Appendix A Probabilistic Erosion Modelling

A.1 Erosion Processes Overview

All beach sediment systems are in a constant state of flux due to various processes either adding (accretion) or removing (erosion) sand from the beach system. These processes are highly complex and can interact with one another to cause sudden, or long-term continuous changes. While these systems are often 'metastable' (dynamically fluctuating, but returning to an average condition), they can be interrupted by permanent changes in the coastal processes, such as SLR, shifts in wind/wave directions, and any changes to the beach/shoreface system due to human construction and intervention.

A.1.1 Cross-shore transport

As waves approach the shore, they experience a friction effect from the bed. This friction effect reduces the energy of the wave and causes it to shoal up, and eventually to break. The shear stress on the bed can also cause sediments to move if it is strong enough to overcome the consolidation and weight of the sediment grains.

This creates a state that converges towards an 'equilibrium profile'. If the shoreface is shallow enough to experience high enough shear-stresses to mobilise sediments then they will generally be suspended and pushed towards the beach. The theory shows that this profile should form an exponential curve proportional to the sediment grainsize (Dean, 1991). In reality, as the waves also rely on the shoreface profile, the target equilibrium profile will change as the sediment is reworked and the waves change in response. Moreover, as the water level (due to tide) and waves (due to wind) are not constant, the target equilibrium profile will adapt with time.

Additionally, where large waves break nearshore, they can create undertow and rip currents that pull sediment from the beach offshore. During storms with elevated water levels this effect often occurs higher up the shoreface, creating a dune 'scarp'. Sediments are drawn down to a depth beyond which sediment movement is minimal and creates a sand bar.

Many beaches experience a dynamic storm bite and recovery pattern where the nearshore sand bar is reworked back onto the beach in the weeks and months following a storm.

Cross-shore processes can be interrupted by submerged rocky reefs that do not converge towards an equilibrium profile. These features may be buried under normal conditions and become exposed during storms. Offshore breakwaters, artificial reefs and similar structures can result in similar effects, either by design or inadvertently. Seawalls and cliffs can also interrupt cross-shore processes as they limit the range of the shoreline retreat. Furthermore, waves incident on these features can create a scour effect at the toe. These scour effects can cause shoreline retreat to become permanent as the shoreface effectively becomes vertical at this location.

A.1.2 Long-shore transport

Where the waves are incident at an angle to the beach, they can create the effect of pushing sediment along the beach. Often this process is steady, where the loss at one end is offset by a constant inflow from upwind. However, when the prevailing wind/wave direction changes over the long-term it can cause a beach rotation, which presents as accretion at one end of a beach and erosion at the other. In some cases, coastal currents that are not caused by wind-waves can also cause an alongshore movement of sediments.

Longshore processes are often constrained by rocky headlands, a process that can be artificially replicated with structures. The build-up of sediments behind such a feature can result in an accreting beach, or in a convex shoreface due to a surplus of sediments.

River and estuary entrances can also intercept sediments as they move alongshore, starving downdrift beaches from this supply. As these entrances are sometimes dredged to maintain navigability, or scoured out during flooding, this effect can be temporarily increased before these areas become infilled once again.

A.1.3 Other Sediment Source/Sinks

Other processes can increase/decrease the supply of sediment to a beach but are usually considered minor relative to the wave/tide effects. Winds can cause beach sediments to be blown into a large sand-dune system, an effect that aids in the formation of stable sand dunes when these sand particles are trapped within dune vegetation. Rivers can discharge large volumes of sediment during floods, which form sudden pulses of sediment that is then redistributed in the littoral zone by wave and current processes. Organically derived calcium carbonate breakdown (from shells) can create an additional supply from offshore, usually evidenced by a high carbonate content of the sand material. Finally, sediments can also be artificially extracted for sandmining or navigability, which either removes them from the system or moves them within the same sediment compartment.

A.1.4 Sea level rise and recession

Related to the above processes is the changes that can occur in response to permanently rising sea levels. As seas rise, the effective depths of the shoreface and estuarine entrances are increased. This creates an ‘accommodation space’ where sediment is deep enough to not be mobilised by the prevailing waves and currents (also known as depth of closure). As other processes move sediment into these areas, they will become caught and not be available for further transport. In the case of storm demand, some of the sediment that is eroded from the beach and dune system can become caught in the accommodation space and not be available for the recovery processes, effectively causing the shoreline to permanently recede. When the accommodation space is filled in line with the new sea level the recession processes will end and the beach will return to its normal sediment balance. This concept of closure depth or accommodation space is further discussed in Section A.2.1, and how it has been parameterised for the hazard modelling conducted for Kiama.

This process assumes that regular sediment transport events occur, filling the accommodation space at the expense of the adjacent beach and dune. However, beaches with an existing surplus of sediment may experience no such recession at all, or in a localised area the accommodation space may be filled by sediment from outside of that beach system. Similarly, where the wave and current processes are significantly altered along with the SLR, the accommodation space may not eventuate. Finally, the presence of the accommodation space does not instantly result in shoreline recession. Ongoing sediment transport events are required to move the sediments. As such, relatively calm and sheltered areas with minor erosive events will experience a significant lag (possibly decades to centuries) between the ‘creation’ of the accommodation space and the associated recession. This could be especially pronounced for beaches where the active part of the shoreface extends far offshore. In such scenarios many minor storm events may be able to effectively fill the nearshore part of the accommodation space but not have a great enough magnitude to mobilise sediments to deeper areas. In this case, the full extent of the possible recession will not be realised until a sufficiently large storm is encountered.

A.2 Probabilistic Shoreline Erosion/Recession Model

A traditional erosion/recession assessment approach involves developing parameterisations of each process and selecting appropriate values for each input (such as sea-level). This approach is inflexible in that it relies heavily on the selection of these input parameters and does not provide any understanding of the uncertainty associated with them.

To alleviate this limitation, a probabilistic (stochastic) model of the coastal erosion and recession hazard potential of the Kiama open coast has been developed following what is commonly referred to as a *Monte Carlo* approach. A Monte Carlo model uses probability distributions (ranges of values) for each parameter, based on the natural variability of the parameter (known as aleatory variability), or based on the uncertainty of that parameter (known as epistemic uncertainty). Therefore, instead of a single set of values being selected, many thousands of simulations are modelled, each with its own set of inputs randomly sampled from the distributions. The result is many thousands of outputs that form a probability distribution of erosion/recession hazard for the study area. These outputs can be interrogated to determine not just the likely shoreline erosion potential, but also the uncertainty and range of that hazard.

For this study, the set of input distributions was developed based on the literature review underpinning the development of conceptual models of the study area (see Section 2) and refined in a modelling expert workshop. Each distribution has been sampled one-million times (1,000,000), with the same number of outputs interpreted based on the percentage of simulations that exceed their magnitude (as exceedance probabilities). The model has been developed in the MATLAB programming platform (MATLAB, ver. R2020a), which provides a random number generator (RNG) to rapidly select parameters and calculate the associated setback.

A.2.1 SLR Recession and Accommodation Space Parameterisation

The response of the shoreface to SLR has been modelled using the Bruun Rule (Bruun, 1962). The Bruun rule assumes that the shoreface profile rises in line with the sea levels, and will retreat until the volume of set-back is equal to the accommodation volume. This model assumes that all other net inflows of sediment are negligible and that the sediment must come from the beach and dune part of the active profile. It also effectively assumes that the shoreface is well-approximated by a concave Dean-type profile (Dean, 1991).

The Bruun rule relates the ratio of SLR to shoreline retreat as the same as the average beach profile slope between the dune crest and a depth of closure (see Figure A-1). This depth of closure is the depth beyond which cross-shore sediment exchange is zero (or negligible) and will therefore not respond to SLR.

For this study, the SLR has been applied as a normal distribution as described in Appendix B and Section 2.4.1. The beach slopes have been taken from the shoreface profiles have been approximated as ‘calibrated’ Dean profiles (Dean, 1991) of the form:

$$Z(x) = Ax^b$$

Where *x* is the cross-shore distance and *Z(x)* is the depth associated with it. *A* and *b* have been calibrated for at least one cross-shore profile for each beach sub-compartment in the study area, based on the bathymetry observed in the 2018 Marine LiDAR (DPIE, 2018). These cross-shore profiles were taken at several locations through each of the key beaches and are shown (along with the calibrated profiles) in Figure A-2 to Figure A-6.

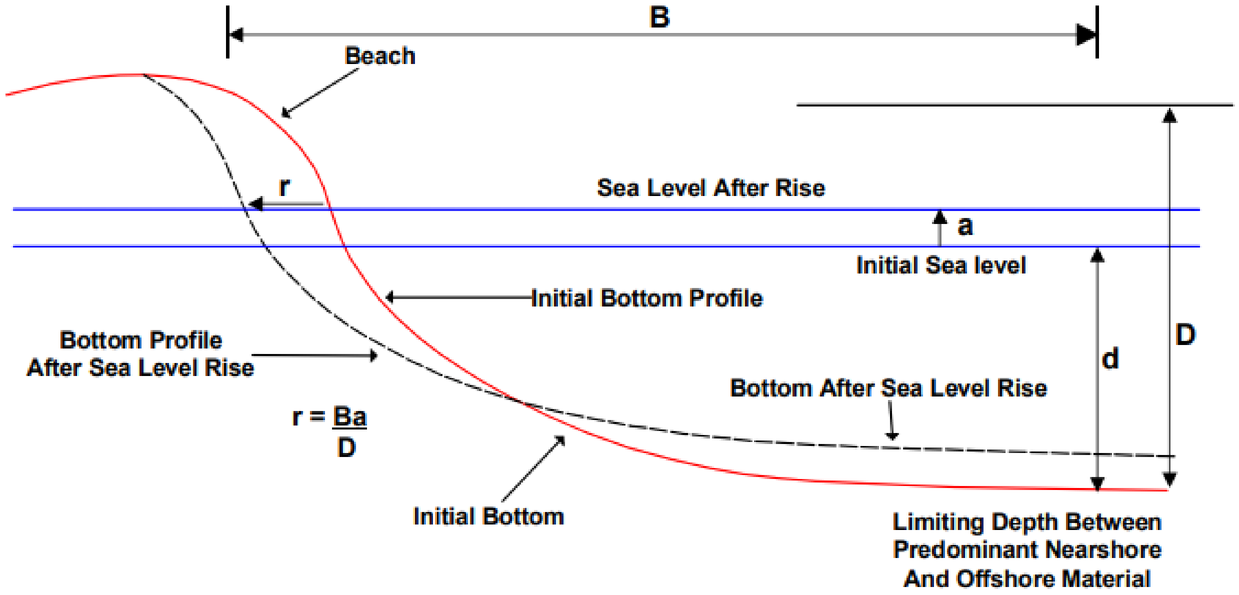


Figure A-1 Bruun Rule for Shoreline Response to Rising Sea Level (from Rollason et al., 2010)

Shoreline recession (r) predicted by the Bruun Rule is given by:

$$r = \frac{Ba}{D}$$

where *a* (meters) is the SLR, *B* (meters) is the width of the bottom influenced by SLR extending to d (meters), where *d* is the depth of closure (or offshore limit to sand transport), and *D* (meters) is the depth to closure including the dune height. Both *B* and *D* can be calculated from the nearshore profile once *d* is known.

The depth of closure has been applied as a triangular distribution with bounds spanning from the Hallermeier littoral zone limit to the outer shoal depths (Hallermeier, 1981) based on the wave record at Port Kembla (to 2020), which results in depths of closure from ~10m to ~30m respectively for beach sand. Hence, the adopted depth of closure triangular distribution was parameterised with a minimum, mode, and maximum of 10m, 20m and 30m respectively. Additionally, for each beach, the distribution has been truncated by applying a minimum depth of closure where analysis of the cross-shore profiles demonstrates existing natural controls on the sediment exchange. Table A-1 outlines the minimum depth of closure values used for each beach based on a representative profile taken in the middle of the beach. Table A-1 also includes the minimum and maximum Bruun Rule slope factor (B/D) at each beach at this same profile.

These values have been truncated by applying a maximum depth of closure where analysis of the cross-shore profiles demonstrates existing natural controls on the sediment exchange. These appear as convex features in the shoreface profile and often coincide with the bounds of rocky substrate that restricts further sediment transport. Examples of such features are shown in the concavity of Kendalls Beach in Figure A-3 between -15 and -20m, or the maximum depths of ~20m seen in the bay off Minnamurra Spit (shown in Figure A-6). More prominently, offshore of Jones Beach (Figure A-5) there are significant rock features that may constrain cross-shore transport beyond the 25-30m contour.

