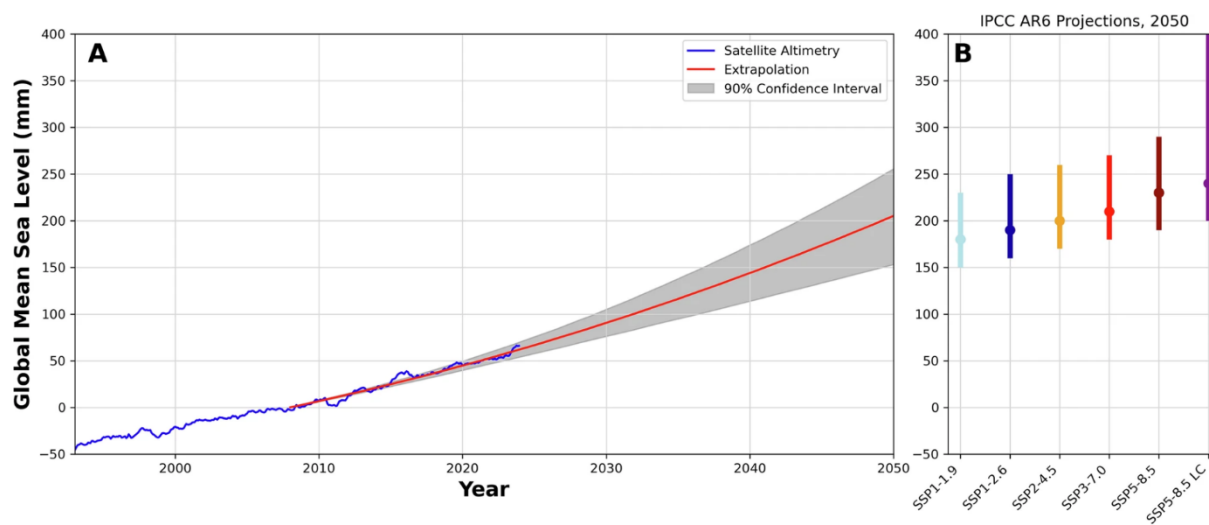


Figure 2. IPCC AR6 sea level rise scenarios. Source Hamlington et al. (2024) and https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf.

The first part of this study therefore reviews the principal methods used to estimate sandy beach responses to sea-level rise. Reviewing these approaches is important for determining which methods are appropriate for the coastal environments under investigation, identifying the strengths and limitations of alternative prediction techniques, and potentially establishing a defensible basis for estimating future beach change.

Building on this review, we analyse the potential effects of future sea-level rise on representative beaches within the Coorong, Lower Lakes and Murray Mouth (CLMM) region and selected nearby coastal areas. The inclusion of sites slightly beyond the immediate CLMM region is intended to ensure that the analysis captures the principal beach morphodynamic states or types represented across the broader coastal system, rather than being constrained by the geographical distribution of suitable examples within the region alone. Specifically, the analysis considers the three widely recognised modal beach states: reflective, intermediate, and dissipative beaches. These states represent contrasting combinations of beach slope, sediment characteristics, nearshore morphology, and wave-energy dissipation, and therefore provide a useful framework for investigating how differences in beach type may influence responses to rising sea levels. These differences are important because sea-level rise does not act independently of existing beach morphology and hydrodynamic conditions. Instead, the resulting response will depend on the interaction between rising water levels and the processes that govern sediment mobility, profile adjustment, and shoreline change. Comparing representative examples of all three beach states will therefore help establish whether the magnitude and character of projected beach responses differ systematically according to modal beach type.

This comparative approach is particularly relevant to the CLLMM region, where coastal management decisions require an improved understanding of the potential consequences of sea-level rise for beach stability, shoreline position, and sediment dynamics. Establishing how representative beaches may respond under alternative sea-level-rise methodologies will provide an initial assessment of the potential scale and variability of future change. It will also hopefully help identify beaches or coastal settings that may warrant more detailed investigation, monitoring, or management intervention. By extending the analysis to encompass all three modal beach states, the study aims to develop a more transferable understanding of sandy beach responses that can inform assessments beyond individual study sites.

Overall, the purpose of this work is to establish a scientifically grounded and comparative assessment of the potential effects of future sea-level rise on sandy beaches in and around the CLLMM region. Combining a critical review of available predictive methods with an analysis of representative beach types will clarify the likely range of responses, highlight the uncertainties associated with their estimation, and provide a stronger evidence base for regional coastal vulnerability assessments and future adaptation planning. The results should be interpreted as estimates of potential morphological response under specified assumptions and scenarios, rather than precise predictions of future shoreline positions, particularly where other factors such as changing storminess, sediment supply, coastal structures, and human interventions may substantially influence beach evolution.

Thus, to summarise, in the following we review the various methods to estimate the response of sandy beaches to sea level rise. We then conduct an analysis of future sea level rise on some type or modal beaches in the CLLMM region and slightly beyond in order to cover the three modal beach types (reflective, intermediate, and dissipative) present in the larger region.

1.1 The Bruun Model

The most commonly used model to determine beach profile response to sea level rise is the Bruun equilibrium model, often referred to as the 'Bruun Rule'. The model specifies that as sea level rises, the equilibrium surfzone-nearshore profile moves upwards and landwards conserving mass, and also conserving the original morphology of the original profile (Bruun, 1962; Figure 3).

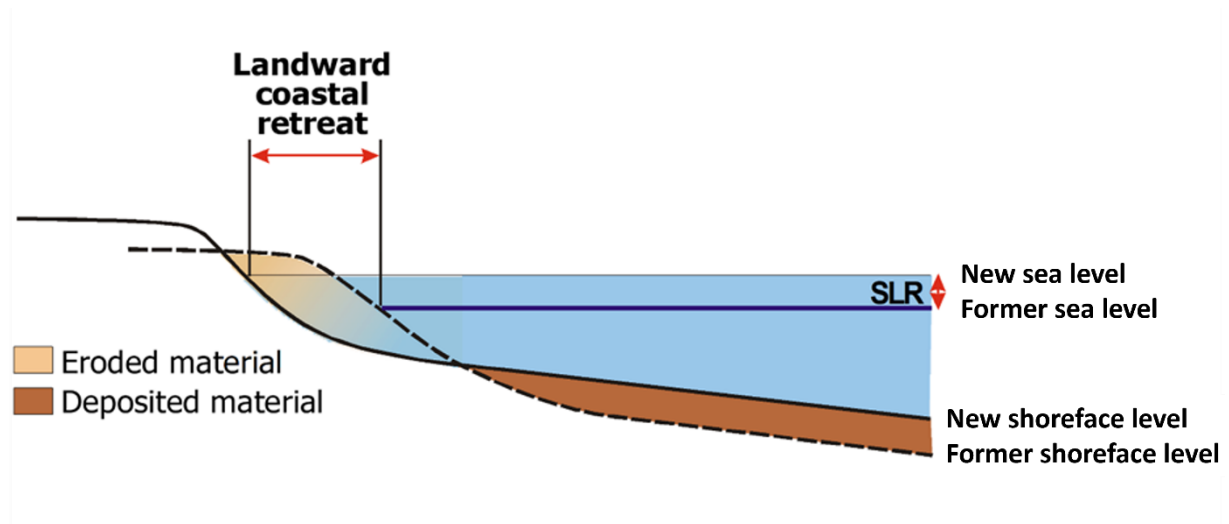


Figure 3. A graphical illustration of how the Bruun model works on a sandy beach (modified from original by R. Davidson-Arnott).

The model can be expressed as follows:

$$R = S \times (L^*) / (B + h^*) \quad (\text{Eqn 1})$$

where R is the extent of landward retreat, h^* defines the maximum depth of sediment exchange, L^* is the horizontal distance from the shoreline to the offshore position of h^* , B is the height of the berm or dune crest on the eroded backshore/dune, and S is the sea level rise.

This may also be expressed as:

$$S_{\text{Bruun}} = \text{SLR} / \tan(\alpha) \quad (\text{Eqn 2})$$

where $\tan(\alpha)$ is the mean slope of the active beach profile between the offshore limit of sediment exchange (i.e. the depth of closure) and the backshore limit which may be the berm, the dune toe or the dune crest, and SLR is sea level rise (D'Anna et al., 2021).

The Bruun model is still the most commonly utilised method to estimate shoreline change related to sea level rise. However, it has limitations due to the following factors extracted directly from Shand et al. (2013):

- The rule assumes that there is an offshore limit of sediment exchange or a 'closure depth', beyond which the seabed does not raise with sea level.
- The rule assumes no offshore or onshore losses or gains.
- The rule assumes instantaneous profile response following sea-level change.
- The rule assumes an equilibrium beach profile where the beach may fluctuate under seasonal and storm-influences but returns to a statistically average profile (i.e. the profile is not undergoing long-term steepening or flattening).
- The rule does not accommodate variations in sediment properties across the profile or profile control by hard structures such as substrate geology or adjacent headlands. (Shand et al., 2013, p. 677).

In the case of (1) above, it seems unlikely that if sea level rise continued long into the future, the seabed would not respond past the closure depth limit, and eventually change to a smoother profile as is commonly observed now in profiles across the nearshore-offshore regions of beach systems. In the case of (2) above, this is likely to be problematic given we are possibly going to see larger storms in the future (Knutson et al., 2010; Pillay and Fitchett, 2021), with sediments being transported further offshore and unable to be transported back onshore under subsequent lower wave energy periods. In some well documented instances, there is an absolute loss of sediment from embayments or portions of coastlines each time there is a storm (e.g. Davidson et al., 2021; Hesp et al., 2022). Beaches have noticeably steepened as erosion has continued so assumption (4) above is unlikely to be maintained on permanently eroding beaches.

In the case of (3) above, as sea level rises, there may be an instantaneous response in the beach profile, but given the day-to-day changes in wave energy on any beach and typical movement of bars related to this, an instantaneous response may also be unlikely. This may not particularly matter because even if the response is delayed, if the model predicts change well, then the response due to sea level rise will eventually take place.

In the case of (5) above, SA exhibits many beaches with intertidal platforms and reefs in the surfzone to nearshore regions, and it is unclear as to whether the Bruun Rule can be utilised at all in such situations. It is also unclear as to where to place the depth of closure (the seaward extent of the envelope of profile change).

In addition, none of the papers that utilise the Bruun model address the issue of the lack of evidence nor the mechanisms for the net offshore transport of sediment and the need for it to accumulate to a thickness exactly equal to the rise in sea level. Finally, the Bruun model can predict much larger rates of transgression than is realistic.

Because the assumptions outlined above are regarded as quite serious by some scientists, some authors have argued for the complete abandonment of the Bruun model (e.g. Cooper and Pilkey, 2004). Others have shown that in certain circumstances, the model works reasonably well. For example, Hands (1983) conducted a study of 25 beach profiles along a 50km stretch of shoreline of Lake Michigan and showed that coastal erosion took place when lake levels rose, and accretion took place when lake levels fell. He witnessed an overall mass balance between offshore erosion and deposition. This Lake Michigan example may well fall within the parameters that Le Cozannet et al. (2016) argue are ideal beaches for using the Bruun model. They state that their results “confirm that low-energy gently sloping beaches with little human impacts and small gradients in longshore drift and sheltered from storms are the most relevant to assess the validity of the Bruun model in the sediment balance equation” (Le Cozannet et al., 2016, p. 12).

