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Report 3: Outer Barrier Coastal Erosion Hazard

Gippsland Lakes/90 Mile Beach Local Coastal Hazard Assessment Project

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GLOSSARY

Accretion	Accretion is the process of coastal sediment returning to the visible portion of a beach or foreshore following a submersion event. A sustainable beach or foreshore often goes through a cycle of submersion during rough weather then accretion during calmer periods.
Aeolian	The erosion, transport and deposition of material by wind.
Aggradation	Aggradation is the term used in geology for the increase in land elevation due to the deposition of sediment. Aggradation occurs in areas in which the supply of sediment is greater than the amount of material that the system is able to transport.
Australian Height Datum(AHD)	A common national plane of level corresponding approximately to mean sea level
Alluvial	Water driven sediment transport process (non-marine)
Astronomical tide	Water level variations due to the combined effects of the Earth's rotation, the Moon's orbit around the Earth and the Earth's orbit around the Sun
Backshore	The area of shore lying between the average high-tide mark and the vegetation, affected by waves only during severe storms
Cainozoic	The geological era covering the period from 66 million years ago to present. This era includes the Quaternary and Tertiary geological periods.
Calibration	The process by which the results of a computer model are brought to agreement with observed data
Coastal Hazard	A term to collectively describe physical changes and impacts to the natural environment which are significantly driven by coastal or oceanographic processes.
Delta	A complex association of geomorphic settings, sediment types and ecological habitats, at a point where a freshwater source enters an estuarine water body.
Diurnal	A daily variation, as in day and night.
Ebb Tide	The outgoing tidal movement of water resulting in a low tide.
Embayment	A coastal indentation which has been submerged by rising sea-level and has not been significantly infilled by sediment.
EVC	Ecological Vegetation Class. These are the basis mapping units used for biodiversity planning and conservation in Victoria. Each EVC represents one or more plant communities that occur in similar types of environments.
Estuaries	The seaward limit of a drowned valley which receives sediment from both river and marine sources and contains geomorphic and sedimentary conditions influenced by tide, wave and river processes.
Eustatic	Eustatic change (as opposed to local change) results in an alteration to the global sea levels due to changes in either the volume of water in the world oceans or net changes in the volume of the ocean basins.
Facies	In geology, a facies is a body of rock with specified characteristics. Ideally, a facies is a distinctive rock unit that forms under certain conditions of sedimentation, reflecting a particular process or environment,
Ferruginised Sands	Iron enriched sand sized sediment

Flood Tide	The incoming tidal movement of water resulting in a high tide
Fluvial	Refers to the processes associated with rivers and streams and the deposits and landforms created by them.
Foreshore	The area of shore between low and high tide marks and land adjacent thereto
Geomorphology	The study of the origin, characteristics and development of land forms
GIS	Geographical Information System
Hindcast	In oceanography hindcasting usually refers to a numerical model simulation of a historical period where no observations are available.
Holocene	The period beginning approximately 12,000 years ago. It is characterised by warming of the climate following the last glacial period and rapid increase in global sea levels to approximately present day levels.
Hydrodynamic Model	A numerical model that simulates the movement of water within a defined model area
HAT	Highest Astronomical Tide: the highest water level that can occur due to the effects of the astronomical tide in isolation from meteorological effects
MHHW	Mean Higher High Water: the mean of the higher of the two daily high waters over a long period of time. When only one high water occurs on a day this is taken as the higher high water
MHWM	Mean High Water Mark, i.e. the man of high water over a long period of time
MLWM	Mean Low Water Mark, i.e. the mean of low water over a long period of time
H_s (Significant Wave Height)	Hs may be defined as the average of the highest 1/3 of wave heights in a wave record (H1/3), or from the zeroth spectral moment (H_{m0})
Intertidal	Pertaining to those areas of land covered by water at high tide, but exposed at low tide, eg. intertidal habitat
Isostatic	Equilibrium in the earth's crust such that the forces tending to elevate landmasses balance the forces tending to depress landmasses.
Lacustrine Deposits	Formed at the bottom of, or along the shores of lakes
Levee	Raised embankment along the edge of a coastal or riverine environment
LiDAR	**Li**ght **D**etection **a**nd **R**anging – also known as airborne laser scanning, is a remote sensing tool that is used to generate highly accurate 3D maps of the Earth's surface
Lithology	A description of the physical character if a rock or rock formation.
Marine Transgression	A marine transgression is a geologic event during which sea level rises relative to the land and the shoreline moves towards higher ground, resulting in flooding.
Meander	A description given to a bend or sinuous watercourse
Mesozoic	The geological era covering the period from around 252 million years ago to about 66 million years ago.
MSL	Mean Sea Level
Neap Tides	Neap tides occur when the sun and moon lie at right angles relative to the earth (the gravitational effects of the moon and sun act in opposition on the ocean).
Nearshore	The region of land extending from the backshore to the beginning of the offshore zone.