These adjustments reflect a potential limitation of the Bruun model for such constrained sub-compartments. In reality, a ‘perched’ shoreface profile, or concave shoreface feature may have a surplus of sediment in the shoreface that can tolerate SLR without an associated shoreline recession (i.e. the ‘accommodation space’ is already at a stable capacity). However, given that the Kiama open coast is at a relatively low risk of erosion (due to steep topography, and prevalence of offshore rock features and underlying bedrock, it is considered fit-for-purpose to assume a Bruun-type recession effect for planning purposes, without introducing inappropriately high conservativism. For site-specific impact assessments where higher levels of precision are required (or can be achieved as new data may become available in future), this approach should be revisited. Please see Section 5 for further information about the Bruun rule and other limitations involved I within the hazard modelling done for this project.

Several small tidal creeks exist within the study area, which also could potentially serve as an accommodation area with ongoing SLR. However, they have a very small intertidal area relative to the length of adjacent active shorelines, existing in a very steep topography that is relatively insensitive to SLR and appear to be largely infilled under present conditions. They have therefore been discounted as a major contributor of sand interception of future timescales for the purpose of this study.

Table A-1 Depth of Closure (DOC) and Bruun Rule slope factor ranges used for each study beach

Beach	DOC min (m)	Bruun Slope Factor Min	Bruun Slope Factor Mode	Bruun Slope Factor Max
Minnamurra	15	33	38	39
Jones	20	36	48	49
Bombo	15	38	45	46
Surf	12.5	33	38	36
Kendalls	12.5	24	36	28
Easts	10	24	28	25
Werri	25	34	24	52
Walkers *	15	33	51	42
Seven Mile *	25	39	42	81

* ***Please note***. *no photogrammetry information is available for these beaches, but there appears to be no significant erosional trends apparent in any of them (based on available LiDAR data). Carvalho (2018), was used to determine shoreline trends for Seven Mile Beach.*

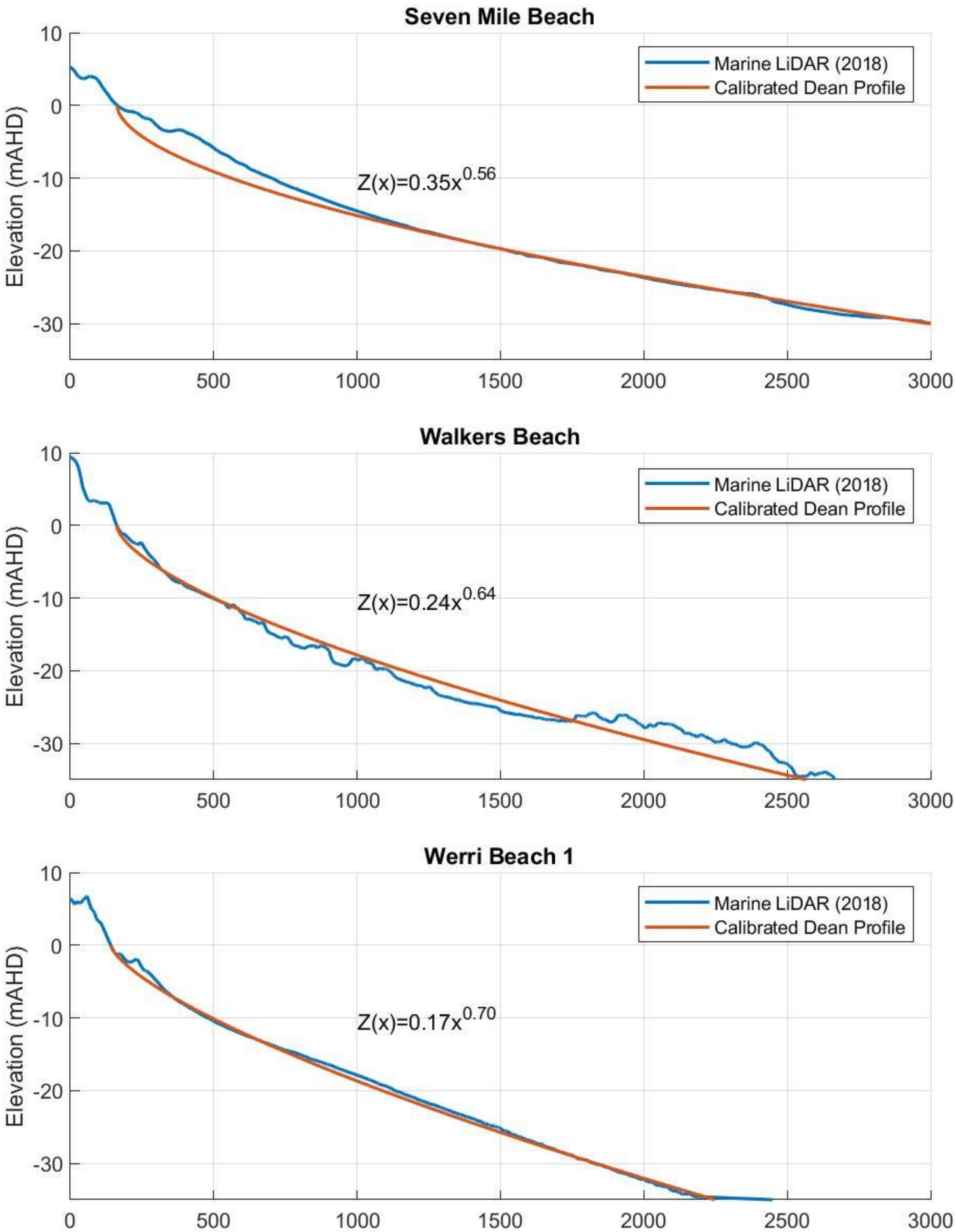


Figure A-2 Calibrated Cross-Shore Profiles for Seven Mile Beach (Top); Walkers Beach (Middle) and Werri Beach South (Bottom)

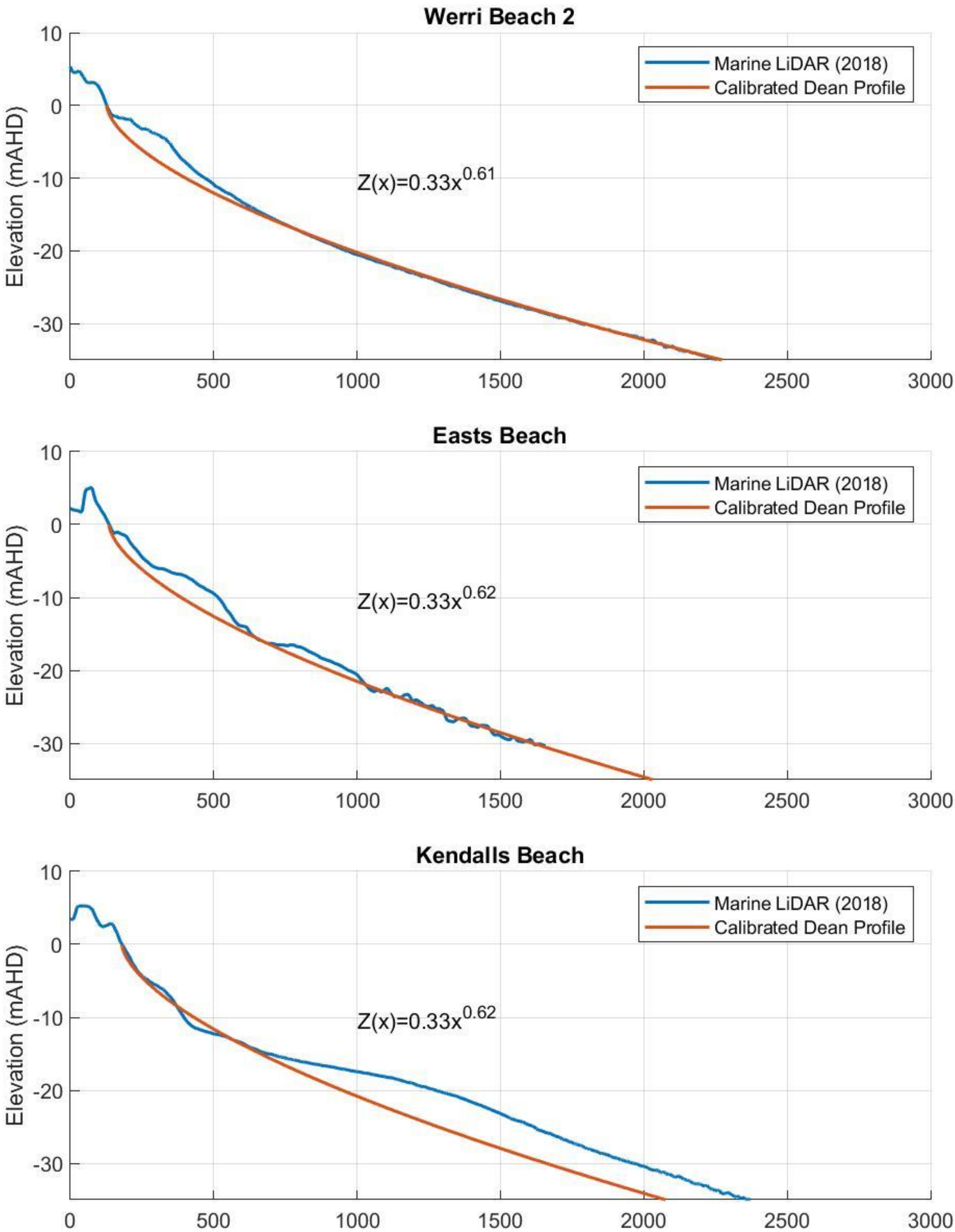


Figure A-3 Calibrated Cross-Shore Profiles for Werri Beach North (Top); Easts Beach (Middle) and Kendalls Beach (Bottom)

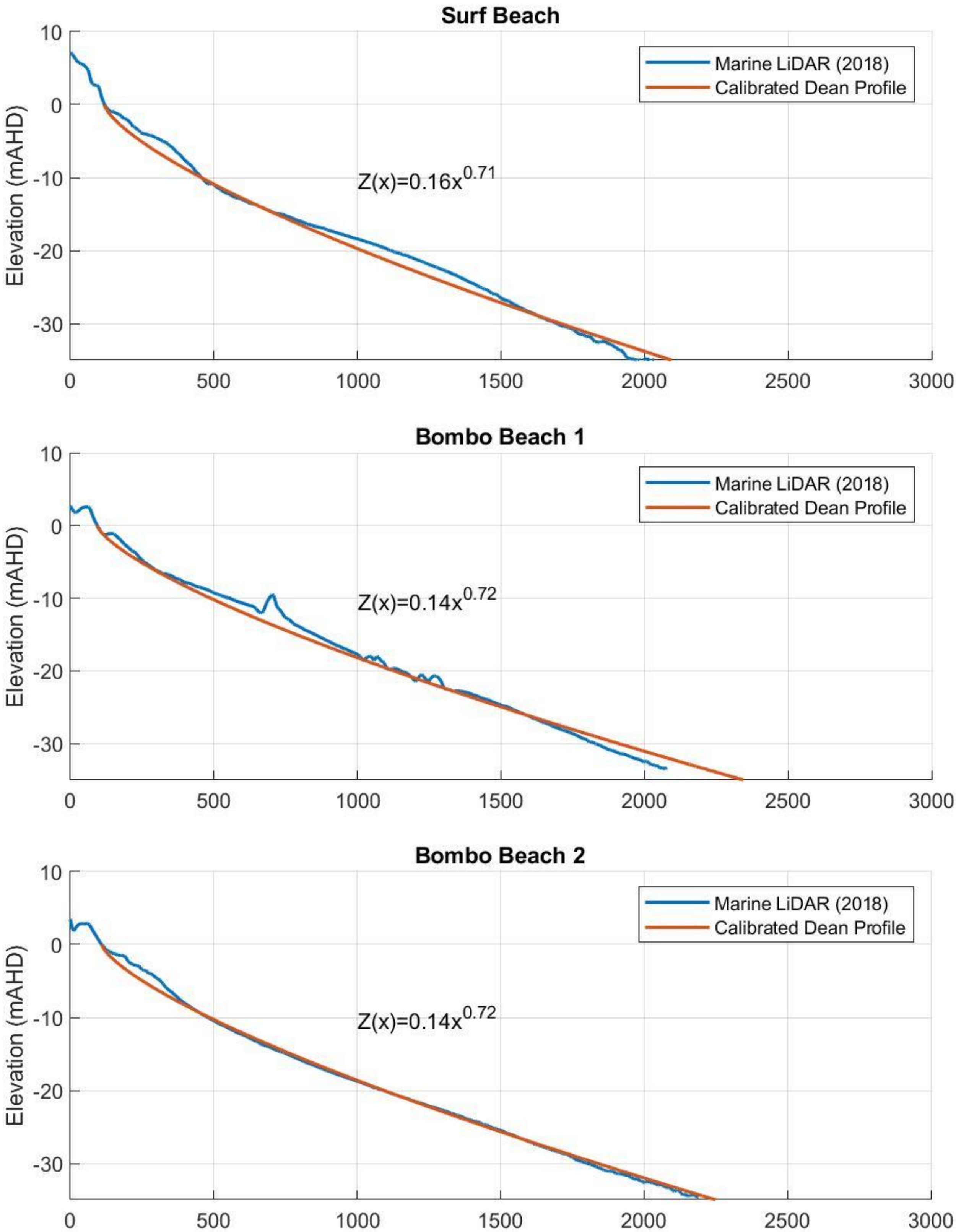


Figure A-4 Calibrated Cross-Shore Profiles for Surf Beach (Top); Bombo Beach South (Middle) and Bombo Beach North (Bottom)