1.2 The Bruun Model with Cross-shore and Alongshore Components

The contribution of cross-shore and along-shore sediment gains or losses have been utilised in a modification of the Bruun Rule (e.g. Cowell et al., 1992; 2006):

$$\Delta S = \Delta \xi / \tan(\beta) + f_{\text{cross-shore}} + f_{\text{longshore}} \quad (\text{Eqn 3})$$

where:

- ΔS is the cross-shore shoreline displacement over a given period of time (typically a few decades),
- $\Delta \xi$ is the change of mean sea-level over the same period of time,
- $\tan(\beta)$ is the average slope between the top of the beach and the closure depth, also referred to as active profile or upper shoreface,
- $f_{\text{cross-shore}}$ and $f_{\text{longshore}}$ are the contributions of other processes causing losses or gains of sediments in the active beach profile.

Unfortunately, there is little evidence or data to provide realistic estimates of actual cross-shore and particularly alongshore sediment transport rates in the Waitpinga to Horseshoe Bay region. This issue therefore makes application of this modified Bruun model difficult to apply in the region.

1.3 Robin's Rule

One of the principal problems with the Bruun model is that it does not consider potential changes in the foredune or dune system backing the beach. Davidson-Arnott (2005) cogently argues that as the sea level rises, in cases where the littoral sediment budget is approximately neutral, the sediment prism comprising the upper shoreface (nearshore), beach, and foredune can be expected to migrate landward and upward synchronously with moderate levels of relative sea level rise (RSLR of approximately 5 mm per annum or less), as conceptualised, as conceptualised in his model. This conclusion is substantiated by empirical evidence regarding the rates of sediment transfers within and between those three zones at sandy beach systems in many locations (Aagaard et al., 2004; Hallin et al., 2019; van IJzendoorn et al., 2021; Castelle and Masselink, 2023; de Alegría-Arzaburu et al., 2025), and it is valid for the decadal to century time scale. Thus, the foredune (typically the first or foremost dune formed by aeolian sand deposition in plants at or above the backshore; Hesp, 2002) can translate upwards and landwards with sea level rise. The Bruun model omits consideration of the dune sediment budget or dune changes (Figure 4), and instead of all sediment being transported into the nearshore as the Bruun model indicates (Figure 3), the entire profile translates upwards and landwards with sea level rise.

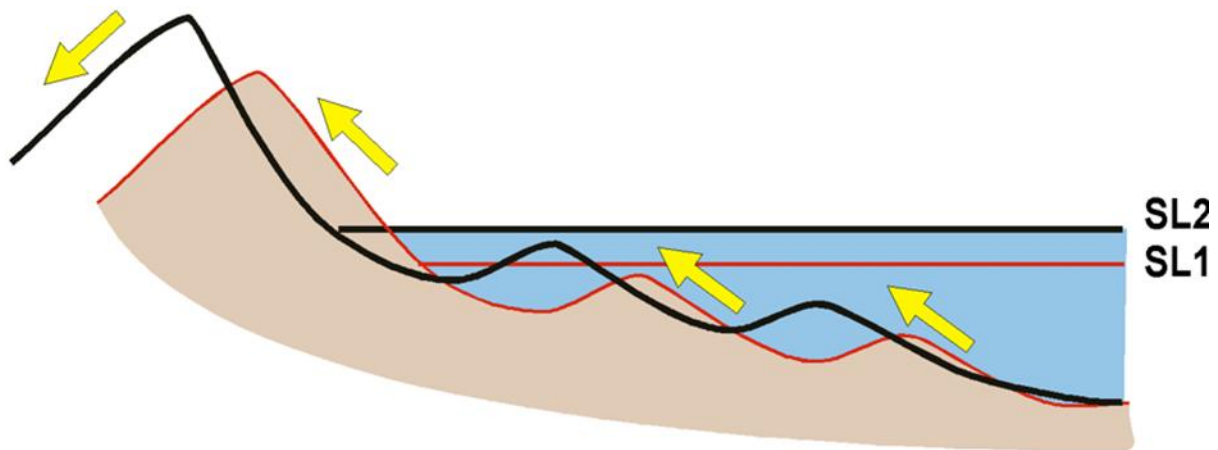


Figure 4. Illustration of the Davidson-Arnott (2005) surfzone-beach and foredune response to sea level rise, or "Robin's Rule" (Source: Robin Davidson-Arnott pers. Comm.).

Several studies of the long term changes to foredunes show that at least for the subaerial portion of the profile, this translation does take place (e.g. Ollerhead et al., 2013; Davidson-Arnott et al., 2018). The dune translation occurs via a series of stages following storm erosion or a sea level rise event (Figure 5): (i) following wave erosion of the foredune, a steep to vertical scarp (essentially a cliff face) is formed. As the scarp dries, slump blocks often fall from the face and are emplaced on the scarp slope or at the base. In addition, drying results in avalanching of the sandy material as the slope adjusts to the angle of repose of the sand (around 30°-33°); (ii) as long as some sand is delivered back to the beach following the storm or sea level rise, sand is blown from the beach up against the scarp, slump blocks and debris fan (avalanche material); (iii) once the scarp is largely filled by an aeolian sand ramp, the wind can then transport sand upslope and it is deposited on and just past the dune crest where wind velocities markedly drop due to flow deceleration (flow expansion and separation), and fine sand is transported in suspension further downwind; (iv) the scarp ramp may start to be colonised by vegetation and stabilise until the next event, and/or a new incipient foredune may form at the base of the ramp (Carter et al., 1990).

Note, however, if the beach is in a state of net erosion or retreat and there is very little to no sediment delivered back to the beach following storm erosion, the dunes will not recover and continue to erode and potentially disappear. Salmon Holes/Post Office Rock Beach near Beachport (Figure 6) is an example of such a beach which is in permanent retreat due to net sediment loss following storms and high-water levels (Davidson et al., 2021).

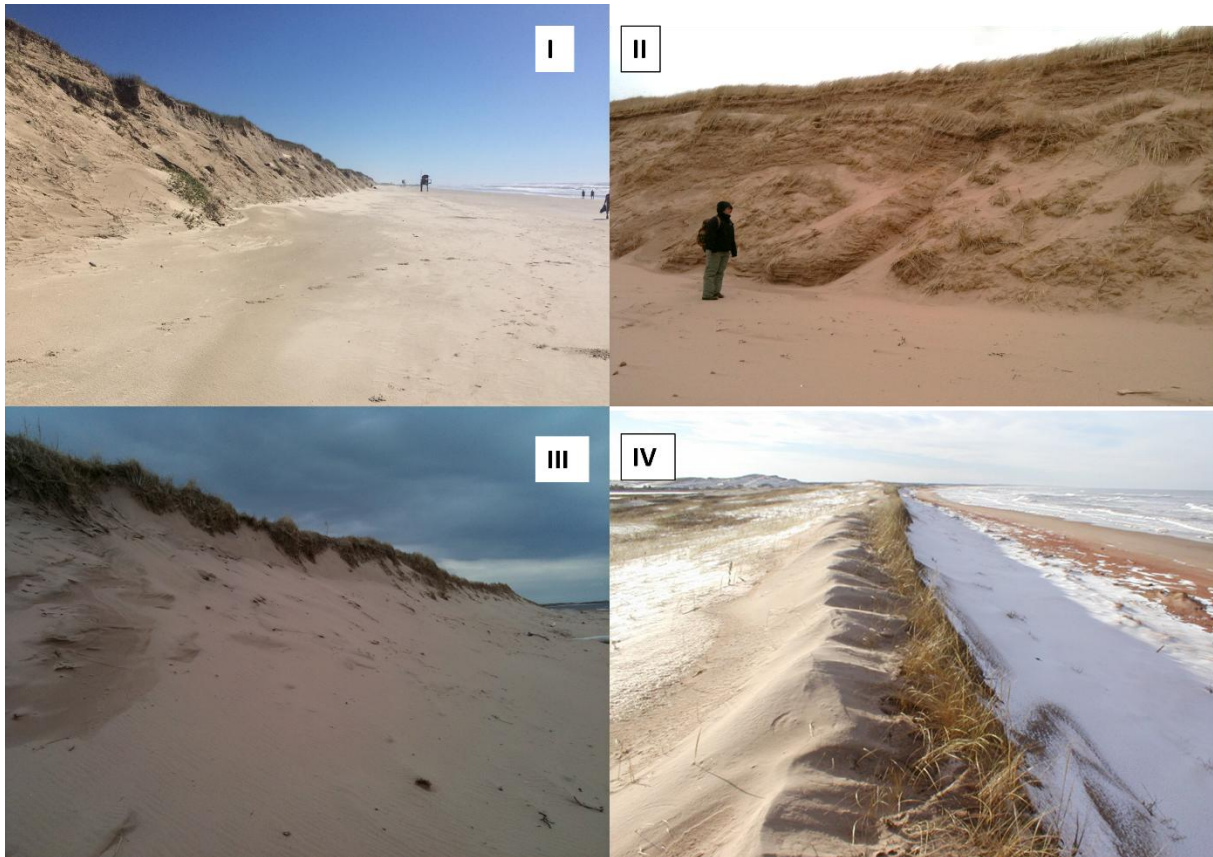


Figure 5. Stages of foredune erosion, recovery and translation. (I) a vertical to steep scarp or cliff is formed during storm wave erosion; (II) slump blocks held by vegetation collapse off the steep face as the sand dries, and dry sand also avalanches down the dune face; (III) once sand is delivered by waves back to the beach in subsequent weeks to months, the wind blows it up the slump/avalanche slope creating a sand ramp; (IV) eventually the wind transports sand up the ramp and over the crest of the dune where it is rapidly deposited. This is the process whereby foredunes and other dune types can translate upwards and landwards due to storm erosion or sea level rise. (P. Hesp photographs).



Figure 6. Salmon Holes/PO Rock near Beachport, South Australia. The dune is in a net erosion state and becoming smaller over time as sand is removed during storms and high-water levels. (P. Hesp photograph).

In addition, there are no empirical studies that provide any evidence world-wide of sediment accumulation on the shoreface related to RSLR and shoreline transgression. This is true especially of transgression associated with the post-glacial rise in sea level. There are numerous empirical studies showing that the Holocene transgression was accompanied on most sandy coasts by the accumulation onshore of large dunefields, including those on coastal barrier systems such as the Sir Richard and Younghusband Peninsula's (Roy et al., 1980; Thom and Roy, 1985; Dillenburg et al., 2020). In some areas onshore transport of sand from the shoreface has led to the creation of ravinement surfaces offshore where sand has been stripped from resistant beds, including bedrock (Davidson-Arnott and Bauer, 2021).