Paleochannel	A remanent of an inactive river or stream channel that has been either filled or buried by younger sediment.
Paleo-river	Another term for paleochannel.
Palaeozoic	The geological area covering the period from about 541 to 252 million years ago. Incorporates the Devonian, Silurian, Ordovician, and Cambrian geological periods
Paludal	Sediments that have accumulated in a marshy or swampy environment.
Physiography	The study of the physical patterns and processes of the environment to understand the forces that produce and change rocks, oceans, weather, and flora and fauna patterns.
Pleistocene	The period from 2.5M to 12,000 years before present that spans the earth's recent period of repeated glaciations and large fluctuations in global sea levels
Pliocene	The period in the geologic timescale that extends from approximately 5.3 million to 2.6 million years before present. The Pliocene follows the Miocene Epoch and is followed by the Pleistocene Epoch
Prograde	In sedimentary geology and geomorphology, the term progradation refers to the growth of a river delta farther out into the sea over time. This occurs when the mass balance of sediment into the delta is such that the volume of incoming sediment is greater than the volume of the delta that is lost through subsidence, sea-level rise, and/or erosion.
Quaternary Age/Period	Is a geologic period spans from approximately 2.6 million years ago to the present. The period is characterized by a series of glaciations and by the appearance and expansion of anatomically modern humans.
Semi-diurnal	A twice-daily variation, eg. two high waters per day
Shoal	A shallow area within a water body; a sandbank or sandbar
Sea Level Rise (SLR)	A permanent increase in the mean sea level
Spring Tides	Tides with the greatest range in a monthly cycle, which occur when the sun, moon and earth are in alignment (the gravitational effects of the moon and sun act in concert on the ocean)
Storm Surge	The increase in coastal water levels caused by the barometric and wind set-up effects of storms. Barometric set-up refers to the increase in coastal water levels associated with the lower atmospheric pressures characteristic of storms. Wind set-up refers to the increase in coastal water levels caused by an onshore wind driving water shorewards and piling it up against the coast
Storm tide	Coastal water level produced by the combination of astronomical and meteorological (storm surge) ocean water level forcing
Stratigraphy	Stratigraphy is a branch of geology which studies rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks.
Subaerial	Processes that take place on the land or at the earth's surface as opposed to underwater or underground.
Susceptibility	The sensitivity of coastal landforms to the impacts of coastal hazards such as sea-level rise and storm waves. This may include physical instability and/or inundation.
Taxa	A taxonomic category or group, such as an order, family, genus or species
Tidal Planes	A series of water levels that define standard tides, eg. 'Mean High Water Spring' (MHWS) refers to the average high water level of Spring Tides

Tidal Prism	The volume of water moving into and out of an estuary or coastal waterway during the tidal cycle.
Tidal Range	The difference between successive high water and low water levels. Tidal range is maximum during Spring Tides and minimum during Neap Tides
Tides	The regular rise and fall in sea level in response to the gravitational attraction of the Sun, Moon and Earth
Tombolo	A tombolo is a deposition landform in which an island is attached to the mainland by a narrow piece of land such as a spit or bar.
Vulnerability	Vulnerability is a function of exposure to climatic factors, sensitivity to change and the capacity to adapt to that change. In this report is means the degree to which a natural system is or is not capable of adapting or responding to the impacts of coastal hazards to which they are physically susceptible and exposed.[1]

[1] Definition taken from the Smartline glossary http://www.ozcoasts.gov.au/coastal/smartline_terms.jsp

1. INTRODUCTION

This report details the analysis undertaken to assess the potential extent of the coastal erosion hazards that could be expected to develop along the 'Outer Barrier' of the Gippsland Lakes study area due to projected mean sea level rise and climate change this century.

This report is part of a series that has been prepared for the Gippsland Lakes Coastal Assessment:

1. Summary
2. Inundation Hazard
3. **Outer Barrier Coastal Erosion Hazard**
4. Lake Shoreline Erosion Hazard
5. Coastal Monitoring

The 'Outer Barrier' is an elongate accumulation of sand initiated by waves, aeolian transport and vegetation growth that extends continuously (except for the artificial entrance at Lakes Entrance) along the entire length of the study area. The most seaward terrestrial expression of the Outer Barrier is known more commonly as the Ninety Mile Beach.

The sandy sediments comprising the Outer Barrier are subjected to the meteorological and oceanographic processes of Bass Strait and the South Tasman Sea and the Outer Barrier is therefore a highly dynamic landform. As its name suggests, the Outer Barrier provides a barrier to the extent of the marine processes and influences that can impact the Gippsland Lakes and associated landforms in its lee. For this reason, risks posed to the Outer Barrier by sea level rise and climate change are critical for understanding the potential extent of erosion and inundation hazards more generally in the study area.

The Outer Barrier coastal erosion hazards have been considered for three future sea level rise conditions and approximate timeframes; +0.2 (2030), +0.4 (2070) and +0.8 m (2100).

This Outer Barrier coastal erosion hazard assessment has been structured as follows:

- Analysis of the geomorphology of the Outer Barrier;
- Analysis of the meteorological and oceanographic processes that can impact the Outer Barrier;
- Review and analysis of the contemporary coastal processes and historical coastal hazard impacts along the Outer Barrier;
- Analysis of the mechanisms and potential extent of the responses of coastal barriers to increased sea levels;
- Analysis of the potential extent of coastal hazard impacts due to sea level rise;
- Evaluation of the uncertainty in the coastal hazard analysis and testing of sensitivity;
- Appendix A – Contains the details of the numerical models used to assist in the coastal hazard assessment.

2. GEOMORPHOLOGY

The susceptibility of the Outer Barriers to coastal hazard impacts, including sea level rise, is integrally related to the nature and variations in geology and geomorphology. The following sections provide a broad overview of the nature and variability of the physical character of the Outer Barrier as a basis for understanding the potential type, extent and susceptibility of the Outer Barrier to coastal hazards.

2.1 Origin

Cutting obliquely across the northern terrace and platform of the Gippsland Basin is a former marine embayment established during late Pliocene and Pleistocene higher sea levels, now enclosed and partly filled by a sequence of coastal sand barriers and lacustrine, paludal and fluvial deposits of Late Quaternary age. These deposits and associated landforms, developed during episodes of higher and lower sea level, comprise the largest coastal barrier and lagoon system on the Australian coast and are regionally referred to as the Gippsland Lakes (Figure 2-1).