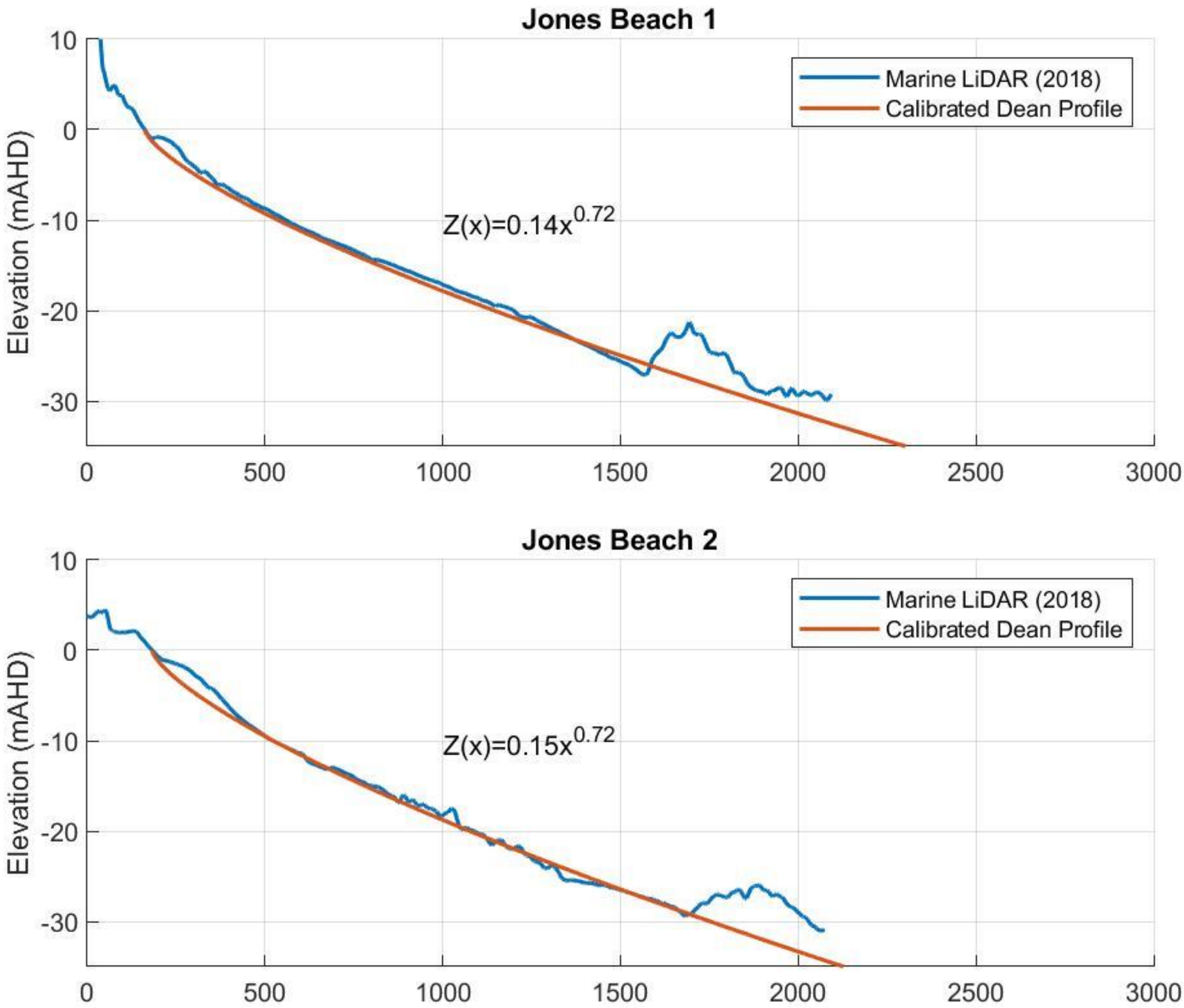


Figure A-5 Calibrated Cross-Shore Profiles for Bombo Beach North (Top); Jones Beach South (Middle) and Jones Beach North (Bottom)

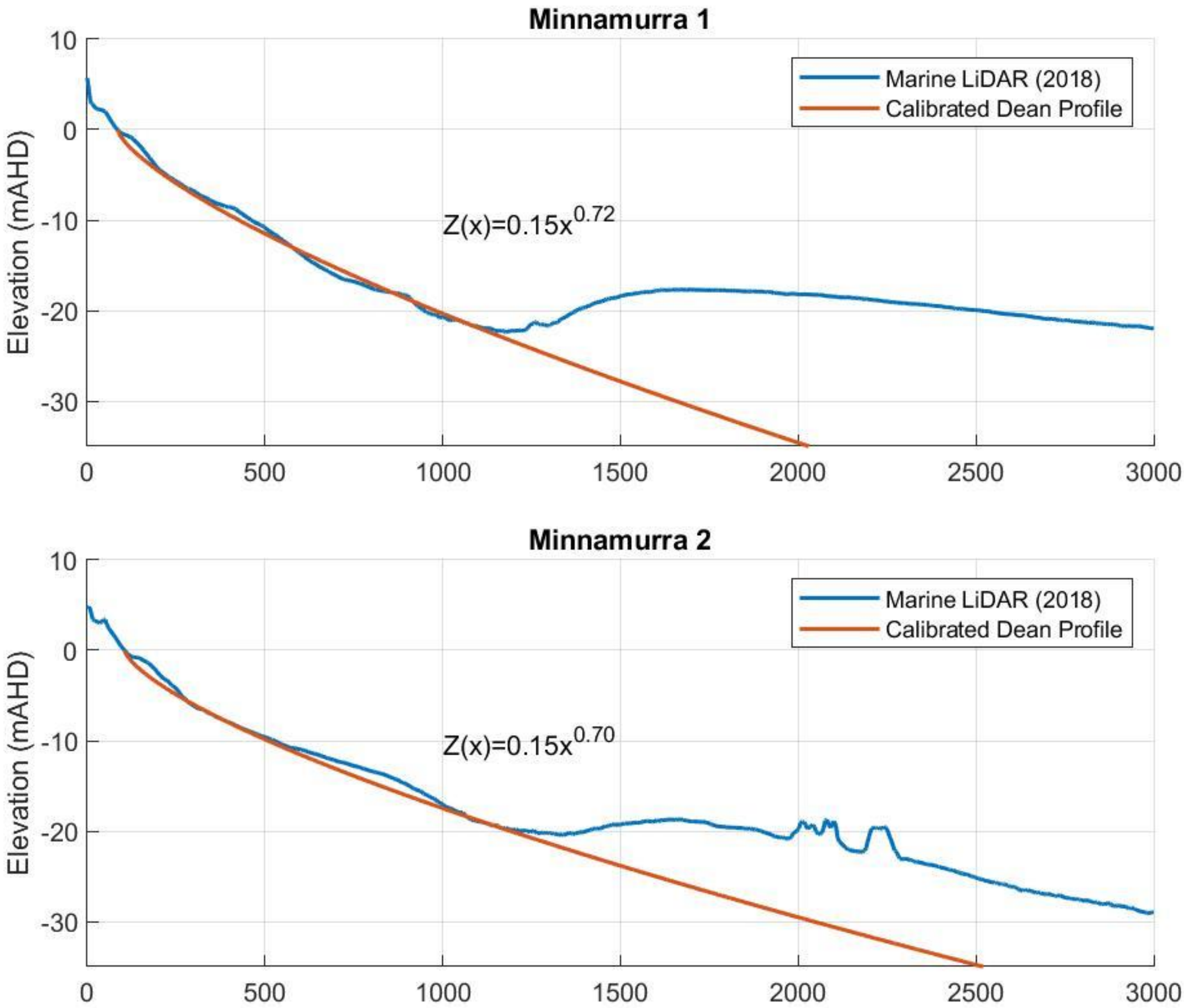


Figure A-6 Calibrated Cross-Shore Profiles for Minnamurra Spit South (Top); and North (Bottom)

A.2.2 Fluctuating Erosion Parameterisation

The 'fluctuating' component of erosion corresponds to the natural short-term changes that largely occur in response to storm events. While such events may be a trigger or instigator of recession corresponding to SLR (by successive events taking more beach sediment into the shoreface accommodation zone), the fluctuating component only represents the volume that is likely to return to the beach after a period of stable conditions. This will usually be due to individual storms but may also include successive storm events that compound one another.

As it is assumed that this component is stable over the long-term, for the purpose of modelling coastal erosion hazard, the only factor of interest is an event that may occur in the final year of the simulated period.

The fluctuating component (i.e. storm demand volume) used in the current modelling of the Kiama coastal environment follows the methods of Kinsela et. al (2017), which used a gamma function derived based on earlier work by Gordon (2015) to define the storm demand for exposed open-coast beaches in NSW. This parameterisation was validated as fit-for-purpose by Kinsela et. al (2017, esp. Appendix B) by comparing the estimates to observations of historical maximum erosion escarpments at exposed beaches.

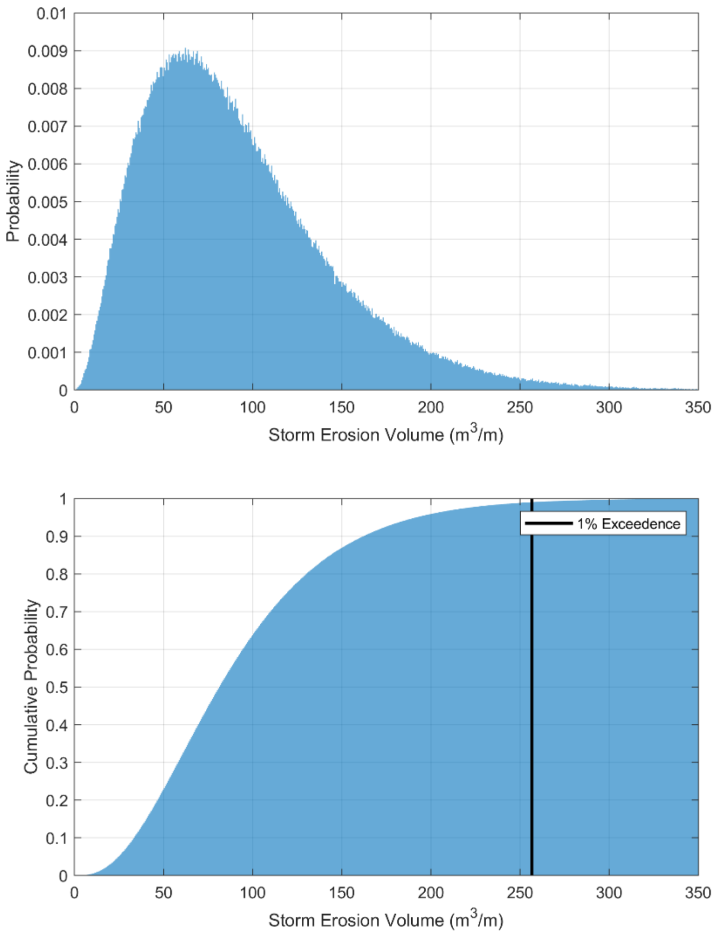


Figure A-7 Storm Demand Gamma Distribution

As not all beaches within the study area are equally exposed to wave energy and the associated erosion hazard, scaling factors for the ‘exposure’ have been applied, which also follows a similar method to work done by Kinsela and others (et al. 2017). These scaling factors have been based on the amount of wave energy that is able to make it to the nearshore areas rather than being dissipated or lost around headlands and shoals. Scaling factors on the fluctuating erosion component have been based on the ratio of significant wave height squared between the offshore and nearshore areas for a series of points along the coastline. This is a simplified approximation of wave energy, but is likely to provide an appropriate scaling factor for more sheltered beaches. This methodology treats offshore wave directions equally (see Appendix C) which may not represent the true exposure of some embayments. Adopted fluctuating erosion scaling factors are presented in Figure A-8.

The storm demand volumes calculated (by the above methodologies, i.e. gamma distribution and scaling factors) have been converted into appropriate erosion setbacks by applying the storm demand (in m^3/m) to beach-normal profiles at 5m spacings along the shoreline as taken from the DEM above 0mAHD. The DEM has been developed based on LiDAR topographic survey data of the onshore areas at 1 m resolution for the Kiama region. This data was collected by NSW Land and Property Information in 2011 or by OEH in 2018 for the marine LiDAR. This methodology allows equal storm demand volumes to result in varied setbacks along a beach where there may be breaks in the dune that would otherwise contain the erosion.