1.4 Non-equilibrium process-based models – SBeach and XBeach

Process-based modelling has been used extensively to model shoreline change during storm events. Two of the most commonly used models are SBEACH and XBeach. XBeach (Roelvink et al., 2009) is an open-source, process-based morphodynamic numerical model originally developed to simulate the impact of extreme storms and hurricanes on sandy barrier island systems (Roelvink et al., 2018, p.103).

The models have been used to estimate shoreline and dune change by simulating a single storm event with a higher sea level which represents some future sea level scenario (for example, 0.5m or 1.0m sea level rise). However, as Shand et al (2013) note, this kind of short-term modelling likely under-predicts the nearshore-beach-dune profile response. Another option is to simulate multiple storms while raising the sea level incrementally after each storm.

1.5 Microtidal Surfzone-Beach Types and Modal Beach Types

Following novel research by Sonu (1973) and Eliot (1974), Short (1979) and Wright and Short (1984) developed the surfzone-beach model for microtidal beaches. In this model, six beach types are identified and range from dissipative to reflective types (Figure 3). Dissipative beaches are typically fine grained, high wave energy, flat to slightly concave beaches where wave energy is principally lost or dissipated by multiple wave breaking across a wide surfzone. Goolwa Beach is in this state regularly although its modal or most common state is multi-bar longshore bar-trough (Figure 7). At the opposite extreme is a reflective beach. Reflective beaches are characterised by narrow surfzones and wave breaking at the base of the beachface. Wave energy is typically low, beaches are narrow and relatively steep and coarser grained. Cusps (scallop-like shapes regularly occurring along the beach face) are common. The beaches are termed reflective because most wave energy is reflected back out to sea off the steep beach face. Port Elliott is a good example of a reflective beach. In between these two states are 4 intermediate beach states which are characterised by some wave dissipation and reflection but also by rips. Rips are discrete seaward-going currents occurring in channels flanked by bars (Figure 7). Waitpinga Beach is an example of a higher energy intermediate beach with significant rips. The original models were developed to show how beaches change over time following storms and calmer periods. After a significant storm, the beach is typically dissipative with sand and bars having been moved offshore to create a profile that is in equilibrium with the storm wave energy. Following the storm, and during a period of low or typical waves, sediment moves back onshore, and the bars move onshore in a standard pattern described by the model. Thus, a dissipative surfzone may eventually become a reflective beach if there is a significant period of low wave energy following the storm as shown by Figure 7.

The model can therefore be utilised to show how a particular beach can change over time with high and low wave energy events. However, it is common for a beach to experience a typical range of wave energy over time. Compare, for example, Goolwa Beach, which is fully exposed to the Southern Ocean and typically (or most

commonly) has a wide dissipative surfzone with multiple bars and troughs and moderate to high energy waves, with the Yilki beach area in Victor Harbor which is sheltered from direct wave approach, has a complex seagrass/sand/reef nearshore system, and displays a low wave energy reflective beach. Thus, we can also define common or modal beach types (Figure 8). Goolwa is a modal multiple longshore bar trough surfzone-beach system, while Yilki is a modal reflective beach (Figure 7).

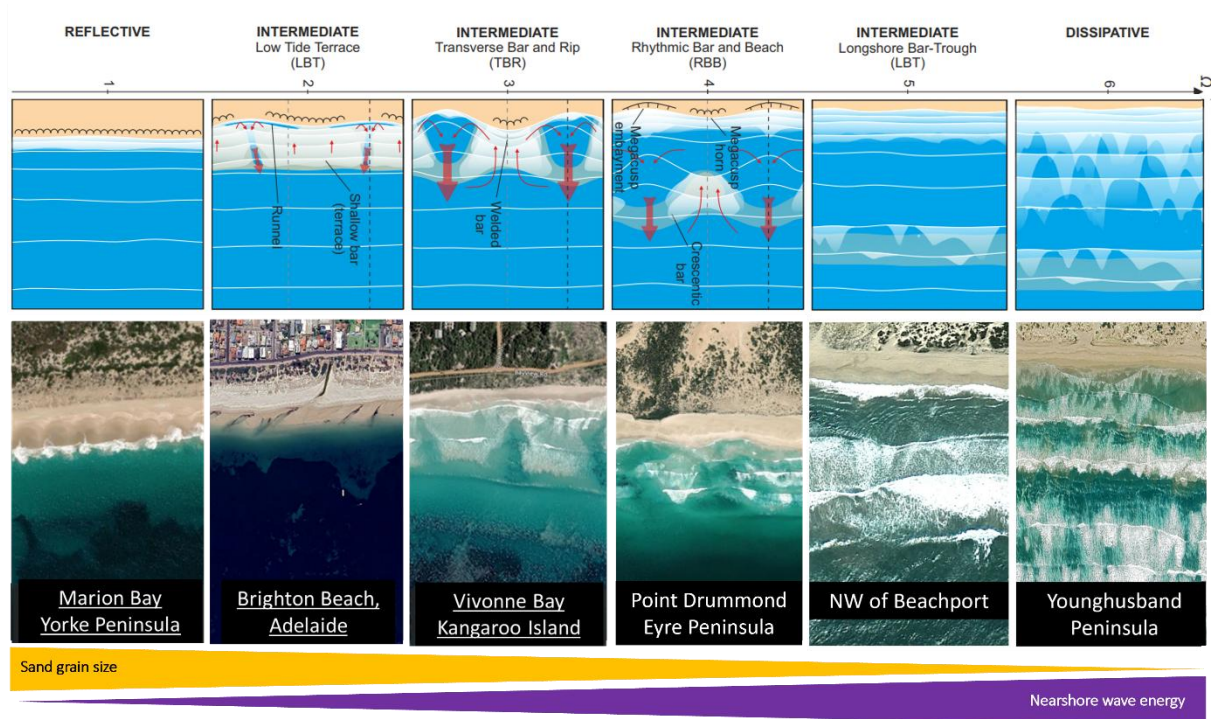


Figure 7. The microtidal surfzone-beach model as redrawn by Castelle and Masselink (2023) (top panels), then modified by P. Hesp, with examples from SA added in the bottom panels.

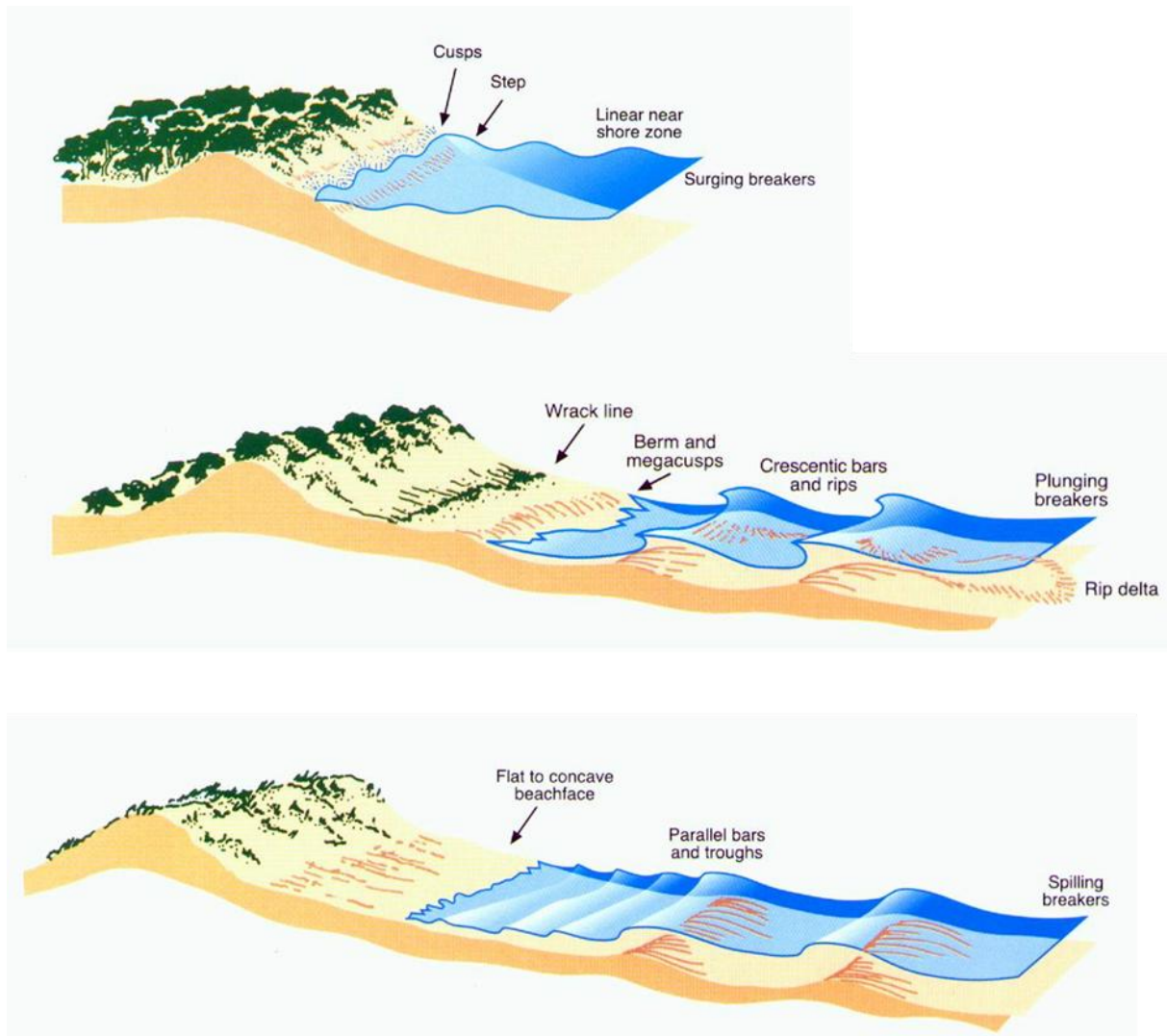


Figure 8. Typical or modal beach types. Reflective beach (top), Intermediate beach (middle), Dissipative beach (bottom). Horseshoe Bay, Waitpinga and Goolwa are typical respectively of each of these surfzone-beach types. (Source: Hesp, 2000).

In the following analyses we have picked three typical modal beaches, Goolwa (dissipative), Waitpinga (intermediate), and Port Elliot (reflective) to examine the effect sea level rise will have on those beaches.

2 Methods

2.1 Robin's Rule

Translation and vertical movement of the entire nearshore-surfzone-beach-dune profile can be estimated via equation 4:

$$R(T) = T (1 / \tan \theta) \Delta S \quad (\text{Eqn 4})$$

where: $R(T)$ = transgression distance (m) for time period T ; T = time interval (years); $\tan \theta$ = average profile slope (defined as the slope of the beach after a major storm); and ΔS = annual rate of RWLR (m a⁻¹). The beach slope defines the trajectory of transgression and its use eliminates the need to define the depth of closure and is independent of complex nearshore topography (Davidson-Arnott and Bauer, 2021).