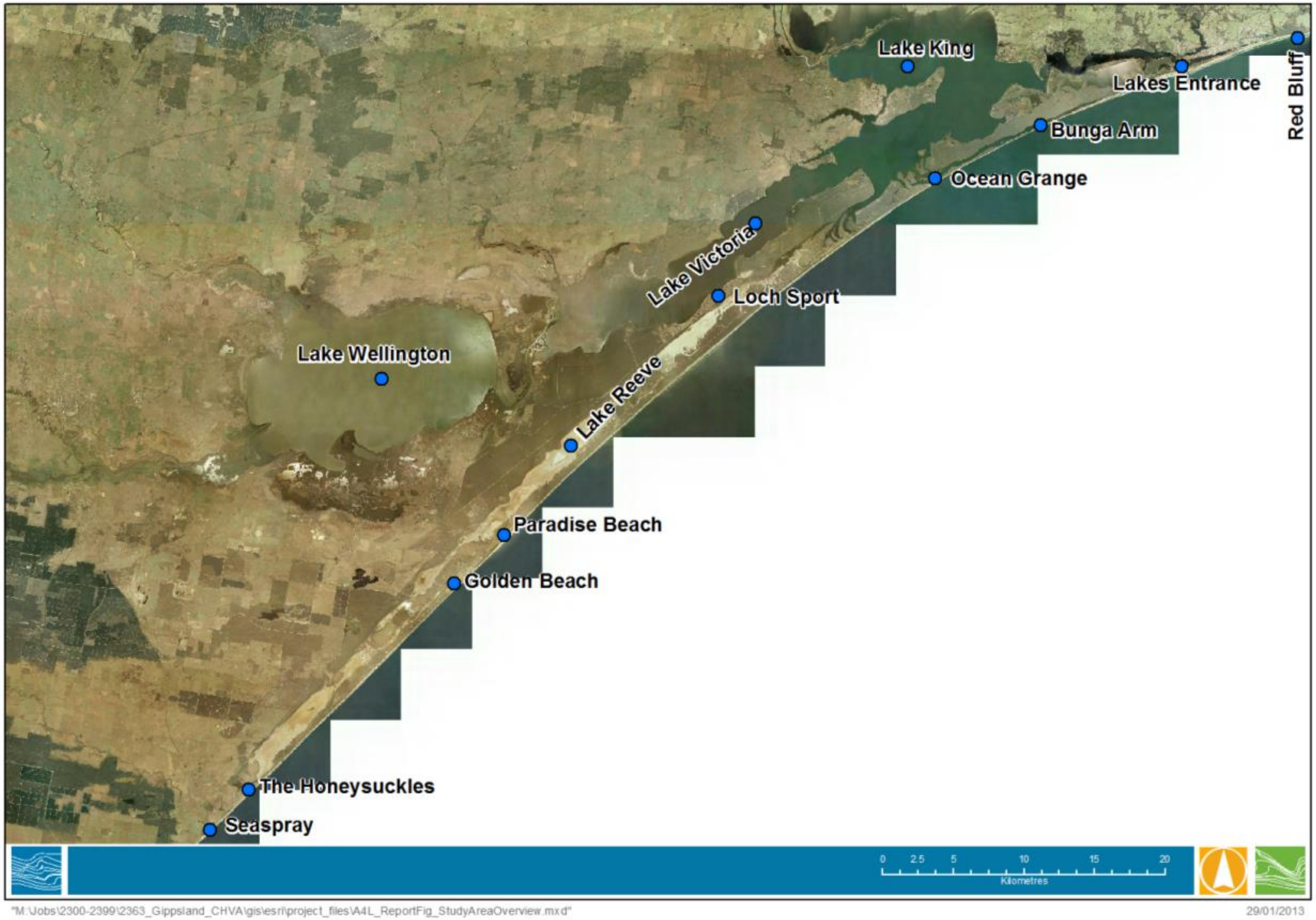


Figure 2-1 Key Locations in the Gippsland Lakes and along Ninety Mile Beach Study Area

The former embayment that contains the Gippsland Lakes is cut into a level to gently sloping surface with a basement of Seaspray Group limestone covered by Haunted Hills Formation sand, clay and gravel. During times of Pleistocene higher sea-levels, wave action during marine transgressions submerged and eroded the edge of this plain forming an active cliffed coastline. The sea extended into the major river valleys forming estuaries. At lower sea levels, the marine cliff was abandoned and streams extended beyond the former shoreline cutting deeper valleys and partly backfilling these with alluvium. This sequence of submergence and emergence occurred on multiple occasions over the past 4 million years in response to global glacial and interglacial conditions. Features formed at low sea-level were rapidly reshaped or submerged during the transgressions. Magnetic and seismic imagery of the lakes region reveals numerous traces of buried river channels and remnants of multiple barrier systems (Figure 2-2). The palaeo-river systems can be interpreted as low sea-level extensions of the modern rivers. The magnetic traces of the oldest coastal barriers have an orientation about 15^0 more northerly than the trend of the modern Ninety Mile Beach, which is not well understood. There is no surface expression either onshore or offshore of these features.