Figure A-8 Fluctuating Erosion Scaling Factors

A.2.3 Cumulative Erosion Parameterisation

Cumulative erosion has been analysed within the Kiama study area by assessing the changes in sediment volumes observed in the photogrammetric data. Where possible this has been conducted by analysing the volume of the foredune which is less prone to short-term 'noise', but for many locations this was only available for assessing the whole beach (or a specific contour), see Table A-3 for site-specific results. The methodology followed Doyle *et. al* (2019), and sought to investigate long-term trends and short-term variations. This methodology used 70 years of aerial photographs (or photogrammetry), and recent LiDAR datasets to assess multi-decadal fluctuations in foredune volumes. This is important, as not only is this timeframe most relevant to management practices, but it is suitable to investigating dune processes (which also typically occur at decadal timeframes). The raw photogrammetric data was acquired from the NSW Beach Profile Database (DPIE, 2020), using aerial photographs taken between 1949 and 2014, and LiDAR data from 2011 and 2018. Horizontal and vertical errors post-1960 imagery are considered to be ±0.5 m and ±0.2 m respectively. For pre-1960 imagery, errors are considered to be generally higher and can range from ±1 to 1.5 m in the horizontal and ±0.5 m in the vertical (due to lack of camera calibration). More specific details of the photogrammetric methods are given in Hanslow *et al.* (1997), or Hanslow (2007).

Table A-2 summarises the beaches included in this study, which were classified in terms of barrier type (classification based on A. Short's NSW Barrier Database, which was derived from field and aerial photo investigations). Table A-2 also summarises the dates of aerial photographs used in photogrammetric analysis (ordered most recent to oldest) as well as the survey dates of the LiDAR data used for each study site.

Table A-2 Key information on each study site included in the photogrammetric analysis.

Beach Name	Barrier Type *	Photogrammetric observations (20- or 19-)	LiDAR Date
Minnamurra	Stationary	'14 93 79 63 50	2018, 2011
Jones	Stationary	'14 05 93 79 71 63	2018, 2011
Bombo	Stationary	'17 14 05 01 96 93 86 79 71 63 49	2018, 2011
Surf	Pocket	'14 05 93 79 74 71 49	2018, 2011
Kendalls	Pocket	'14 05 96 79 71 49	2018, 2011
Easts	Pocket	'14 05 96 79 71 63 49	2018, 2011
Werri	Prograded	'14 05 93 79 71 63	2018, 2011

* *classification based on A. Short's NSW Barrier Database, see Doyle 2019 for more information on sand barriers*

For each of the seven beaches (Table A-2), geomorphic data was extracted to generate sand volume change rate proxies over a decadal timeframe. Due to the highly variable nature of most NSW beach environments (Harley *et al*. 2017), and the complexity and potential bias shown for more commonly used shoreline change proxies (i.e., high water line etc.) (Boak and Turner, 2005), a less variable and more reliable coastal trend indicator, foredune volume, was used to create the sand volume change rates used to analyse long-term shoreline trends along the Kiama coastline (Hanslow, 2007).

In developing the spatially varying coastal trend proxies, the raw elevation data was first interpolated into 3D surfaces from which the proxies were extracted. The native photogrammetric data is a series of point profiles, which were used to make triangulated irregular network (TIN) models for each year there is data, on each study beach (see Table A-2). Similarly, the airborne LiDAR data, were interpolated into a TIN model (following the methods of Doyle and Woodroffe (2018).

Using the TIN surfaces (derived from both the photogrammetry and LiDAR) quantitative parameters were extracted that describe NSW foredune features (e.g., foredune volume, width, crest height, beach volume, width etc.; see Figure A-9 for definitional sketch of these morphometrics). The method to extract morphometric variables from the derived TIN models follows a very similar procedure to that demonstrated in Doyle and Woodroffe, 2018), but reapplied to each year there is elevation data available. A foredune “Area of Interest” (AoI) is outlined for each year, using the TIN and available aerial imagery (Figure A-9, A). Due to the photogrammetric precision, this foredune AoI includes both the established and incipient foredune features. The beach volume was taken from the seaward side of the dune (typically where the vegetation ends) to 0m AHD.

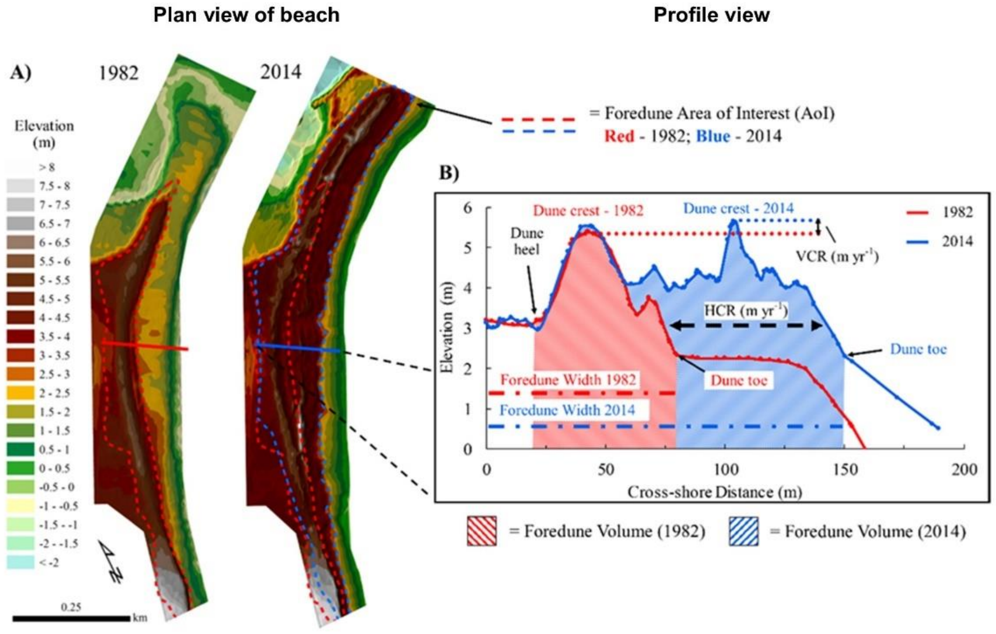


Figure A-9 Example TIN elevation surfaces from Doyle et al, showing the northern end of a NSW Beach (A), as an example of the analysis that follows and representative cross-shore profiles extracted from these surfaces (B). (B) Also shows the foredune parameters extracted from these elevations datasets (from Doyle *et al*., 2019).

Several coastal trend proxies were derived to integrate the main physical processes of sand availability and dune evolution / shoreline change (at a decadal timescale). The foredune volume change rate (FVCR) (m^3 m^{-1} $year^{-1}$) is the rate at which each foredune at a given study site increases in sand volume (accretes/progrades) (positive rate), loses sand volume (recedes) (negative rate), or maintains a similar volume (stable) (zero or close to zero), over time. This rate was calculated from the volume of each foredune AoI digitised (for each year there is topographic data), which extended from the foredune toe (start of incipient foredune) to the foredune heel (topographic low landward of the established foredune crest) and a base height set to 0 m AHD (Australian Height Datum) (see Table A-2, B).

The absolute foredune volume change and overall foredune volume change rate (FVCR) were used to determine the type of evolution the foredune systems have undergone (and hence the shoreline condition); accreting, stable, or receding. Those with a positive FVCR higher than 1.5 m^3 m^{-1} yr^{-1} were deemed accreting systems (gaining sand overtime), while those with a FVCR between 1.5 to −1.5 m^3 m^{-1} yr^{-1} were considered stable (due to the upper error margin of the photogrammetry being ±1.5m) (Hanslow, 2007). Finally, the foredunes that were found to have a FVCR lower than −1.5 m^3 m^{-1} y^{-1} were considered to be receding, because they are beyond the error threshold. Table A-3 presents the results of photogrammetry analysis, particularly highlighting the FVCR and absolute volume change for each beach included in the study.

Figures presenting timeseries of the relevant foredune and beach volume and width changes are shown in Figure A-10 to Figure A-14, and where appropriate both the foredune and beach volumes of the same beach have been presented for comparison.

These figures show that most of the beaches in the study area appear to have accreted or remain meta-stable over the long-term (1960-present). The rates vary between beaches but appear to be of the order of 0-2 m^3/m/year. Bombo shows the greatest accretion, having increased the foredune by 30m over the past 40 years, but with the analysis of the beach area showing a large amount of noise and no consistent trend. Easts, Kendalls Werri and Jones Beaches showed similar trends, with low volumes/widths in the earliest years analysed, before stabilising from the 80s-onwards. Surf Beach shows the clearest information, with significant drops around the 1974 and 2016 events, and a steady accretion between 1975-2015 of ~1 m/year. However the most recent volumes/widths of Surf Beach are not significantly higher than immediately prior to the 1974 events, suggesting a fairly long-term meta-stability process.

Overall the analysis suggests that there is no significant net-erosive effect from these beaches. Rather there may even be a minor accretion processes, though this is hard to distinguish from long-term storm recovery effects. Any accretionary processes is likely to be of the order 30 m in 70 years (40-50cm/year), based on the long-term average changes in the widths. Over a 100-year period this can result in an additional 40-50m buffer if it were maintained consistently.

However, as any accretionary processes is likely to reach a stable maximum, these rates are unlikely to persist indefinitely. Further, as the data may be affected by significant biases (i.e. early data skewed by the some of the largest storm events in NSW records, and interventions such as dune revegetation skewing data in the 1980s-1990s) it cannot be reasonably assumed that these trends are not artifacts of short-medium changes.

As such, for the purpose of modelling it is reasonable and conservative to assume a net zero trend in the data. At worst this may ignore a protective benefit of a net supply of sediment and the erosion hazard extents would be too conservative by a maximum of 50m by 2120. Most conclusively, this assumption is allowing for no net-erosion that would serve to increase hazard extents which appears to be one of the more reasonable conclusions that can be drawn from this dataset.

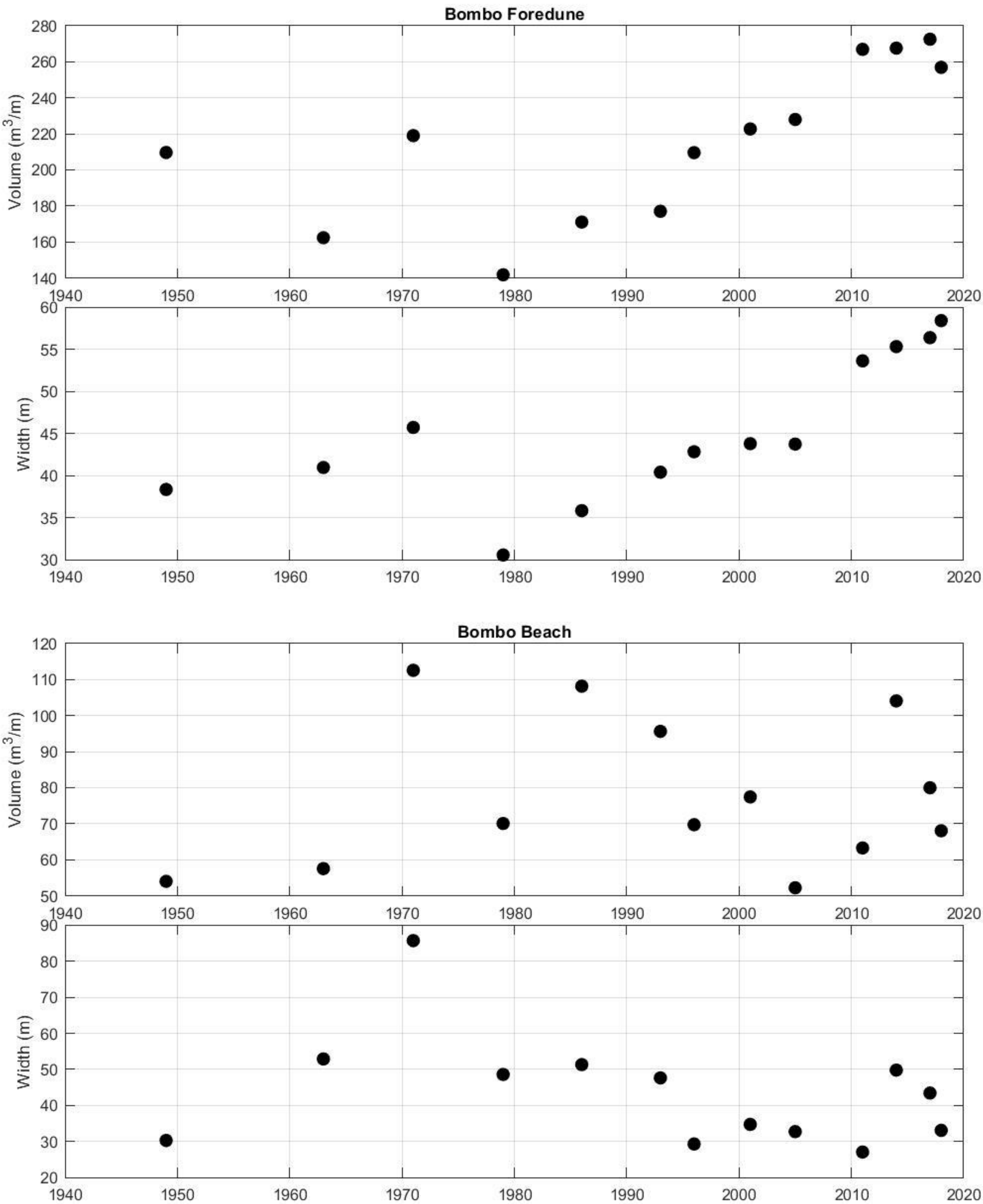


Figure A-10 Bombo Beach Changes for Foredune (Top); and Beach (Bottom)