The method is to take the latest topographic profile of the nearshore-beach-dune system and merely translate it entirely upwards and landwards by a given amount of sea level rise (in this case 1.0 m by 2100). The distance that the profile is translated horizontally is determined by maintaining the distance between two topographic points on the original profile in the projected future translated profile (i.e. by maintaining the original slope of the beach-surfzone profile). For example, if the distance between zero m or AHD on the current profile and the foredune toe is, say, 15m, then that distance between those two points is maintained in the translated 2100 profile. The shoreface-beach and dune translation model is illustrated in Figure 4.

2.2 XBeach

2.2.1 Topography and Bathymetry Input Data

Three beach/nearshore profiles, measured annually by the Department of Environment and Water (DEW), were selected to represent the topography of three morphodynamically distinct beaches: Goolwa (dissipative surfzone-beach type), Waitpinga (intermediate [rip dominated] surfzone-beach type), and Port Elliot (reflective beach type) (Table 1 and Figure 7). Beach/dune elevations were measured above Australian Height Datum (AHD).

Profiles were selected based on offshore distance able to capture the depth of closure, and on landward extent to ensure adequate representation of dunefields, avoiding complete dune erosion in the XBeach model domain under extreme storm conditions and a +1 m Sea Level Rise (SLR).

Table 1. Coastal monitoring profiles and grain size data used as input data for the XBeach model.

LOCATION	PROFILE CODE (NATURE MAPS)	SURVEY DATE	GRAIN SIZE (MICRONS)
Goolwa	615009	10/11/2009	210
Port Elliot	615002	09/11/2009	354
Waitpinga	620001	22/07/1981	354

2.2.2 Water Levels

Water level data were obtained from the Victor Harbor tide gauge (Latitude: 35°33'45"S, Longitude: 138°38'07"E), available from the Bureau of Meteorology. The dataset covers a 4-day (93-hour) period during a spring tide.

Water level measurements from Victor Harbor (originally referenced to Lowest Astronomical Tide (LAT)) were adjusted to AHD by adding ~0.73 m to the water level data using the AusCoastVDT Tool.

2.2.3 Wave Data

Wave buoy data from Cape du Couedic (available from the Bureau of Meteorology) were analyzed to extract significant wave height (H_s) and peak period (T_p) during extreme storm events (95% Probability Exceedance), while data from AusWaves (Victor Harbor offshore buoy) were used to represent a typical storm event (75% Probability Exceedance). All events had a duration of 93 hours. Offshore buoy data were used for both Goolwa and Waitpinga, while at Port Elliot, wave conditions were synthetically reduced to account for local sheltering effects.

Typical storm events were characterized by maximum H_s = 3.5m and associated T_p = 12s (Goolwa and Waitpinga), and maximum H_s = 1.6m and associated T_p = 9.5s (Port Elliot). Extreme storm events were characterized by maximum H_s = 5.5m and associated T_p = 12s (Goolwa and Waitpinga), and maximum H_s = 2.5m and associated T_p = 13s (Port Elliot).

2.2.4 Model Setup and Scenarios

The process-based model XBeach (Roelvink et al., 2009) was used in this study. One-dimensional (1D) XBeach models were developed for each of the three beach/nearshore profiles and forced with wave and water level conditions as described in Section 1.1 (Figure 9). The 1D model domains extended from approximately -15 m AHD, seaward of the depth of closure, to the foredune and transgressive dune system (up to +12 m AHD in Waitpinga) or seawall (Port Elliot). The 1D models were run in surfbeat mode with sediment transport enabled, and the seawall in Port Elliot was represented by a non-erodible layer. There was no fieldwork included in the scope of this project to allow for validation/calibration of the models. To assess the potential influence of SLR and extreme wave events the following scenarios were tested:

- - Typical storm event
- - Extreme storm event
- - Increase of 0.5m in water levels for both typical and extreme events

- - Increase of 1m in water levels for both typical and extreme events.



Figure 9. Location of beach/nearshore profiles analysed in this study. A) Profile 615009, Goolwa, B) Profile 615002, Port Elliot, C) Profile 620001, Waitpinga (Source: Nature Maps).

3 Results

3.1 *Bruun Modelling of Beach Changes*

Bruun modelling for both Goolwa and Horseshoe Bay has previously been conducted by the senior author of this report (Western et al., 2019a and b), and those results are repeated here.

For a sea level rise of 1.0 metre, depth of closure (d_c) of 13.35 (assumes a significant wave height [H_s] of 1.5m), and beach profile width (W in eqn 1) of 2000m, the Bruun model indicates a shoreline recession at Goolwa of 96.7m by 2100 (Western et al., 2019a).

For a sea level rise of 1.0 metre, a mean significant wave height (H_s) of 0.5m, a closure depth (d_c) of 4.45m and a beach profile width (backshore to depth of closure distance (W)) of 220m, the Bruun model indicates a shoreline recession of 26.3m by 2100 at Horseshoe Bay (Western et al., 2019b).

For a sea level rise of 1.0 metre, a mean significant wave height (H_s) of 1.5m, a closure depth (d_c) of 13.35m and a beach profile width (backshore to depth of closure distance (W)) of 1200m, the Bruun model indicates a shoreline recession of 62m by 2100 at Waitpinga Beach. Due to the fact that the bathymetry is poor in the region, a beach profile width of 1200m may be an underestimate of the distance out to the depth of closure point. Thus, if the distance is increased to 2000m, i.e. similar to Goolwa, the recession is in the order of 103m.

Note that the 'estimates' of closure depth are actually approximate estimates but at least for Goolwa are similar to those estimated by Short and Cowell (2009).

The recession estimate for the Goolwa profile using the Bruun model is similar to the estimate derived by Short and Cowell (2009) using Cowell's 'shoreface translation model' (Cowell et al., 2006). Short and Cowell (2009) estimated that the shoreline-recession probability for a +1.0 m rise in sea level to 2109 was 114 m with a probability of 99%. However, they found that the maximum probable recession with a probability of 1% was 210 m by 2109.

3.2 *Robin's Rule Translation Modelling of Goolwa, Horseshoe and Waitpinga Beaches*

Beach or shoreline recession is estimated via Robin's rule utilising equation 4 above. Table 2 indicates the parameters used to estimate recession using Robin's Rule. The average slope of the beach profile ($\tan \theta$; defined as the slope of the beach after a major storm) was calculated from the DEW topographic profile data. The time used was 75 years (taking us to 2100), and two average rates of sea level rise were used, 0.0033 m/year and 0.045 m/year respectively. The lower rate is the average rate in Australia (<https://soe.dcceew.gov.au/climate/environment/sea-level>), and the latter rate is based on the current global sea level rate of rise.

Table 2. Estimates of the shoreline recession using Robin's Rule for the three beaches for two rates of sea level rise. ΔS (m/yr.) refers to the rate of sea level rise per year, T is number of years over which the 1m sea level rise occurs, and R_t is the estimated retreat in metres.

LOCATION	BEACH SLOPE	ΔS (M/YEAR)	T (YEARS)	R_t (M)
Goolwa	1:40	0.0033	75	9.9
	1:40	0.0045	75	13.5
Waitpinga	1:37	0.0033	75	9.16
	1:37	0.0045	75	12.5
Port Elliot/Horseshoe Bay	1:18.7	0.0033	75	4.62
	1:18.7	0.0045	75	6.3

The amount of shoreline recession for each beach depends on the beach slope and the rate of sea level rise. Naturally with an increased rate of sea level rise, the amount of shoreline recession for a given period is greater; for example, there is a ~10 m horizontal recession for a sea level rise of 3.3 cm/year versus 13.5 m retreat for a sl rise of 4.5 cm/year.

3.3 Total Translation of the Goolwa Surfzone-Beach-Dune System

If the entire surfzone-beach-dune system merely translated landwards by a vertical rise of 1m equivalent to a 1m rise in sea level, it is possible to estimate the horizontal distance landwards that the system would translate.

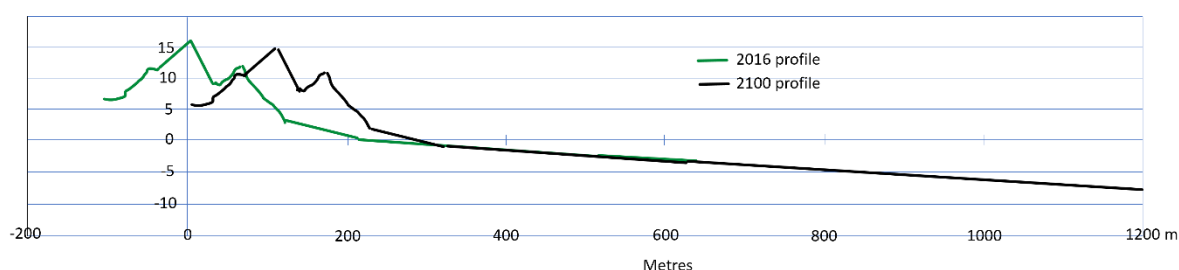


Figure 10. Total translation of the surfzone-beach-dune profile. The black profile is from 2016 DEW data, and the green profile is that 2016 profile translated to a position where sea level is 1m higher by 2100. Source: Hesp analyses in Western et al., 2019a.

The distance that the profile is translated horizontally is determined by maintaining the distance between two topographic points (i.e. the slope of the beach backshore) on the original profile in the projected future translated profile. For example, if the distance between zero m or AHD on the current profile and the foredune toe is, say, 15 m, then that distance between those two points is maintained in the translated 2100 profile.

The figure indicates detail of the Goolwa beach-dune system segment of a topographic profile (CPB 615005) from a 2016 survey which has been used for calculation of likely shoreward translation (Figure 10). The calculations result in a

theoretical shoreward translation of the foredune system at approximately 105 metres by 2100. Note that this assumes there is enough sediment in the system to allow this to occur, and it also assumes that the foredune is maintained as the shoreline retreats and sea level rises (another unknown).

3.4 *XBeach Modelling of Beaches*

3.4.1 Beach and nearshore profile changes

Figure 11 illustrates beach and nearshore profile changes for each model scenario at Goolwa. Under a +1 m sea level rise (SLR) scenario, the foredune is entirely eroded during a typical storm event. In the case of extreme storm events, complete foredune erosion occurs even under a +0.5 m SLR scenario. Surfzone bars form following storm events and are located further onshore under SLR scenarios.