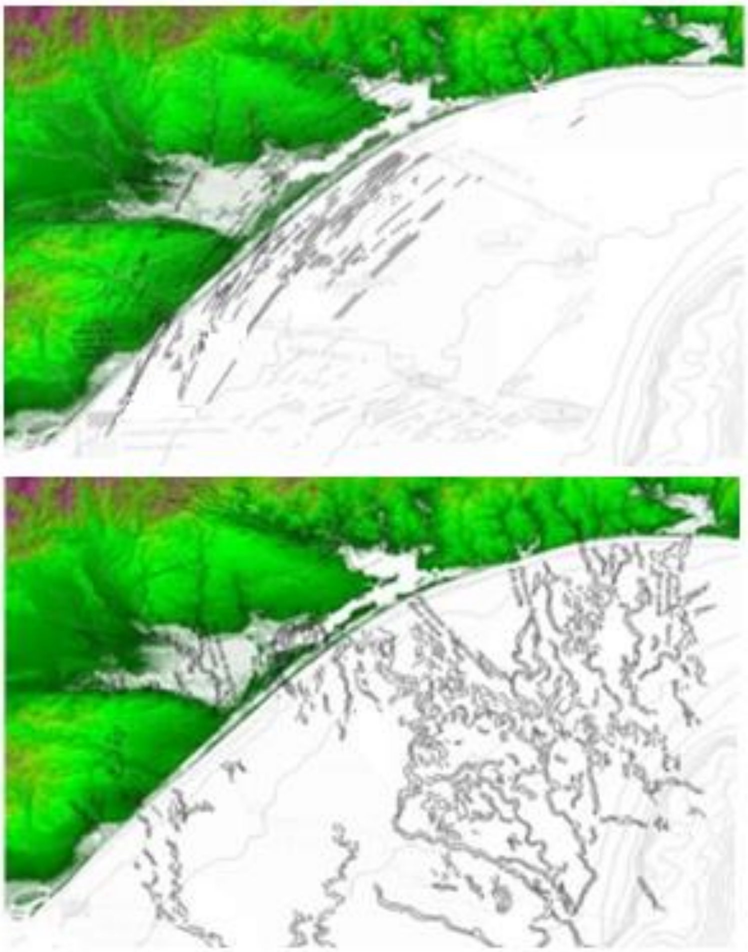


Figure 2-2 Palaeo Barrier and River Systems Onshore and Offshore – Gippsland Lakes. (Modified From Holdgate *et al.* 2003)

2.2 Coastal Barriers

A coastal barrier is an elongate accumulation of sand and/or gravel initiated by waves and tidal currents and modified by wind action and vegetation growth. Barriers may develop as shore-parallel features or parallel to net wave energy flux and rise above the present sea level often blocking terrestrial drainage and forming lagoons. Barriers are complex and compound landforms. Barriers may form as attachments against existing mainland shorelines, extend as elongate or looped spits at changes in shoreline orientation at promontories or headlands, link offshore islands forming a tombolo, or form single or multiple nearshore islands. Barriers are a depositional record of previous beach, backshore and dune environments. They undergo periods of intense activity during formation and reworking by wave action and then may be abandoned, mobilized or drowned as sea levels and sediment sources change or become modified by wind and fluvial processes. There are three major geomorphic elements in barrier systems (Thom B. , 1984):

(i) The sand/gravel barrier that rises from below low-water to above high tide. It includes a range of nearshore and onshore sedimentary environments which are dynamically linked through the beach-face by depositional and erosional processes. Generally the barrier is partly vegetated and may consist of one or more ridges landward of the subaerial beach. The outermost (seaward) ridges may be over-washed during high magnitude storm surge conditions.

(ii) Enclosed or partly enclosed backbarrier depressions (inland of the barrier or between the barrier ridges) with associated tidal flats, lagoons or swamps.

(iii) Ephemeral, intermittent or permanent channels cut through the barrier and connect the backbarrier to the ocean forming tidal inlets. These can develop flood and ebb-tide sand bodies (tidal deltas).

There is an extensive literature detailing barrier morphology and dynamics. Many barriers are composite features, although three broad types are recognized:

Type I: *Prograded or Regressive barriers*. These develop where there is abundant sand supply for onshore transport with the sea at a constant level (stillstand) or falling. Swash deposits (wave action) at the rear of the beach are built upward by wind action into ridged or terraced foredunes. In areas of plentiful sand supply the beach face migrates seaward forming new ridges in front of earlier formed one(s), thus developing a beach ridge or strand plain that may be hundreds of metres to kilometres wide.

Type II: *Stationary barriers.* These develop where there is a balance between sand supply and energy conditions. They result in a single ridge of complex internal geometry and stratigraphy reflecting periods of limited accretion followed by periods of erosion i.e. “cut and fill” sequences.

Type III: *Transgressive or Receded (Receding)* barriers. These form during periods of rising sea level and/or where there is shorezone deficient of sand relative to wave energy. They result in the landward migration of a single barrier ridge during periods of rising sea level or reduction in sediment supply and are characteristic of eroding shorelines. Terrestrial deposits, including lagoon and swamp deposits are exposed at the seaward base of the barrier. As the shoreline advances inland, the barrier may remain an entity if there is sufficient sand supplied from the nearshore zone. If sand supply diminishes, the barrier will become segmented and dispersed.

Coastal barriers, dominantly of siliceous sand are widespread on the coast of eastern Australia. The barrier systems of the Gippsland Lakes are among the most extensive and complex of these and elements of the three types above are present and are discussed in Section 2.2.1 below.

2.2.1 Gippsland Lakes Barrier Systems

The coast of Gippsland between Corner Inlet and Red Bluff, east of Lakes Entrance, is fringed by sand barriers of varied width, complexity and history. Although the focus of this study is the coast between Merriman Creek and the marine cliff at Red Bluff (as these define the seaward geographical extent of the Gippsland Lakes), a broader regional geomorphological context is needed in assessing the development and modification of coastal barriers. To that end, the barriers southwest of Seaspray and the eastern sand islands of Noramunga are described as these are part of the onshore and offshore coastal process continuum.