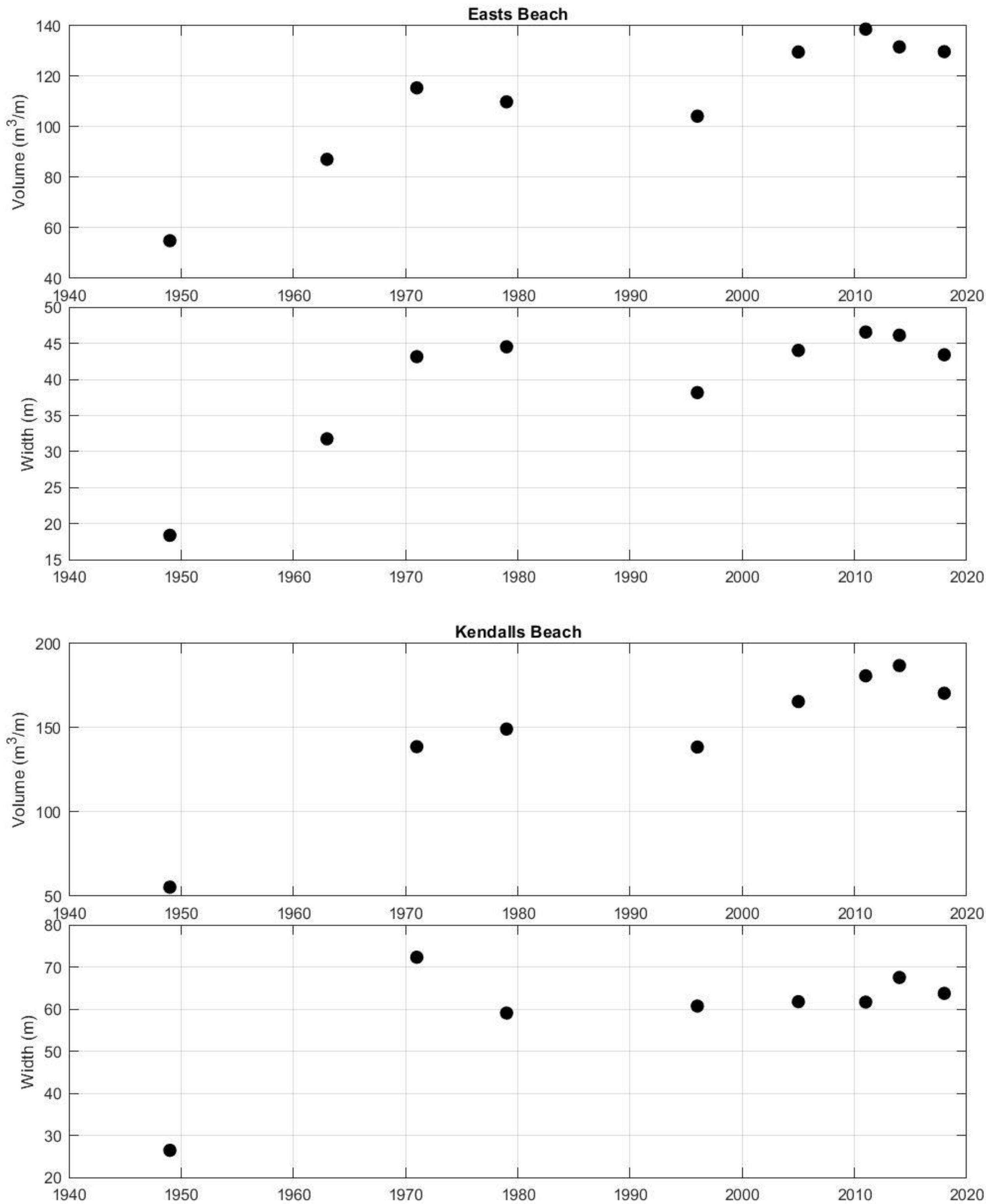


Figure A-11 Beach Changes for Easts Beach (Top): and Kendalls Beach (Bottom)

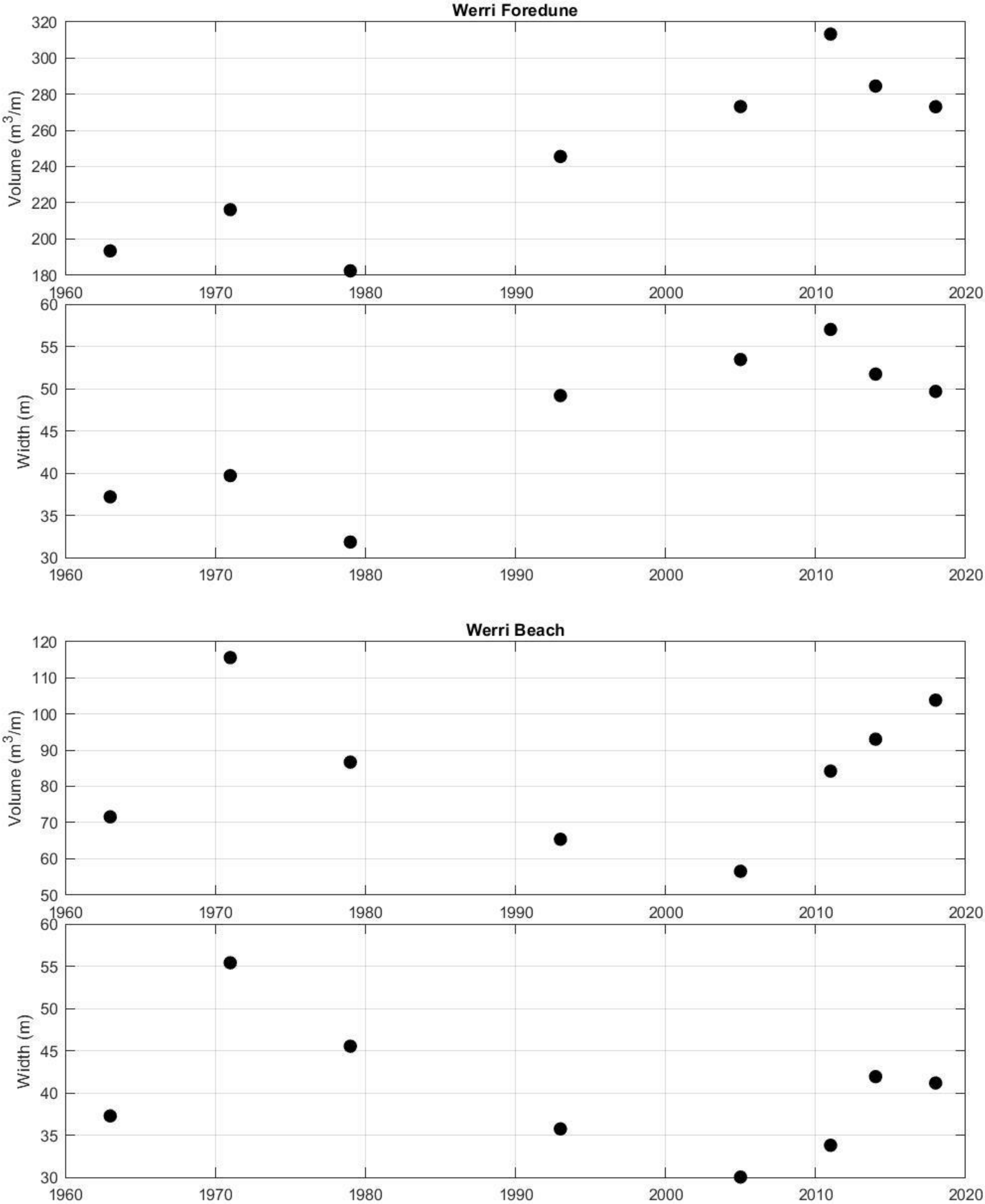


Figure A-12 Werri Beach Changes for Foredune (Top); and Beach (Bottom)

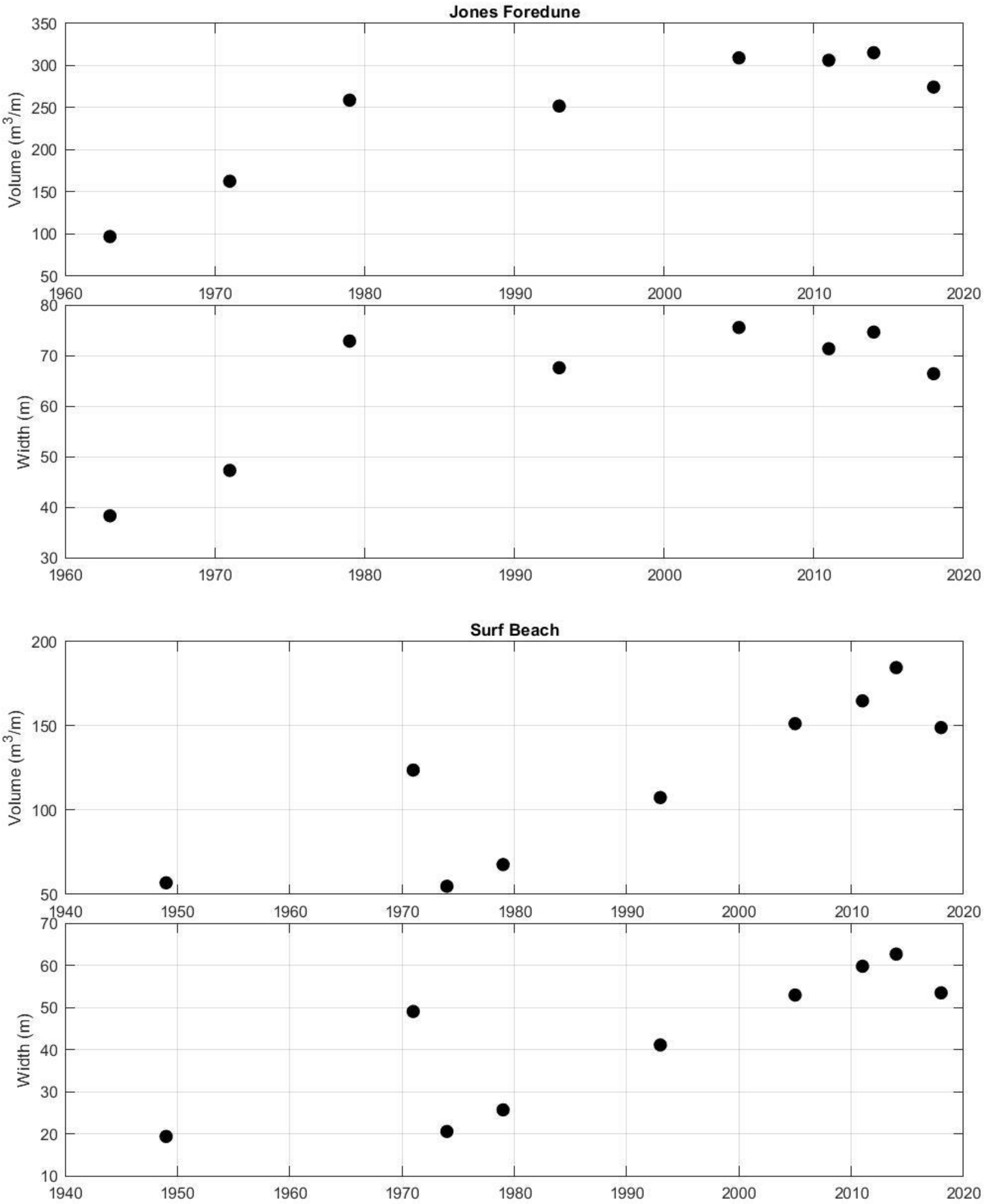


Figure A-13 Changes for Jones Beach Foredune (Top); and Surf Beach (Bottom)