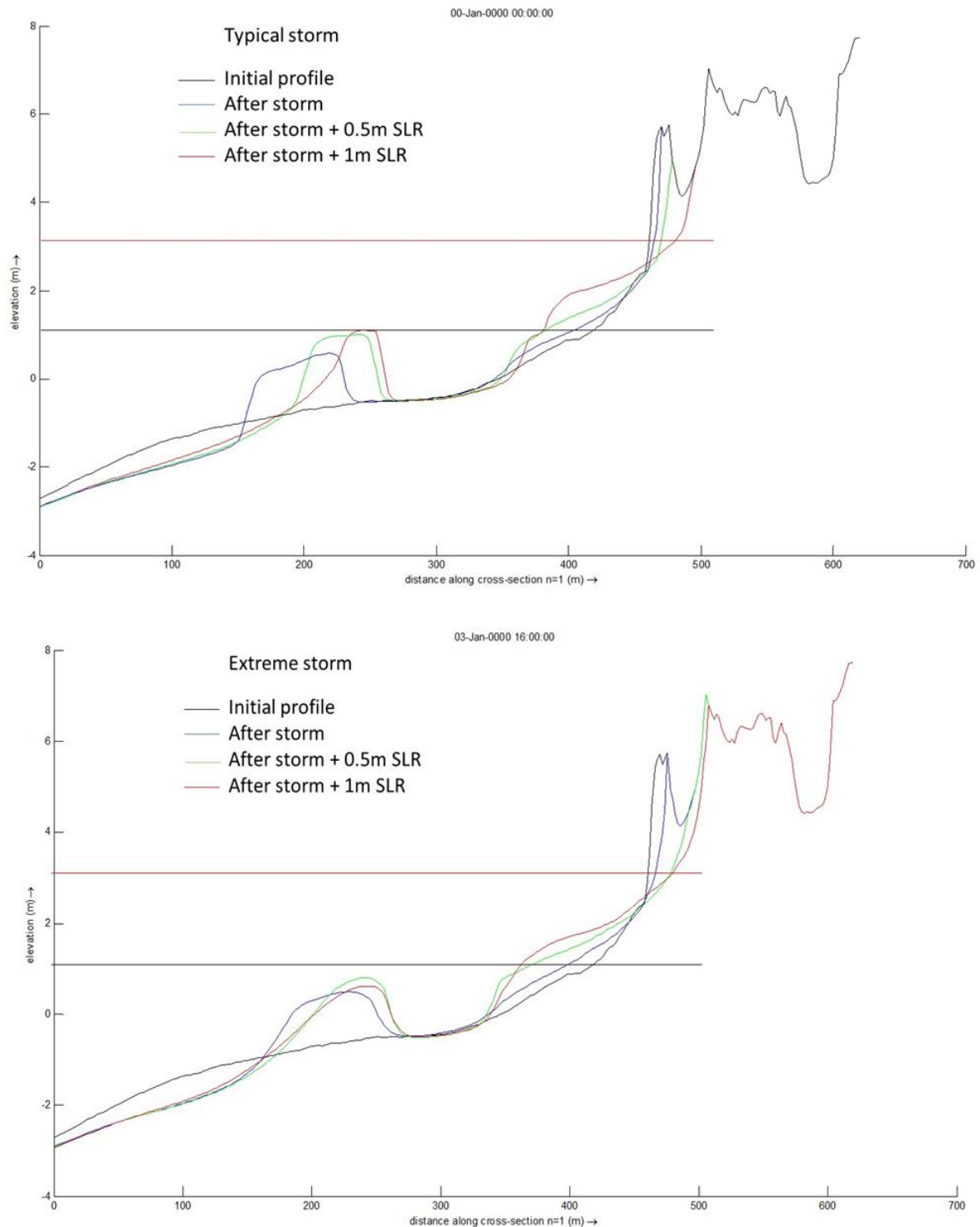


Figure 11. Beach and nearshore profile changes at Goolwa for each model scenario during typical (A) and extreme (B) storm events. Black and red horizontal lines represent minimum and maximum water levels (minimum 1.8m AHD and maximum 3.25m AHD under a +1m SLR scenario [red line]). There is approximately an 87m recession from the initial profile at +1m AHD and the storm plus 1m sea level rise shoreline position.

Figure 12 presents the modelled beach and nearshore profile responses for each scenario at Port Elliot, a site characterized by a seawall-backed shoreline. Scour is

observed at the base of the seawall during both typical and extreme storm events. While vertical accretion occurs within the intertidal zone under SLR scenarios, it remains insufficient to restore pre-storm elevations.

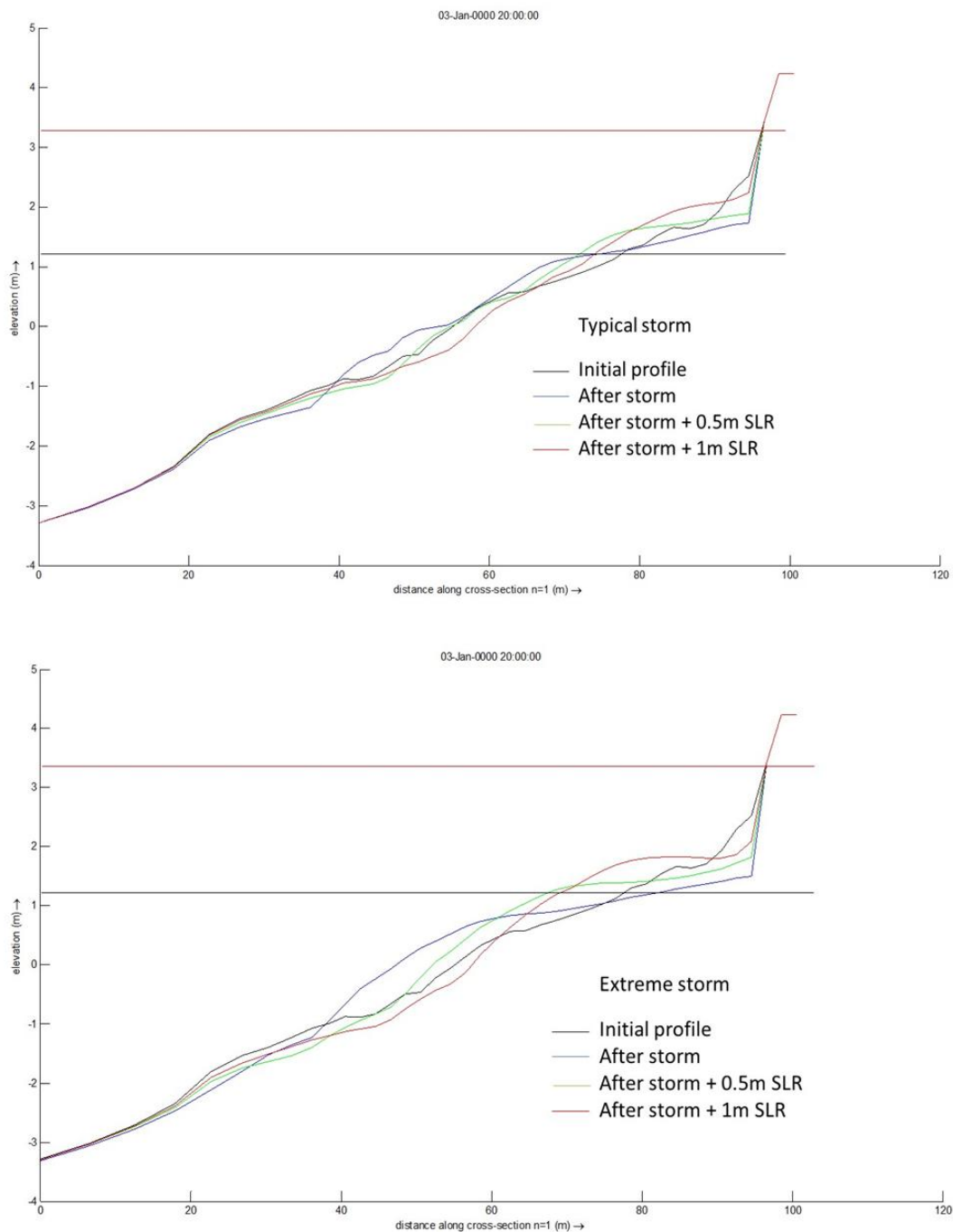


Figure 12. Beach and nearshore profile changes at Port Elliot for each model scenario during typical (A) and extreme (B) storm events. Black and red horizontal lines represent minimum and maximum water levels (minimum 1.8m AHD and maximum 3.25m AHD under a +1m SLR scenario). There is approximately a 30m recession from the initial profile at +1m AHD and the storm plus 1m sea level rise shoreline position.

Figure 13 presents the modelled beach and nearshore profile responses for each scenario at Waitpinga. Near-complete foredune erosion occurs during extreme storm

events and under the +1 m sea level rise (SLR) scenario. In contrast, during typical storm events, a substantial portion of the foredune remains intact, even under the +1 m SLR scenario. Submarine bars develop after storm events and are located further onshore under SLR scenarios.

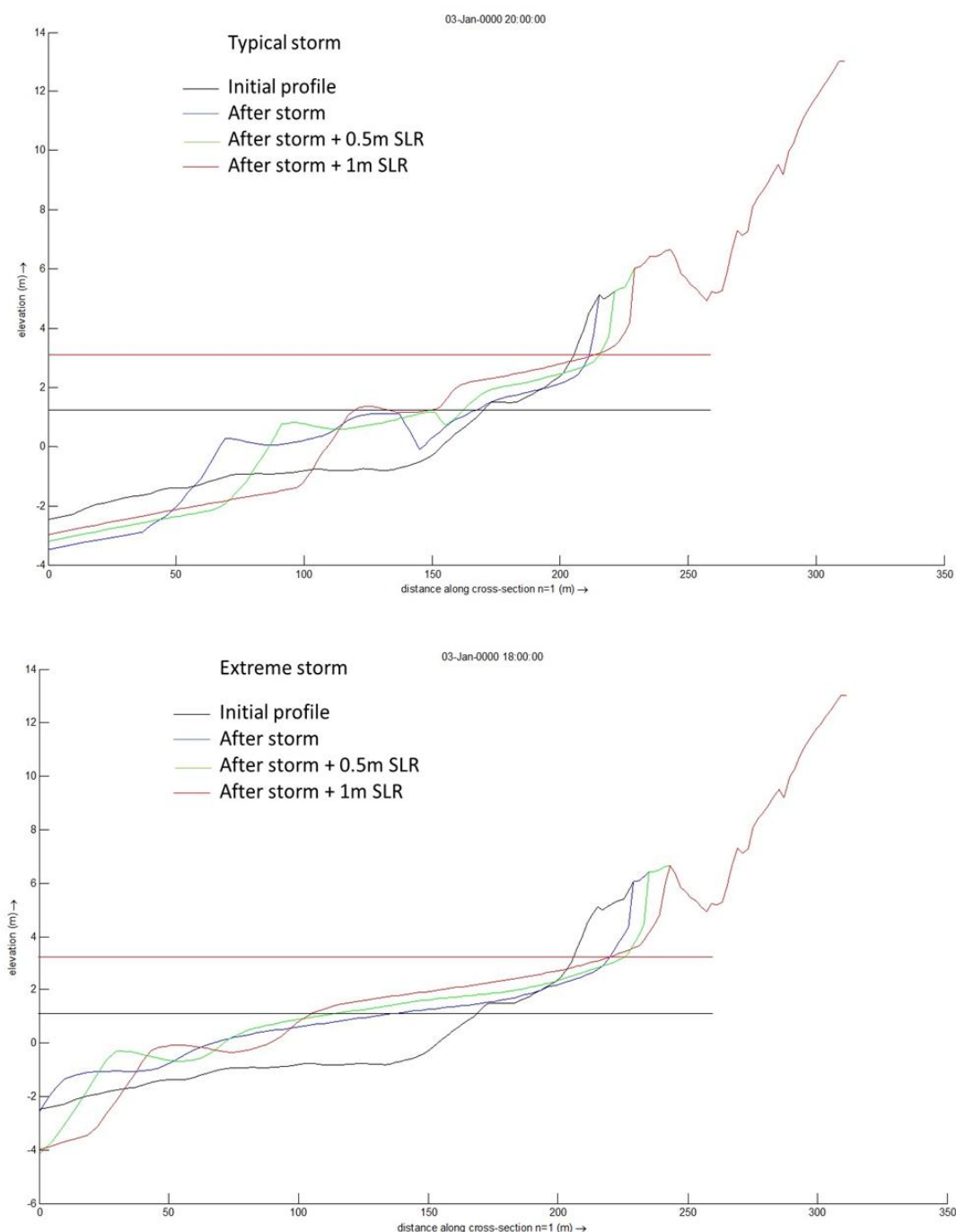


Figure 13. Beach and nearshore profile changes at Waitpinga for each model scenario during typical (A) and extreme (B) storm events. Black and red horizontal lines represent minimum and maximum water levels (minimum 1.8m AHD and maximum 3.25m AHD under a +1m SLR scenario). There is approximately an 85m recession from the initial profile at +1m AHD and the storm plus 1m sea level rise shoreline position.