There are several groups of coastal barriers in the Gippsland Lakes with differing morphology and history. Terminology and interpretation of barrier history varies between authors but there are at least three groups of elongate, more-or-less parallel sand ridges (some with a locally significant gravel component) initiated and broadly configured by wave action that have developed at different stages of sea level during the Pleistocene and Holocene.

Classifications of Bird (1978) and later Jenkin (1968) are in broad agreement as to the relative chronology of barrier sequences but differ in some details regarding the configuration and emplacement of the youngest barriers. Neither scheme was supported by absolute dating. Absolute chronology of barrier development has been advanced by Ward (1977), Thom (1984), and Bryant and Price (1997).

At least three stages of barrier formation can be recognised in the Gippsland Lakes region, each with a distinctive morphological and sedimentary style. (Bird (1965) and subsequent papers) grouped and named the barriers as:

(i) *Prior barrier.* This is a remnant and discontinuous feature on the inner margin of the lakes and lies at the foot of the marginal bluff or is separated from it by a narrow waterway. It extends from the northern edge of Lake Wellington and Lake Victoria with the most prominent remnants being Banksia Peninsula and Raymond Island. It includes areas of deeply leached and ferruginised sands and local concentrations of gravel. This barrier formed at a time of higher Pleistocene sea level in open ocean conditions.

(ii) *Inner barrier.* This is an extensive and complex group of landforms extending as a continuous broad, elongate peninsula from near Golden Beach to Sperm Whale Head. It is comprised of varied sand bodies but is predominately built of multiple, long, straight parallel and curving ridges separated by swales and closed depressions with swamps and lakes. Various characteristics of these ridges indicate they developed as prograded barriers during higher sea level and have undergone dissection and partial backfilling during lower sea level. In places they have been extensively modified by wind action forming parabolic dunes. The inner barrier system forms the southern margin of Lake Wellington and Lake Victoria and may originally have continued east to Red Bluff before being dissected and eroded here by the Mitchell and Tambo Rivers at lower sea level.

(iii) *Outer barrier.* The outer barrier extends continuously from the sand islands of eastern Corner Inlet to Red Bluff east of Lakes Entrance. It is the youngest of the coastal barriers and the morphology and present dynamics is highly variable. The assessment of coastal barrier hazards focuses largely on the landform referred to as the Outer Barrier.

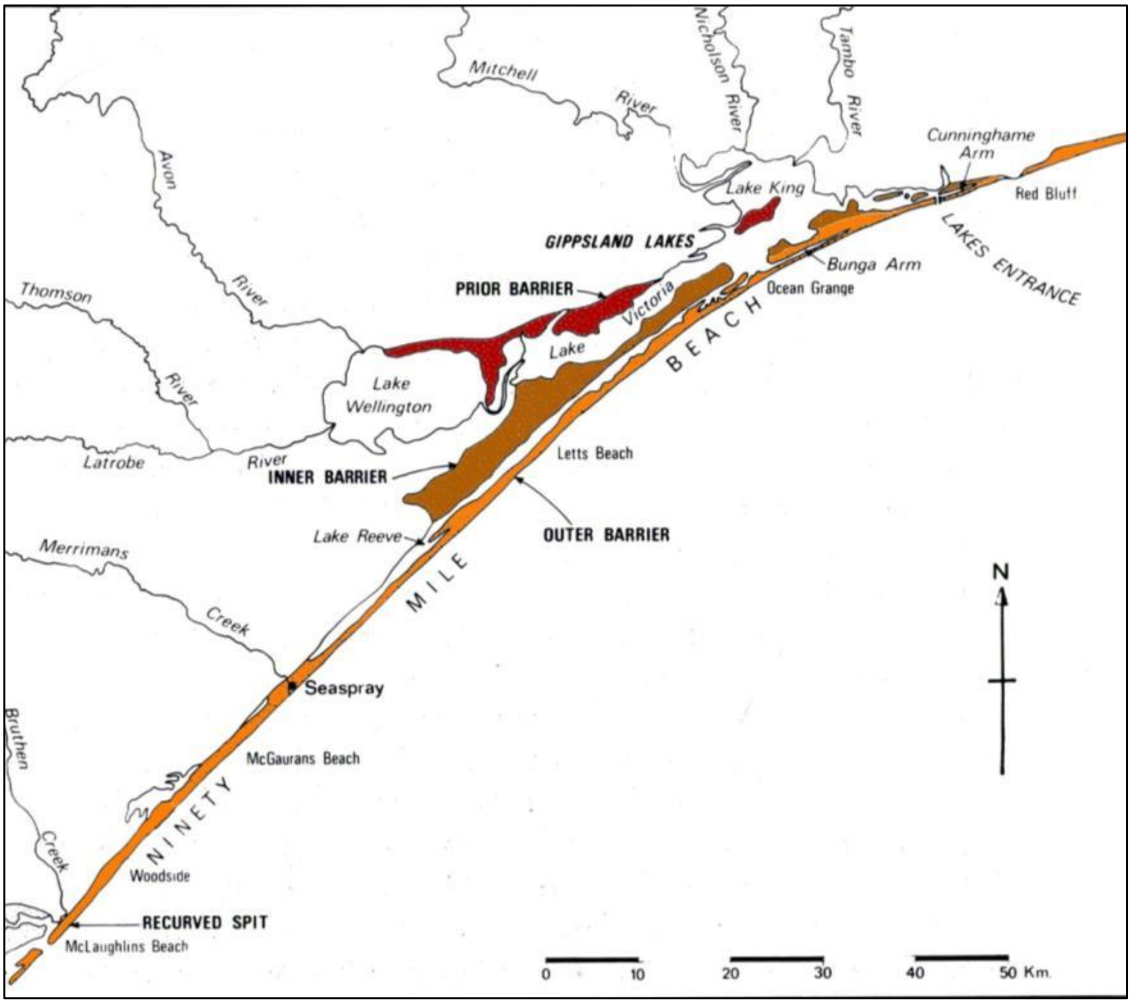


Figure 2-3 Simplified Outline of the Barrier Systems of the Gippsland Lakes, after Bird (1993).