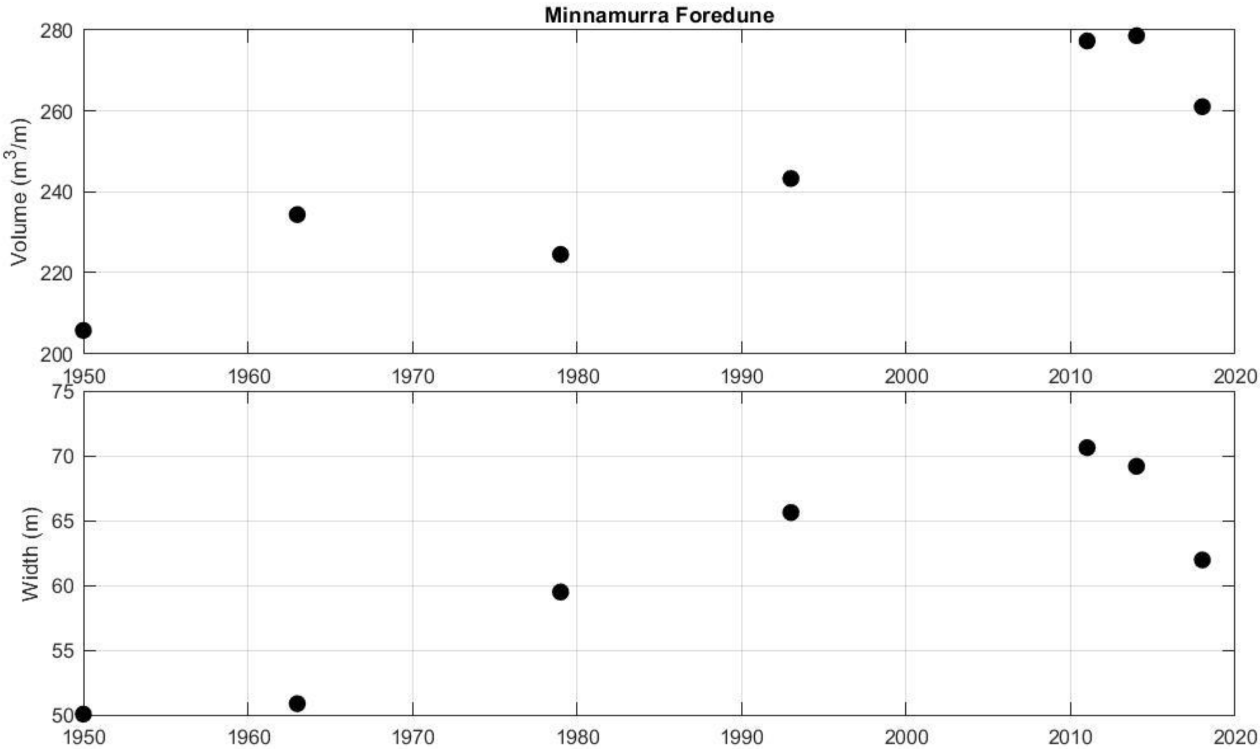


Figure A-14 Foredune Changes for Minnamurra Spit

Table A-3 Shoreline change rates based on NSW photogrammetric analysis

Beach	**Foredune Volume change rate (FVCR)** (m^3 m^{-1} y^{-1})	**Volume change rate (absolute)** (m^3 m^{-1} y^{-1})	**Width change rate** (m y^{-1})	**Elevation change rate** (m y^{-1})
Minnamurra - foredune	0.14	0.81	0.18	0.05
Jones - foredune	2.41	3.23	0.51	0.22
Bombo - foredune	0.55	0.69	0.29	-0.01
Bombo - beach	N/A	0.20	0.04	-0.03
Surf - 1.5m contour	N/A	1.34	0.49	-0.01
Kendalls - 1.5m contour	N/A	1.67	0.02	0.00
Easts - 1.5m contour	N/A	1.09	0.36	0.00
Werri - foredune	-0.05	1.45	0.23	0.01
Werri - beach	N/A	0.59	0.07	0.01

***Note**. Colours represent the different types of shoreline evolution; orange = stable; green = accreting*

A.2.4 Geological Influence on Erosion Hazard

A key driver of uncertainty in erosion hazard analysis is the underlying geological influences. The study area is a complex mix of erodible sands, alluvial deposits, as well as high-level bedrock substrate and exposed rock cliffs. The methodology of the probabilistic erosion hazard model assumes that all topography is readily erodible and generally represents erodible sands. As such, a treatment has been applied to limit the erosion hazard extent where known bedrock deposits will limit the erosion hazard. To do this, a 'likely bedrock' extent has been developed and used to clip the extent of the erosion hazard so as to not extend into this area.

This likely bedrock extent has been developed based expert judgement drawing on quaternary geological information (Roy, 1980), the Marine LiDAR from 2018 (DPIE, 2018) and recent aerial imagery taken from Nearmap. In many cases, clear rock and reef features can be seen in the Marine LiDAR, or the aerial imagery, as well as other hard structures that can limit erosion (e.g. seawalls). Where the topography or geological mapping suggests that bedrock may extend into an area, but the depth to the bedrock is unknown, it has been conservatively assumed that the overlying strata extend down to all depths that are likely to erode.

Additionally, the study area may contain regions of indurated sands (coffee rock), which may limit the erosion over the short-term (i.e. storm erosion) but will likely weather and erode over the longer-term (i.e. with recession). These effects have not been accounted for within the modelling, and all such areas are assumed to erode as readily as beach sand. A more detailed geotechnical investigation is required to identify the locations of such materials.

These assumptions can be updated for site-specific studies by conducting detailed geotechnical investigations including boreholes and ground-penetrating radar (GPR) to determine accurate bedrock extents and depths.

A.2.5 Erosion Hazard Probabilistic Modelling Results

Example exceedance probability curves for a central location at each beach within the study area are presented below. These outputs provide the basis for erosion hazard mapping presented in Appendix F.

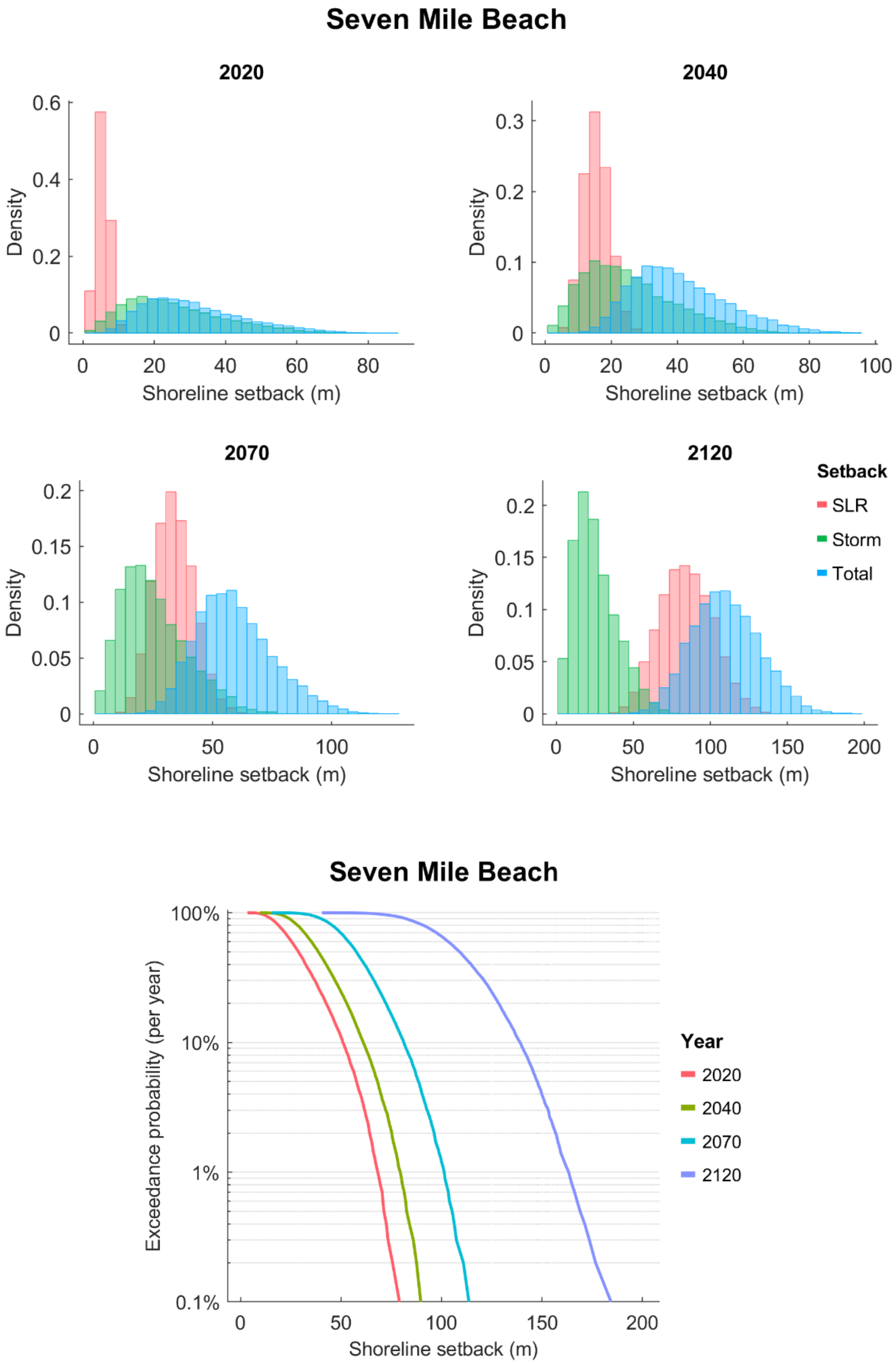
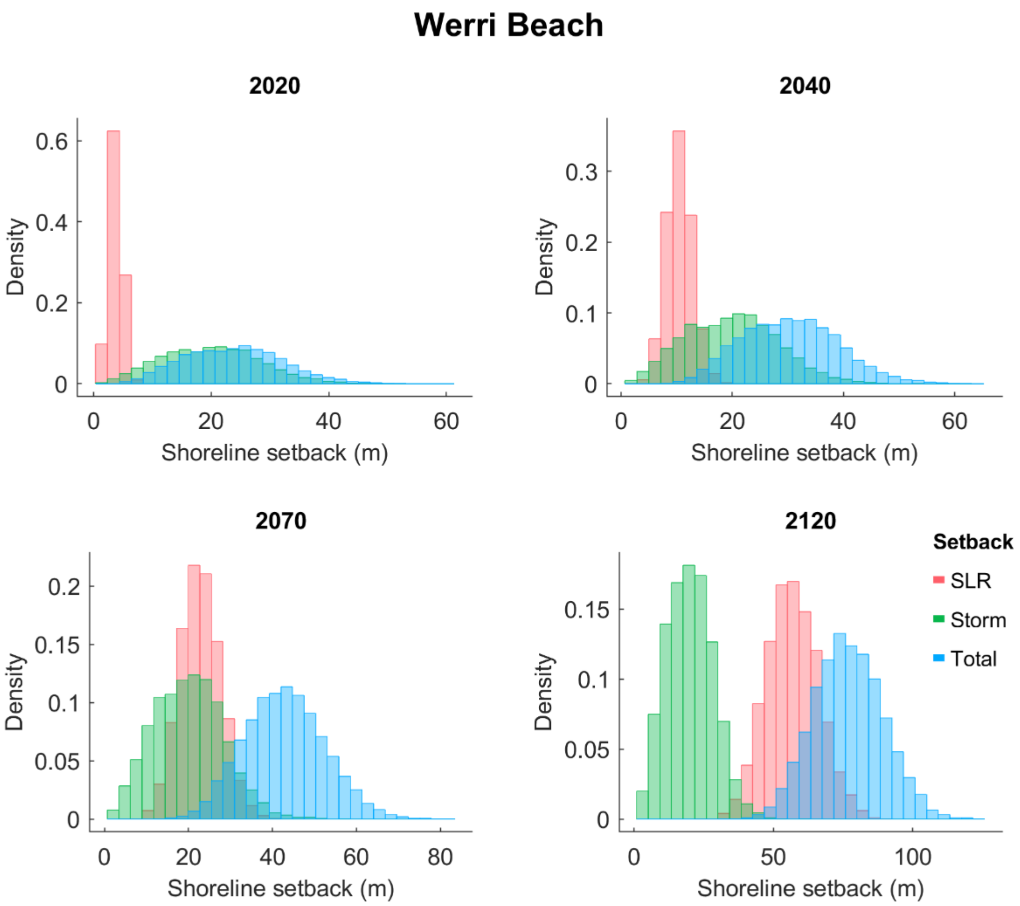


Figure A-15 Erosion Hazard Probabilistic Modelling Results at Seven Mile Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)