3.4.2 Volume changes

Table 2 and Figure 14 show the percentage loss/gain of sediment volume for each model scenario, in comparison to the initial profile at each beach. In this study, the dune toe is located at the maximum water level reached during all scenarios (3.25m

AHD) and the sub/intertidal area is between minimum (1.18m AHD) and maximum water levels (or between the black and red horizontal lines in Figures 11 to 13).

At Goolwa (Figure 14A) dune volumes decrease in all cases, especially during extreme storm events combined with higher SLR scenarios. Total foredune erosion is observed under two conditions: a typical storm event combined with a +1 m SLR, or an extreme storm event occurring under a +0.5 m SLR scenario. Sub/Intertidal areas experience sediment gain in all scenarios due to offshore sediment transport from beach and dune erosion and/or onshore migration of nearshore bars. Maximum accretion occurs during a typical storm event under a +1 m sea level rise (SLR), while minimum accretion is observed during a typical storm event under current sea level conditions (Table 3).

Port Elliot (Figure 14B), a reflective beach, exhibits the smallest variation in sediment volume compared to Goolwa and Waitpinga, which are dissipative and intermediate beaches, respectively. The upper backshore area (here referred to as the 'dune') is backed by a seawall and undergoes the greatest sediment volume loss during storm events under current sea level (SL) conditions. Under higher sea level scenarios, water levels reach the base of the seawall (a non-erodible layer). Additionally, the landward shift of the depth of closure under elevated sea levels promotes sediment accumulation in the sub/intertidal zone.

At Waitpinga (Figure 14C), the dune section lacks a marked swale (as opposed to Goolwa) so it gradually loses volume as storm intensity and sea level rise (SLR) increase. The sub/intertidal zone experiences accretion and increases in vertical elevation especially under higher SLR scenarios, as the eroded sediment from the dune is transported offshore.

Table 3. Percentage of changes in sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios.

		Goolwa		Waitpinga		Port Elliot	
		Dune	Sub/Intertidal	Dune	Sub/Intertidal	Dune	Sub/Intertidal
Typical storm	Storm	-5.26273	0.89656122	-5.79106	-0.945898264	-2.30	-12.72565296
	Storm +0.5m SLR	-13.0053	9.924586409	-9.89727	18.15605035	-1.87696	0.728118631
	Storm +1m SLR	-20.6927	27.42967102	-14.0463	37.24905494	-0.83627	11.58614048
Extreme storm	Storm	-9.70483	5.326519006	-18.2966	-0.164709919	-3.02597	-24.07612055
	Storm +0.5m SLR	-20.7322	13.024672	-25.3364	12.39410498	-2.07417	-10.81936069
	Storm +1m SLR	-26.1423	20.89880032	-28.3064	33.62373659	-1.29412	6.388433144

Table 4 and Figure 15 show the total loss/gain of sediment volume for each model scenario, in comparison to the initial profile at each beach. Although Port Elliot shows the smallest absolute change in sediment volume (attributable to its initially limited sediment supply), the relative (percentage) change, particularly in the sub/intertidal zone, is comparable to that of Goolwa and Waitpinga (Figure 15).

Table 4: Total volume changes in sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios.

		Goolwa		Waitpinga		Port Elliot	
		Dune	Sub/Intertidal	Dune	Sub/Intertidal	Dune	Sub/Intertidal
Typical storm	Typical Storm	-20.0445	0.981523112	-19.7637	-0.952064158	-0.78	-5.910610872
	Storm +0.5m SLR	-49.5339	10.86508173	-33.7774	18.27440164	-0.63729	0.338185074
	Storm +1m SLR	-78.8135	30.02902139	-47.9372	37.4918651	-0.28394	5.38134806
Extreme storm	Extreme Storm	-36.9634	5.831282227	-62.4426	-0.16578359	-1.02741	-11.1824973
	Storm +0.5m SLR	-78.964	14.2589444	-86.4682	12.47489668	-0.70424	-5.02520626
	Storm +1m SLR	-99.5696	22.87925806	-96.604	33.8429149	-0.43939	2.967198815

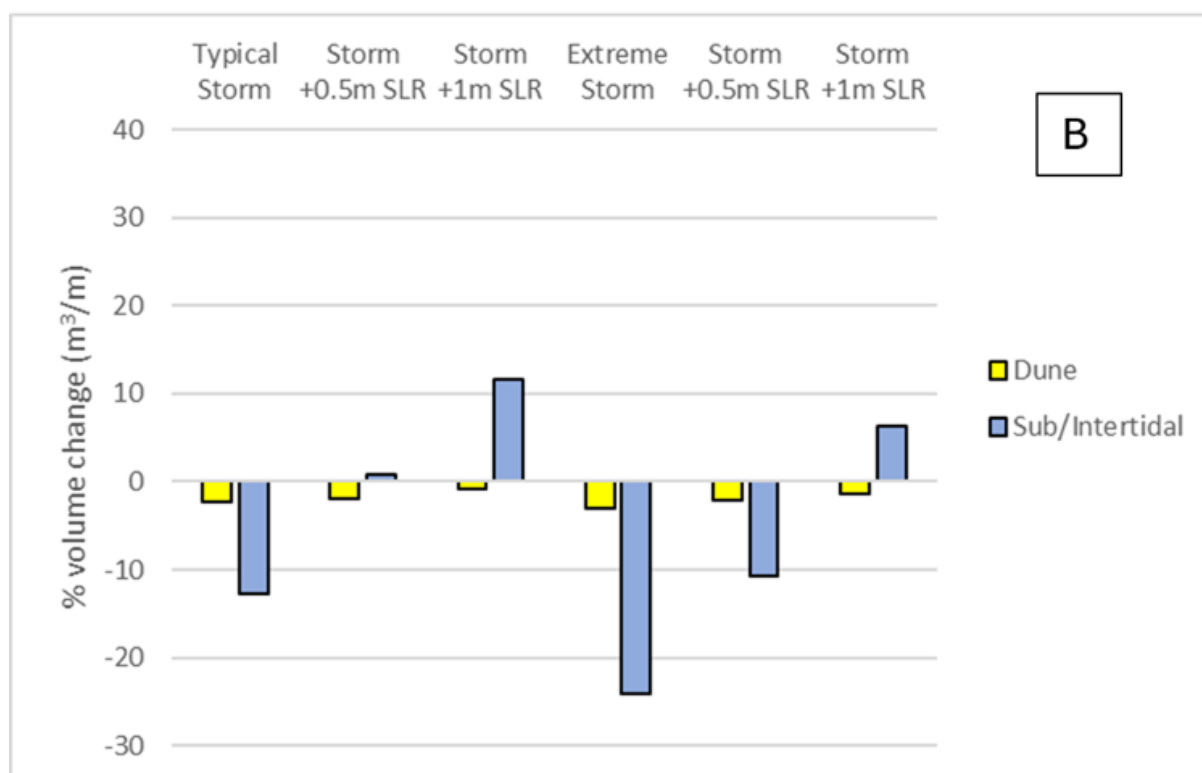
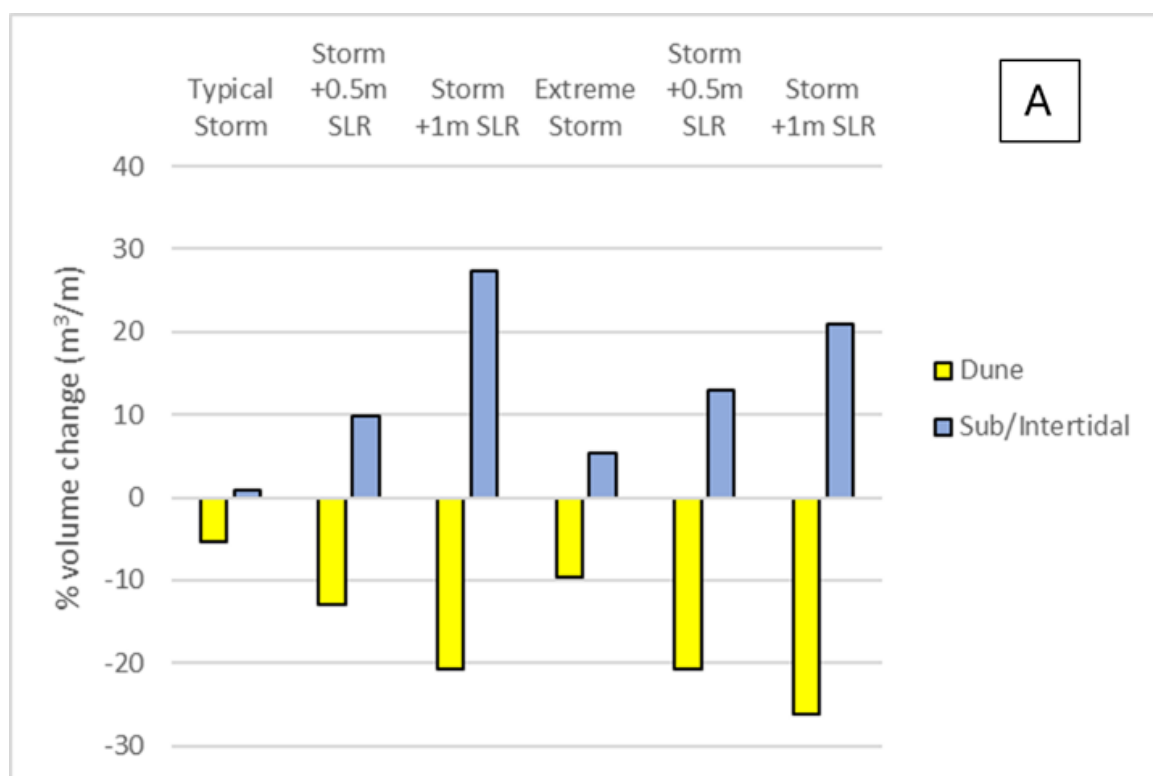


Figure 14. Percentage of changes in sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios, for dune and sub/Intertidal zones at Goolwa beach (A) and Port Elliot (B).