Wolinsky and Murray (2009) suggest that the mechanism of coastal barrier evolution over long term, millennial scales varies as a function of the inland substrate slope in relation to the nearshore coastal barrier slope, to produce a steep coast or gentle coastal barrier response trajectory to rising sea levels.

Figure 2-4 displays a cross-sectional profile developed from a combination of LiDAR survey and offshore bathymetric data through the Gippsland Lakes basin. From Figure 2-4 the coastal barrier formations can be seen perched upon the slope of the underlying continental landmass.

Figure 2-4 also shows that the average slope of this compound coastal barrier is less than the inland substrate slope ($S_o >> S_s$). Under these conditions the retreat trajectory of the barrier response to rising sea level is less than the inland substrate slope. The millennial scale coastal barrier response under these conditions is predicted to result in the formation of a cliff face and the aggradation of sediment offshore until the nearshore slope is equal to the inland substrate slope. Evidence of this coastal configuration, comprising an active marine cliffed coastline and offshore sediment deposits exists within the Gippsland Lakes basin during higher sea level still stands in the Piestocene. The remnants of a cliffed coastline can be traced around the study area in the form of the marginal bluff with the sand body referred to as the Prior Barrier likely comprising the remnants of the aggraded barrier material that formed at the base of the cliff.

The model of coastal barrier response postulated by Wolinsky and Murray (2009) suggests that millennial scale transgression of the coastal barriers in the Gippsland Lakes basin is potentially controlled by the inland substrate slope.

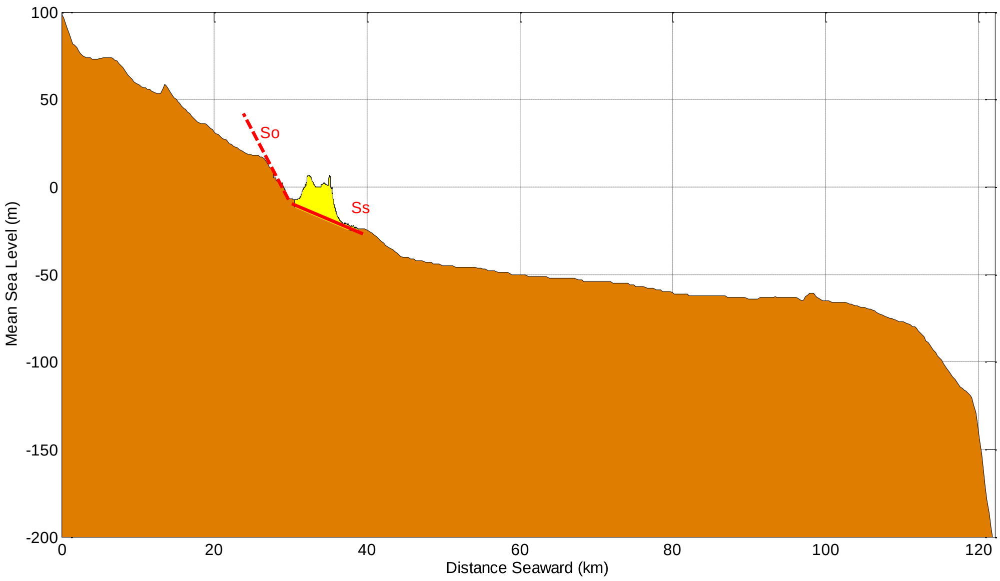


Figure 2-4 Comparison of Coastal Barrier and Inland Substrate Slope through Gippsland Lakes Basin

2.2.2 Outer Barrier Geomorphology

Bird (1965) applied the term Outer Barrier to the most seaward a mass of unconsolidated to weakly consolidated sand, shaped either as a single narrow ridge, or a broad, compound feature with multiple ridge crests and intervening swales. Based on width, volume and number of ridges and the back-barrier morphology, the present study has identified eleven geomorphic units between Corner Inlet and Red Bluff as shown in Figure 2-5.

In order to provide a broad geomorphological context, the barrier systems southwest of Seaspray, outside the main study area, are incorporated in the classification as they form part of the coastal process continuum of the Outer Barrier. The main characteristics of each unit are detailed in Sections 2.2.3 to 2.2.13 from existing literature, low-level aerial inspections and through analysis of LiDAR survey data. The analysis has included quantification of the outer barrier volume and maximum crest elevation along the length of the study area. The analysis was undertaken by extracting cross-sections perpendicular to the coastline at 100 m intervals from approximately mean high water, extending landward to the intersection of backshore lagoon or swamp terrain. A total of approximately 1000 cross-sections were extracted from the LiDAR survey from Merriman Creek in the south west to Red Bluff at the north eastern extent of the study area. The volume of the outer barrier dune was quantified by determining the area under each cross-section above the mean higher high water tidal plane. The variation in the volume of the outer barrier and maximum crest height determined from this analysis is displayed in Figure 2-6.

The data available from this analysis and plotted in Figure 2-6 provides a first order assessment of the vulnerability of different sections of the Outer Barrier to costal hazard and the effects of sea level rise. Areas of the barrier with low crest height and small dune volumes are clearly more vulnerable or susceptible to coastal erosion than areas with significantly greater volumes of sand.