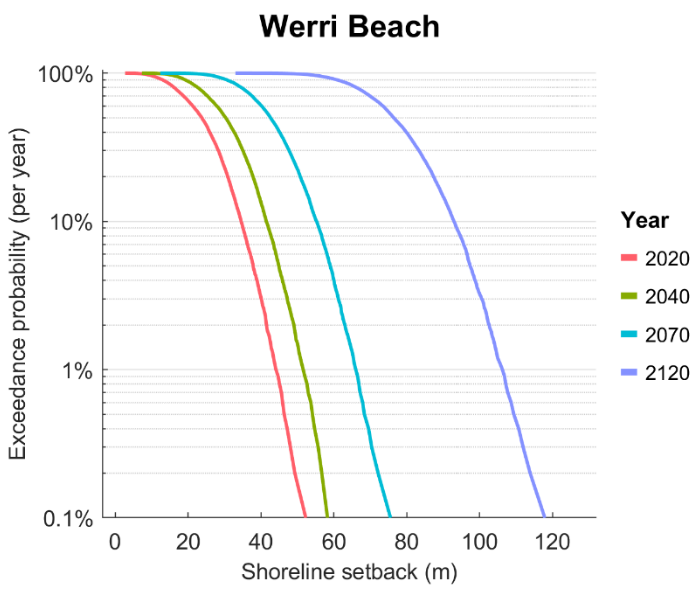


Figure A-16 Erosion Hazard Probabilistic Modelling Results at Werri Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)

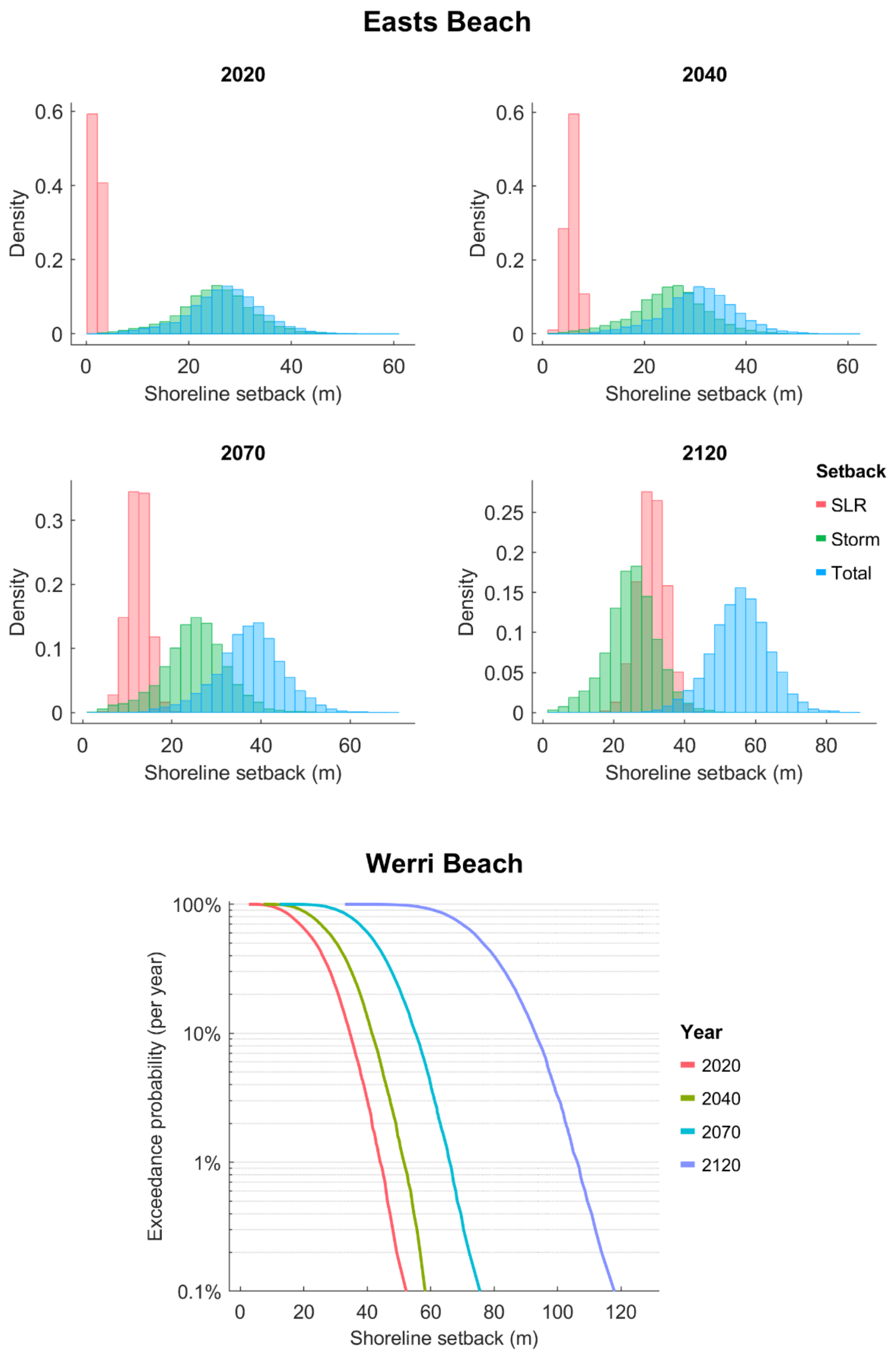


Figure A-17 Erosion Hazard Probabilistic Modelling Results at Easts Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)

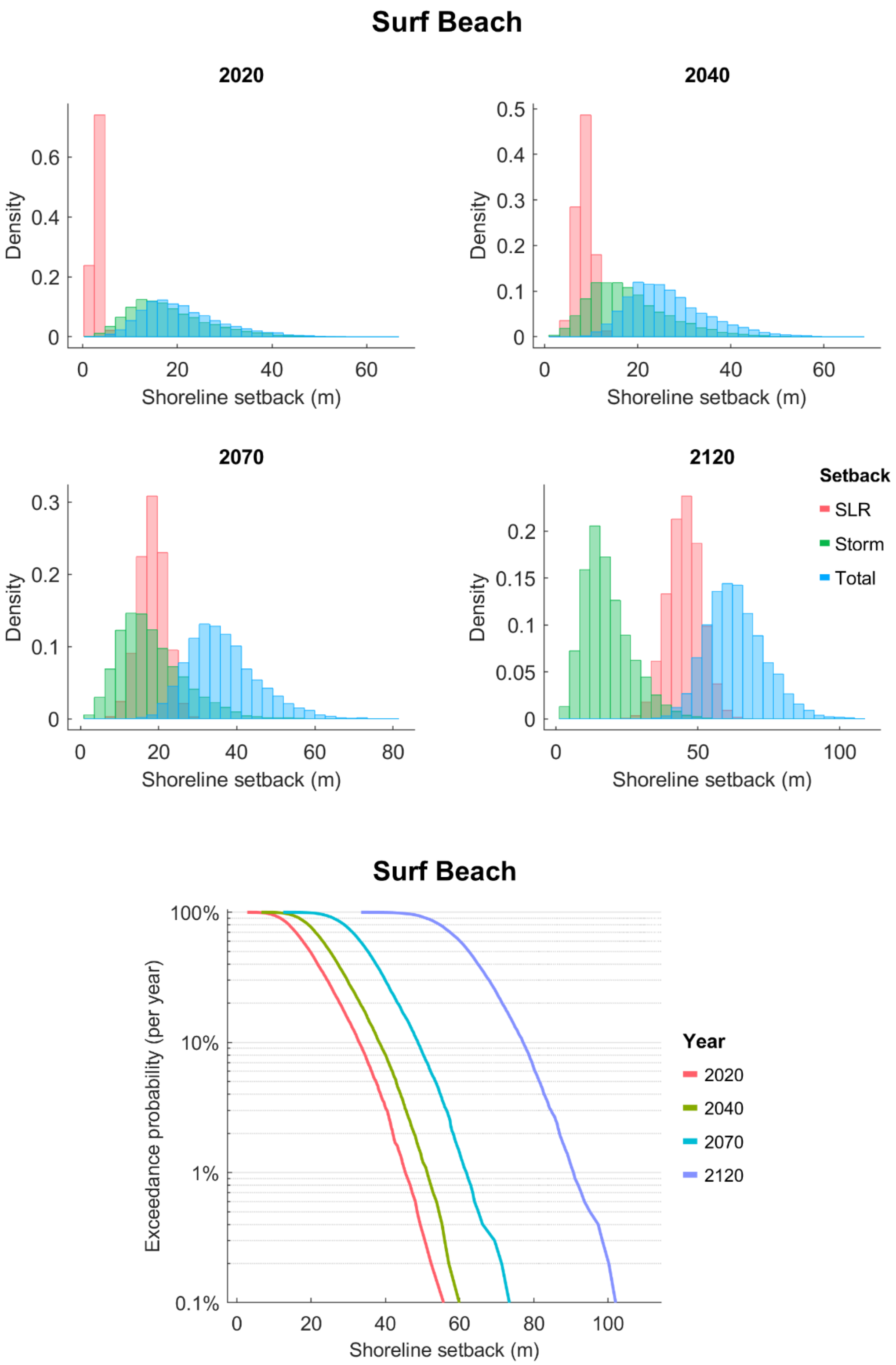


Figure A-18 Erosion Hazard Probabilistic Modelling Results at Surf Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)

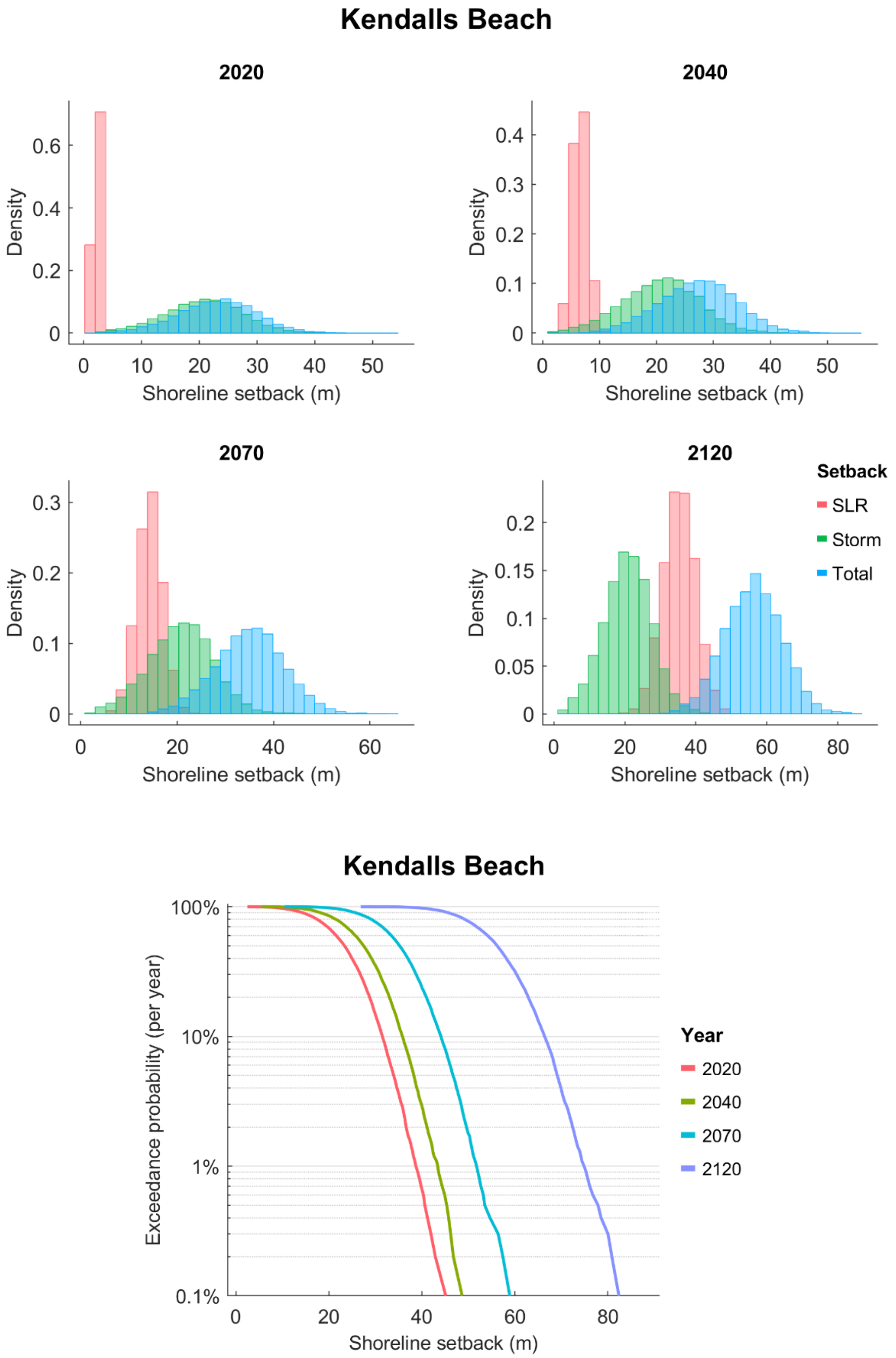
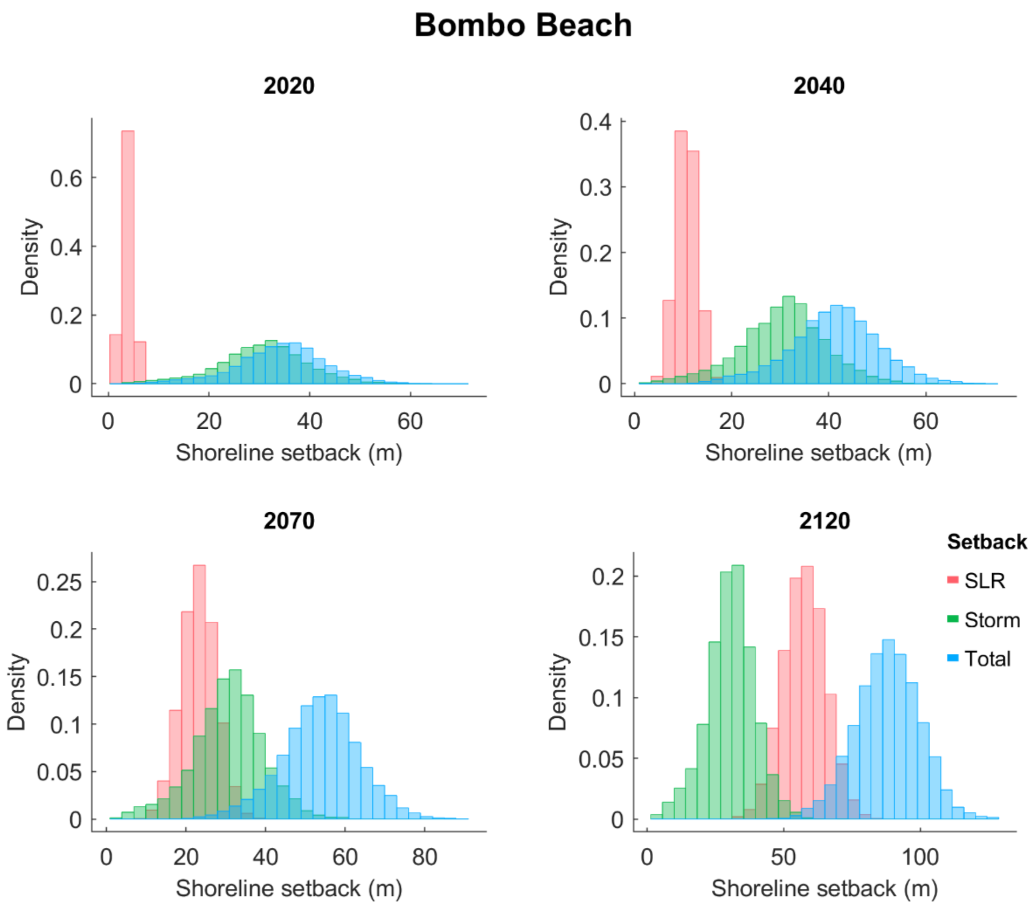