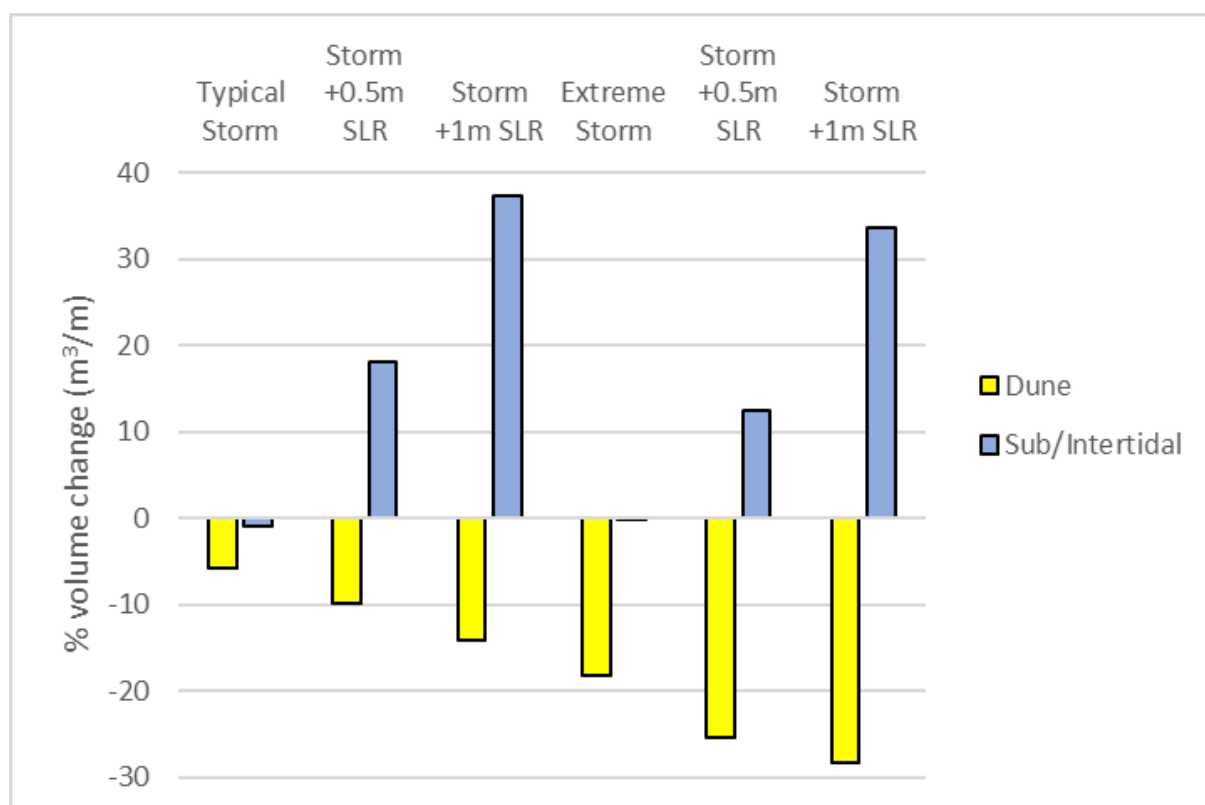


Figure 15. Percentage of changes in sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios, for dune and sub/Intertidal zones at Waitpinga beach.

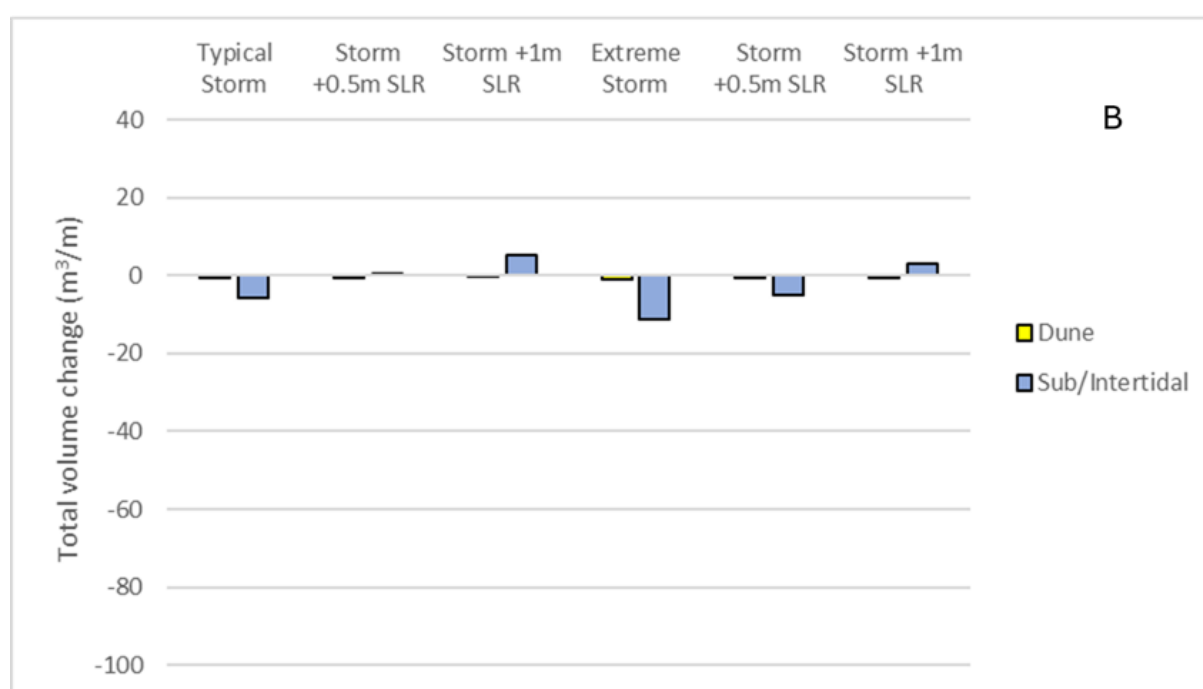
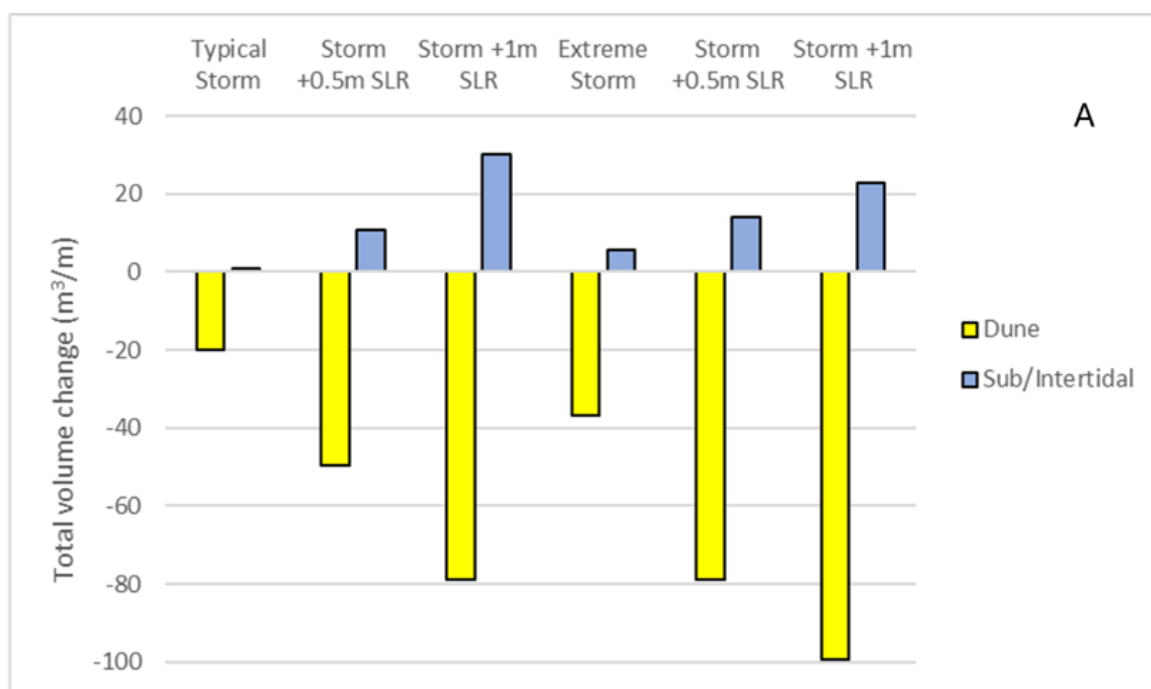


Figure 16. Changes in total sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios, for dune and sub/Intertidal zones at Goolwa (A) and Port Elliot (B) beaches.

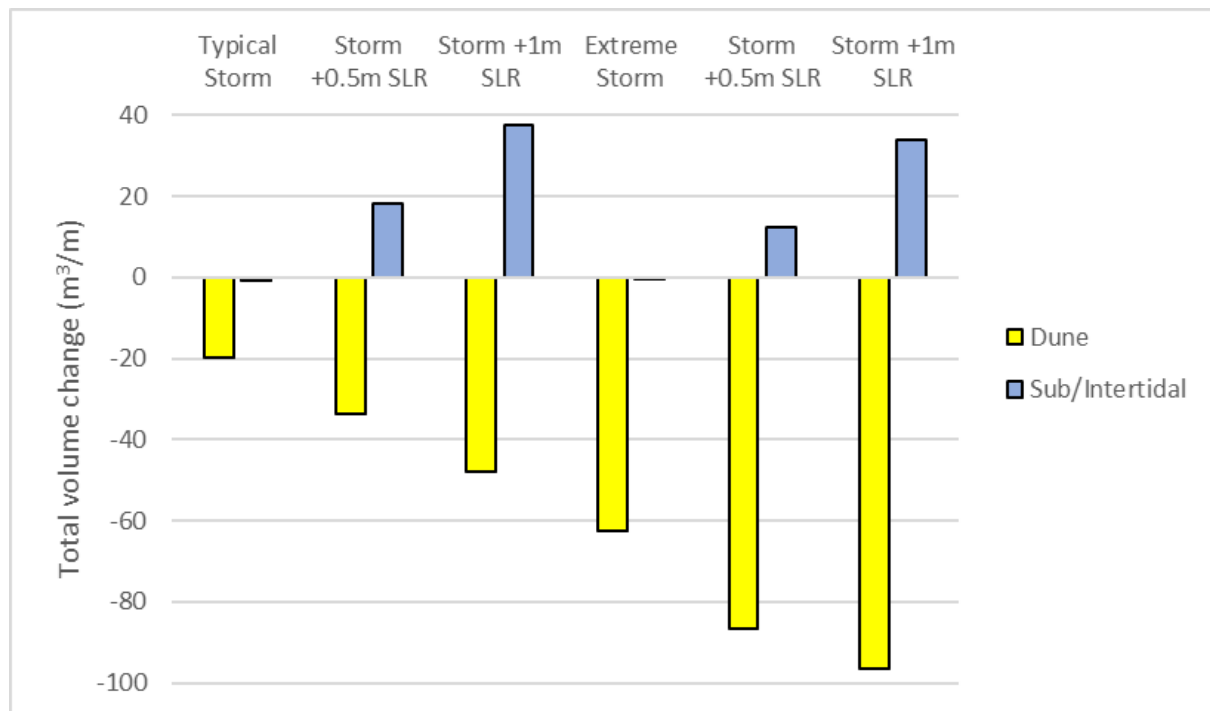


Figure 17. Changes in total sediment volume (compared to a pre-storm/current SL profile) after typical and extreme storm conditions and under +0.5m and +1m SLR scenarios, for dune and sub/Intertidal zones at Waitpinga beach.