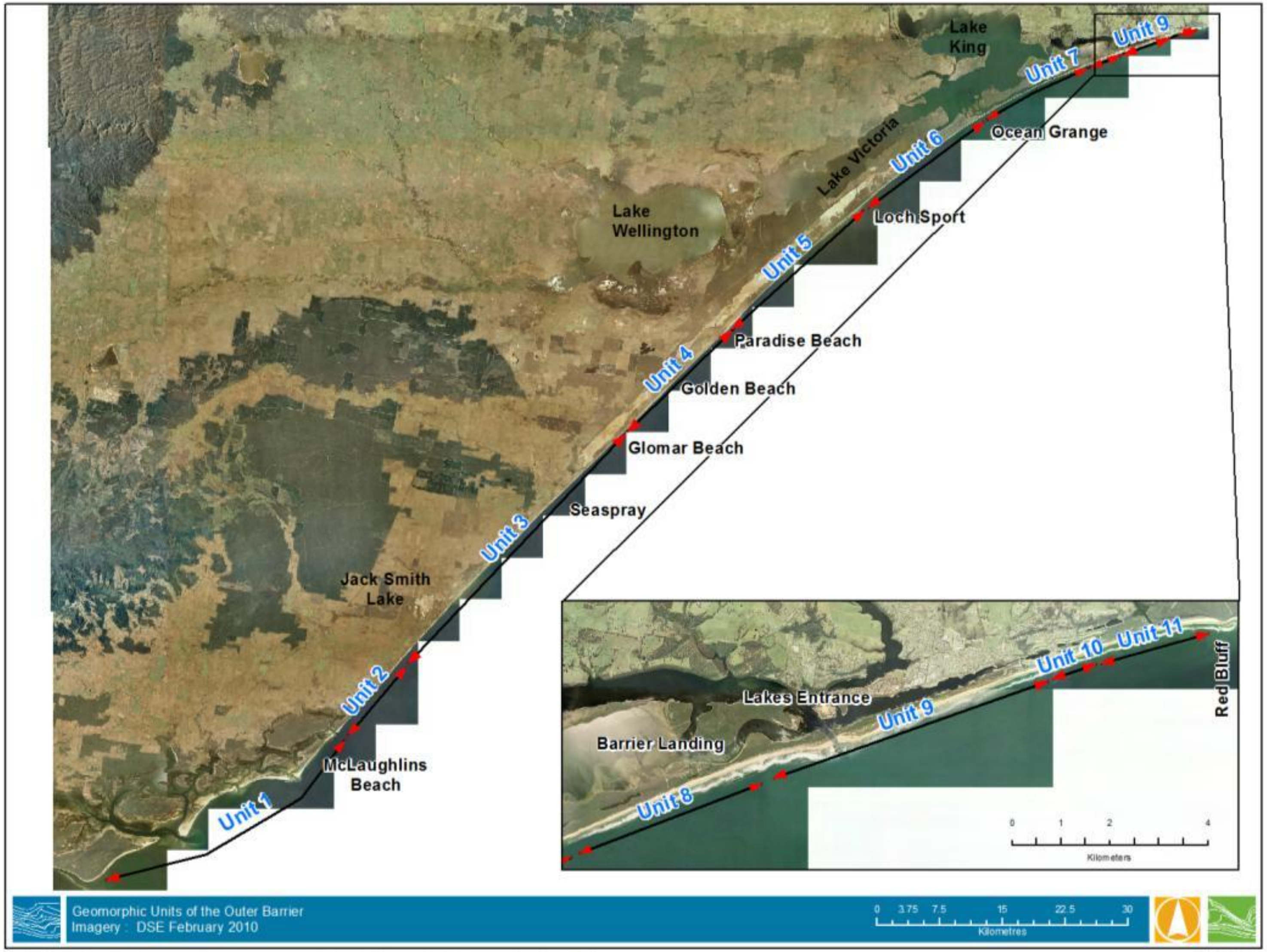


Figure 2-5 Geomorphic Units of the Outer Barriers

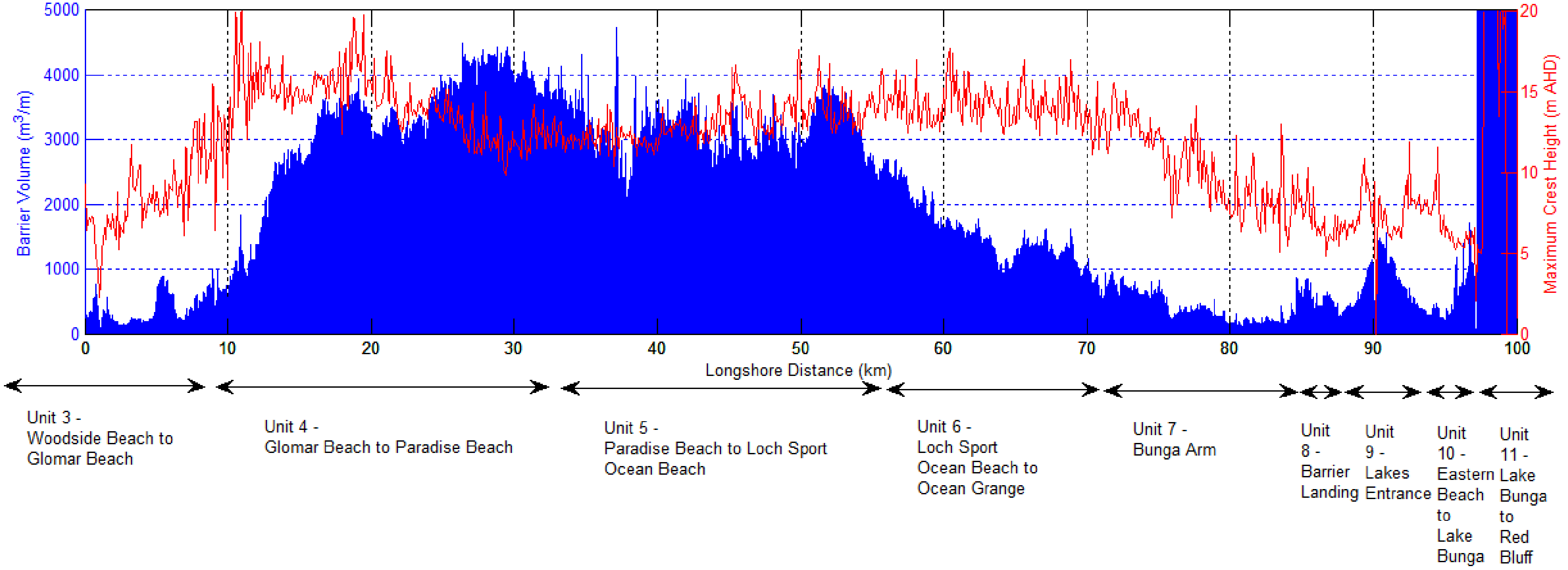


Figure 2-6 Relationship between Barrier Volume and Maximum Crest Height and Geomorphic Units of the Outer Barrier

2.2.3 Unit 1: Nooramunga Barrier Islands

Unit 1 comprises the islands of Nooramunga east of Corner Inlet. This area is a complex of parallel, converging and curving sand ridges with intervening grassy or wetland swales fringed by sandy barrier beaches. Between the Port Albert Entrance and Shallow Inlet are two narrow barriers forming a concave arc extending 15.5 km and separated by the tidal Kate Kearney Entrance and there are several frequent washover points into the lagoons and tidal channels behind the barriers. East of Shallow Inlet (also known as Shoal Inlet), the coastal orientation becomes northeasterly, a similar alignment to the Ninety Mile Beach. A breach in the outer barrier, developed in a storm in June 1961, has been maintained as a tidal “New Entrance”. The breach was a combination of storm wave overwash and erosion of the back of the barrier by a tidal channel (Figure 2-7). The new entrance quickly became over one kilometre wide but has narrowed to 250 metres as sand spits have developed and extended northeast from the western side of the breach.

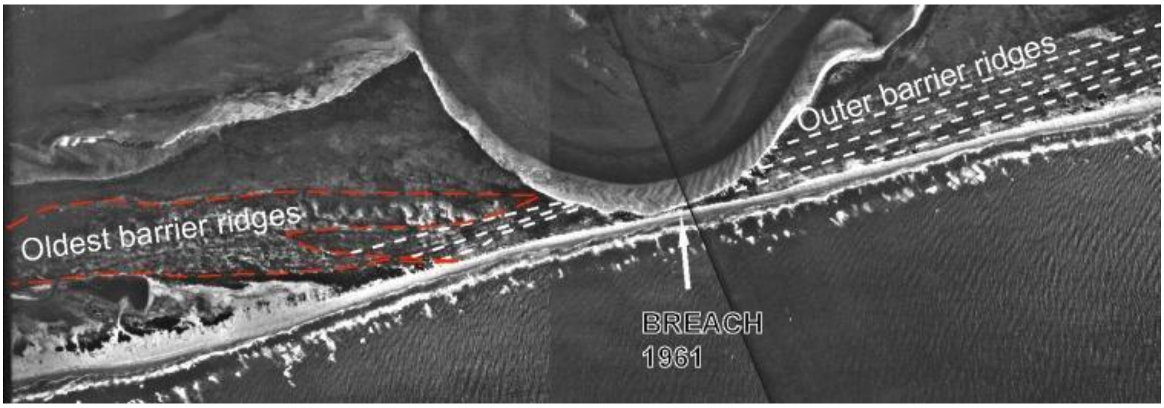


Figure 2-7 Overwash Site where New Entrance Developed after 1961 (Vertical aerial photograph 1941: RAAF)

2.2.4 Unit 2: New Entrance to Woodside Beach