Figure A-19 Erosion Hazard Probabilistic Modelling Results at Kendalls Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)



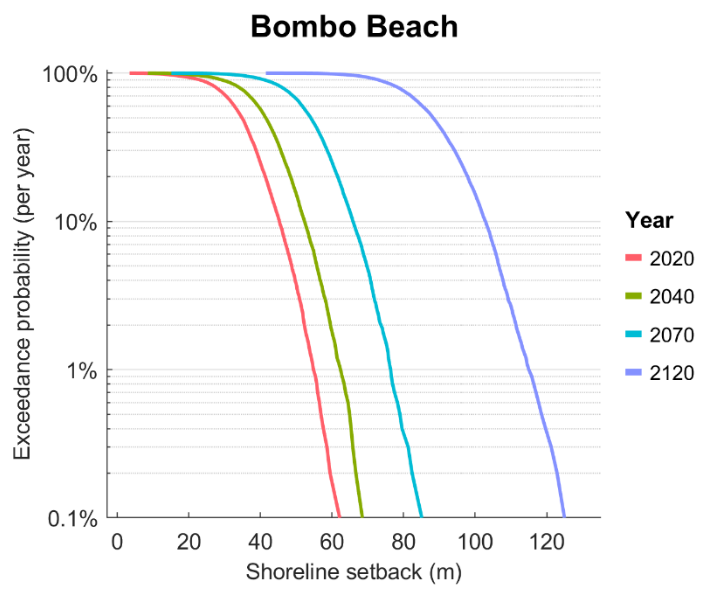


Figure A-20 Erosion Hazard Probabilistic Modelling Results at Bombo Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)

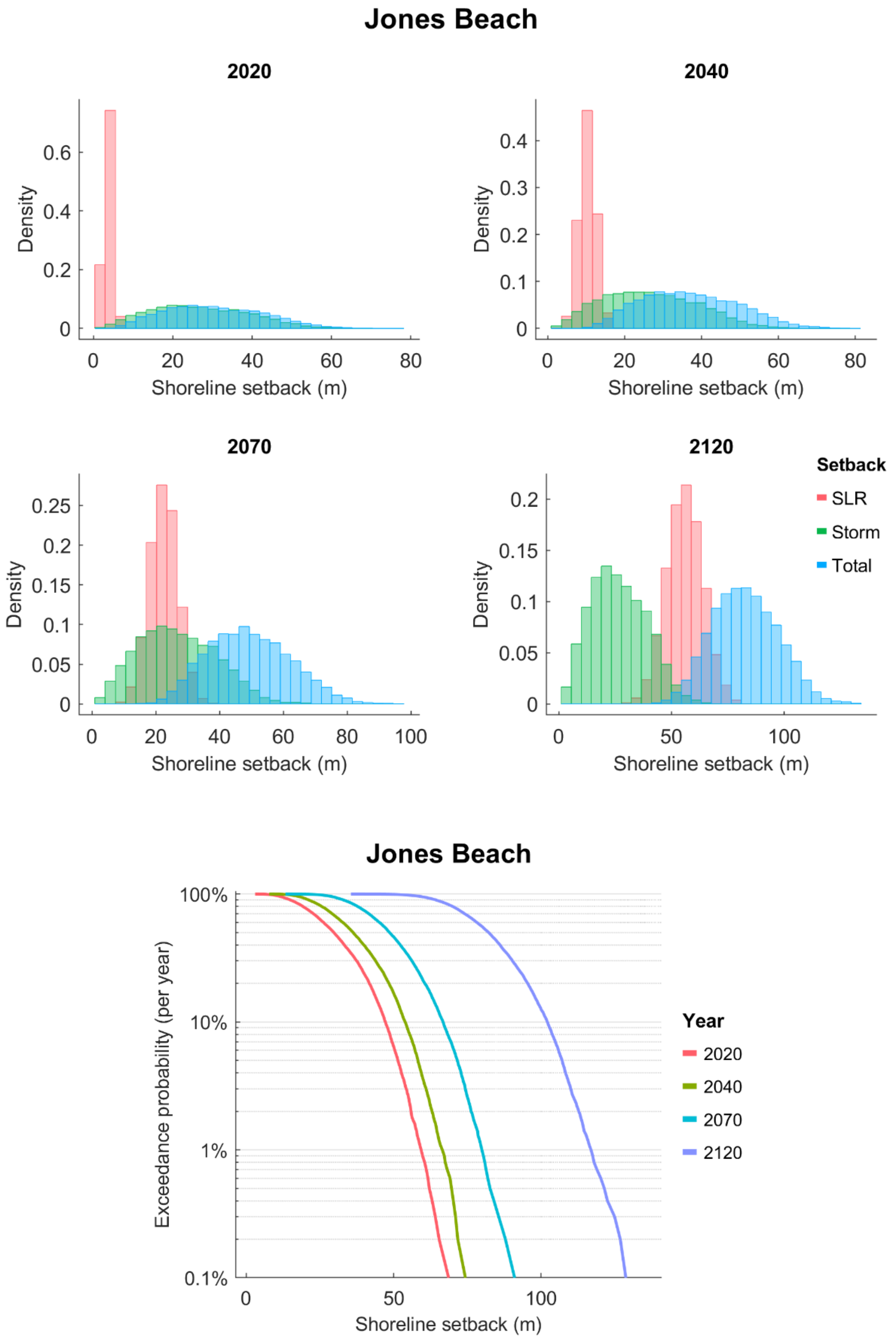


Figure A-21 Erosion Hazard Probabilistic Modelling Results at Jones Beach: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)

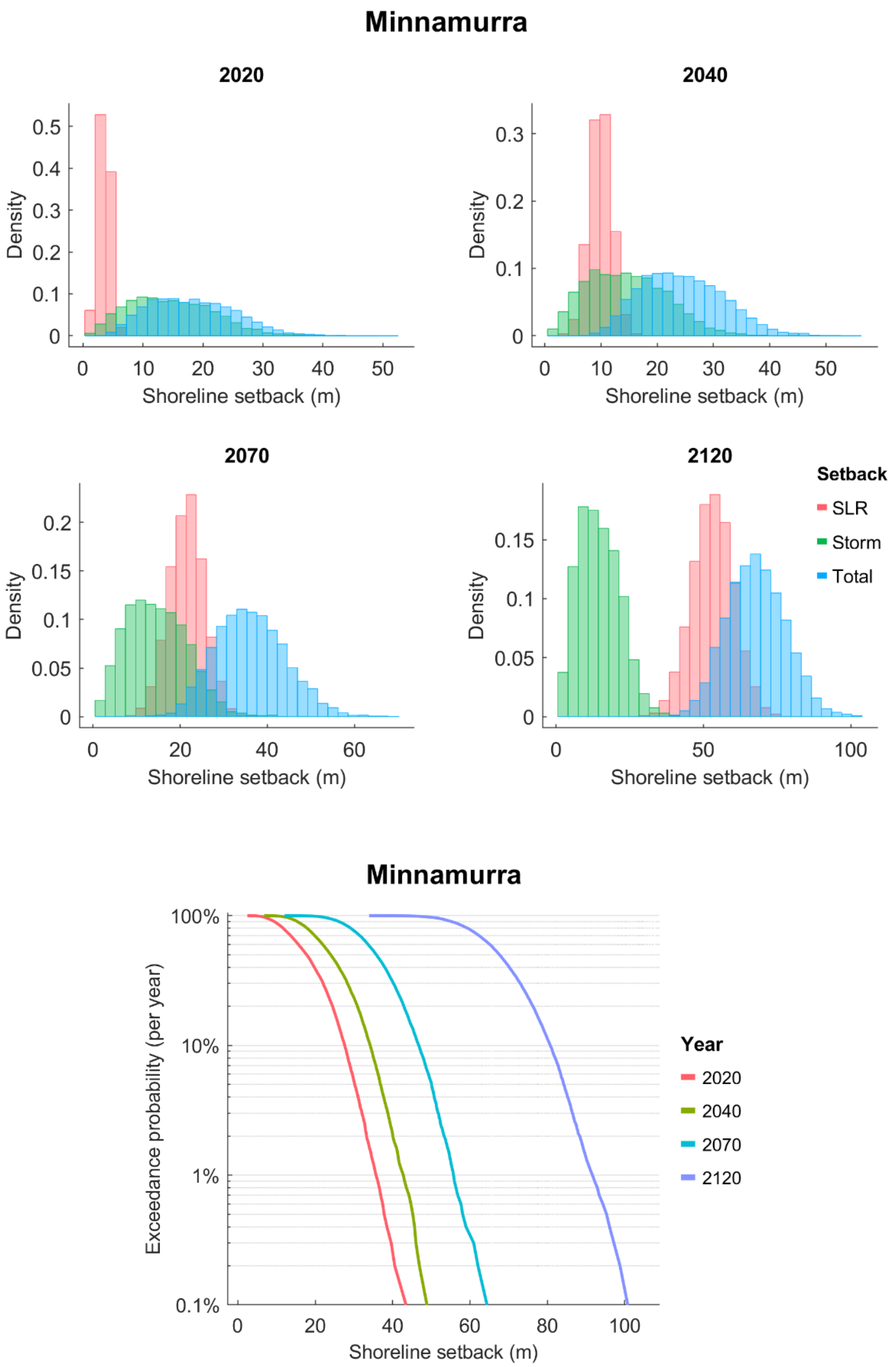


Figure A-22 Erosion Hazard Probabilistic Modelling Results at Minnamurra: Histograms Illustrating the Shoreline Setback Contributions and Results Density (top); Exceedance Probability Curves (bottom)