3.5 Horseshoe Bay/Port Elliot Shoreline Changes modelled by Wavelength (2024)

Wavelength (2024), in conjunction with Port and Coastal Solutions conducted detailed modelling of shoreline changes due to sea level rise at Horseshoe Bay/Port Elliot. Their work utilised field data and a validated modelling that we could not utilise for Waitpinga and Goolwa, and therefore for comparative purposes did not use for Horseshoe Bay. In their modelling they found that the short term event erosion rate ranged from 8-12m while the long term sea level rise rate ranged from 10-13m. This resulted in a combined erosion rate of 18 to 25m. The erosion or recession rates varied around the bay as expected with the highest rate in the middle of the bay. The maximum recession predicted by Wavelength/Port and Coastal Solutions modelling (25 m) is of the same order of magnitude, although slightly lower, than the combined storm and sea level rise recession predicted

by the XBeach modelling undertaken in this report (30 m). These differences may reflect the use of different beach profiles in the simulations, and the fact that different modelling packages were used (LITPROF & ShoreTrans vs. XBeach). In addition, unlike the Wavelength study, the modelling undertaken in this report could not be field-validated or calibrated due to the absence of field observations. Nonetheless, the 25–30 m range may fall within the probabilistic uncertainty bounds of the respective modelling approaches.

4 Discussion

It is critical to note that none of the methods described above or the results shown account for subsequent collapse and slope adjustment of a vertical scarp following wave erosion. Nor do they account for subsequent reduced foundation capacity landwards of the zone of slope adjustment. Following vertical scarping by waves, sand dunes and most soft coast slopes collapse and slump to a natural angle of response (i.e. a zone of slope adjustment). This angle is typically $\sim 30^\circ$ to 32° for fine to medium sands. When this occurs, the top of the scarp will naturally retreat, so the actual eroded dune crestline will be located several metres landwards of the original scarp crestline determined by the modelling presented here in the XBeach and Bruun models. There is then also a zone landwards of the slumped slope that has lesser bearing capacity (Nielsen et al., 1992). This is known as the zone of reduced foundation capacity. Any buildings that are located in this zone are therefore likely to be in a zone of the reduced bearing capacity of the sand adjacent to the dune erosion escarpment. Structures not piled and located within the zones of slope adjustment and reduced foundation capacity may possibly be subject to foundation failure associated with a subsequent severe storm erosion event (Nielsen et al., 1992).

The modelling does not account for any effects of increased hydraulic pressure on the rear or landward side of a foredune or structure placed at the top of the backshore produced by high water levels and flooding due to high rainfall events. Storms are commonly accompanied by high rainfall events, but even when high rainfall events occur in isolation, significant seawards pressures can be present due to the high groundwater and surface water levels produced. A recent example of this occurred in late August, 2026 when a high, short period rainfall event with rainfall greater than 50mm in less than a day occurred in the Victor Harbor – Goolwa region. The foredune at Ratalang-Bashams Beach was broken through by concentrated overland flow and a deep washout was created (Figure 18). In the same event an old seawall at Port Elliot was partially destroyed by groundwater flow (Figure 19). These events show that groundwater and overland flows need to be carefully considered when creating adaptation plans in addition to adapting to sea level rise. Wherever possible, storm water flows and outlets should be removed from beaches as higher water tables are produced when stormwater exits onto a beach and greater local beach erosion ensues.



Figure 18. Washout created by intense, localised overland flow eroding a gap through the foredune at Ratalang-Bashams Beach in late August, 2026. Person in blue is 1.8m tall for scale. (P. Hesp photograph, 30-08-2026).



Figure 19. The destroyed seawall at Port Elliot on the 30th August, 2026. Groundwater flow pressure blew out a section of the wall and eroded out a significant amount of sand underneath the promenade and potentially the cafe. (P. Hesp photograph).

This study generally compares well with other studies of shoreline erosion related to sea level rise for the beaches studied. Estimates for Goolwa Beach based on the Bruun model by Short and Cowell (2009) using the shoreface translation model of 114m by 2109 roughly correspond to estimates in this report of 97m by 2100 (also in Western et al., 2019a). Estimates for Horseshoe Bay/Port Elliot range from 26m by 2100 (this report) to 5-30 m of recession over 50 years (Caton et al., 2007), to 25m (Wavelength/Port and Coastal Solutions modelling; Wavelength, 2022). These are all of the same order of magnitude, although slightly lower, than the combined storm and sea level rise recession predicted by the XBeach modelling undertaken in this report (30 m). The differences relate to slight differences in input parameters. Robin's Rule estimates clearly vary considerably from the Bruun Model estimates by an order of magnitude.

Adaptation strategies range from hold the line by (i) installation of protection works (e.g. seawalls), or by (ii) occasional to regular sand nourishment of beaches and potentially dunes, (ii) adding to, or building inshore reef structures which reduce wave energy, potentially act to hold sediment in the nearshore, and protect beaches (while potentially increasing marine fauna and recreational opportunities), and, (iii) retreat.

Where retreat is not considered viable for political, publicly unpalatable, or economic reasons, beaches in front of hard protection works will narrow and may be lost. SLR will also reduce the impacts of reef protection, inciting greater wave energy at the shore. There are several examples in the SE region where net recession is ongoing and alternate adaptation plans should be or could be considered. Wyomi Beach, Kingston SE, for example, has been in net recession for several years and a seawall constructed. Multiple nourishments have taken place and the sediment rapidly eroded despite this beach being a low energy environment. The question is: when will retreat be considered?

The longer term strategy recommended is to maintain dunes as long as possible, then facilitate recession through sand nourishment of beaches and foredunes and vegetation maintenance and planting where space allows. At a certain point, retreat may be, or likely will be the only option.



Figure 20. Wyomi Beach, Kingston SE, sea wall and nourishment sand in 06-07-2020. (P. Hesp Photograph).

5 Conclusion

Various analyses of the degree of shoreline recession for three typical modal beaches in the CLLMM region and beyond, namely Goolwa, Waitpinga, and Horseshoe Bay (Port Elliot) have been conducted. Table 5 shows the different results gained from the various analyses conducted and clearly indicates the significantly different outcomes for the beach types and between the methods.

Table 5: A comparison of beach retreat or erosion distances due to 1m sea level rise calculated from each method utilised.

LOCATION	METHOD	BEACH EROSION (M)
Goolwa		
	Bruun Model	96.7
	Robin's Rule	9.9 - 13.5
	XBeach	87
	Short & Cowell	114
	Translation of the entire beach & dune	105
Waitpinga		
	Bruun Model	62
	Robin's Rule	9.16-12.5
	XBeach	85
Horseshoe Bay		
	Bruun Model	26.3
	Robin's Rule	4.6-6.3
	XBeach	30
	LITPROF & ShoreTrans (Wavelength)	25

The results are in part, determined by modal beach type since the gradient or slope of the beach-surfzone-nearshore system influences the outcome as does the wave energy and depth of closure.

The models produce significantly different results. Recession distances at Goolwa, for example, for a sea level rise of 1.0 m by 2100 vary widely from ~97 m (Bruun model),

~87 m (XBeach modelling), to ~12 m (Robin's Rule). This almost represents an order of magnitude difference in degree of shoreline recession between Robin's Rule and the Bruun and XBeach models. This indicates the difficulty that exists when attempting to determine a line that would represent a shoreline created by a future sea level rise of 1 m by ~2100. A conservative approach (the worst case scenario) might adopt the Bruun model estimate; a less conservative approach might adopt the Robin's Rule estimate. Another option might be to adopt a zone, the boundaries of which are determined by the least and greatest recession distances produced by the different methods.

One major issue that remains unresolved is the future rate of sea level rise, and in particular, if the rate will continue to increase in the future. While we are currently sitting on the IPCC AR6 sea level rise "intermediate" projected rate (Figure 2), this could change in the future to a higher rate. As Le Cozannet et al. (2016) state, *"even if the true climate change scenario was known, future sea-level rise would still remain uncertain, in particular because of insufficient knowledge on future ice-sheets melting and the Earth energy imbalance"* (Le Cozannet et al., 2016, p. 3).

The storms of May-June, 2025 have significantly exacerbated problems along parts of the South Australian coast. If beach erosion continues, significant assets are at high risk (e.g. roads and infrastructure along portions of the Victor Harbor coastline, bowling lawns and facilities at Victor Harbor and Horseshoe Bay, roads and access tracks along Bashams-Ratalang Beach). If the modelled estimates of shoreline recession are accurate, then even if the lowest recession rates indicated by Robin's Rule occur (~8-12m horizontal recession) significant assets and infrastructure are at risk. If the highest estimated rates of recession occur, then, for example, the 2100 shoreline will lie exactly at the rear wall of the Goolwa Surf Lifesaving Club (see Western et al., 2019a). As NCCARF (2019) noted in CoastAdapt, there are a variety of options available, including, as noted above, managed retreat and loss acceptance. If we continue to build seawalls to hold the coast in position, we are at significant risk of losing our beaches and therefore significantly losing tourism dollars and amenity, as well as losing ecological values and habitat.

In conclusion, sandy beaches perform critical environmental, social, and economic functions. They provide natural coastal protection, support ecosystems, underpin tourism economies, and accommodate significant infrastructure and development. Inaccurate estimates of beach response to sea level rise may lead to either under-preparation for coastal hazards or unnecessary and costly adaptation measures. Assessing several erosion estimation techniques allows councils to compare outcomes, understand uncertainty ranges, and potentially apply methods that are most appropriate to local coastal conditions and management objectives. Using several techniques also supports risk-informed decision-making by enabling councils to assess both conservative and moderate erosion scenarios for land-use planning, infrastructure protection, hazard zoning, and adaptation strategies.

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