This unit extends for 12 km from New Entrance to Woodside Beach. It is a zone of multiple barrier ridges varying from over 500 m wide at McLoughlans Beach to 100 m near Woodside Beach. Figure 2-8 shows the shoreline changes at the New Entrance between 1941 and 2004 including the interval after the breach. Recent mapping by Coastal Engineering Solutions (CES) (2007) has shown that up to 100 metres of shoreline recession occurred following the 1961 breach and erosion extended for 6 km northeast of the New Entrance. By 2000, deposition of new sand had reversed this trend and irregular ridges and mounds of sand had accreted in the former eroded zone. However, this accretion is irregular and although near McLoughlans Beach recovery is up to 50 m wide, the 1941 shoreline is still at least 50 m seaward of the present shoreline (Figure 2-8).

Figure 2-8 Shoreline Recession following 1961 Breach at New Entrance. (Photo base 2004)

The width of the barrier zone and the number of ridges changes towards the northeast. At the New Entrance the zone is 370 m wide with 4 main ridges, at McLoughlins the zone is 520 m with 6 ridges and to the NE it narrows to become a single ridge 70 m wide near Woodside Beach. From the New Entrance and extending 5.3 km NE, the alignment of parallel sand ridges is discordant with the present orientation of the Ninety Mile Beach. The modern coastline intersects the ridges at an angle of 7^0 and ridges are successively truncated towards the southwest (Figure 2-9). The shoreline when these ridges developed was several hundred metres seaward of the present alignment and has since substantially receded. This indicates a well-defined palaeo-shoreline, developed from near Woodside Beach to the southwest, has been substantially re-aligned (Figure 2-10). There are clearly several generations of parallel ridges in this unit with varied intervals between their formations.

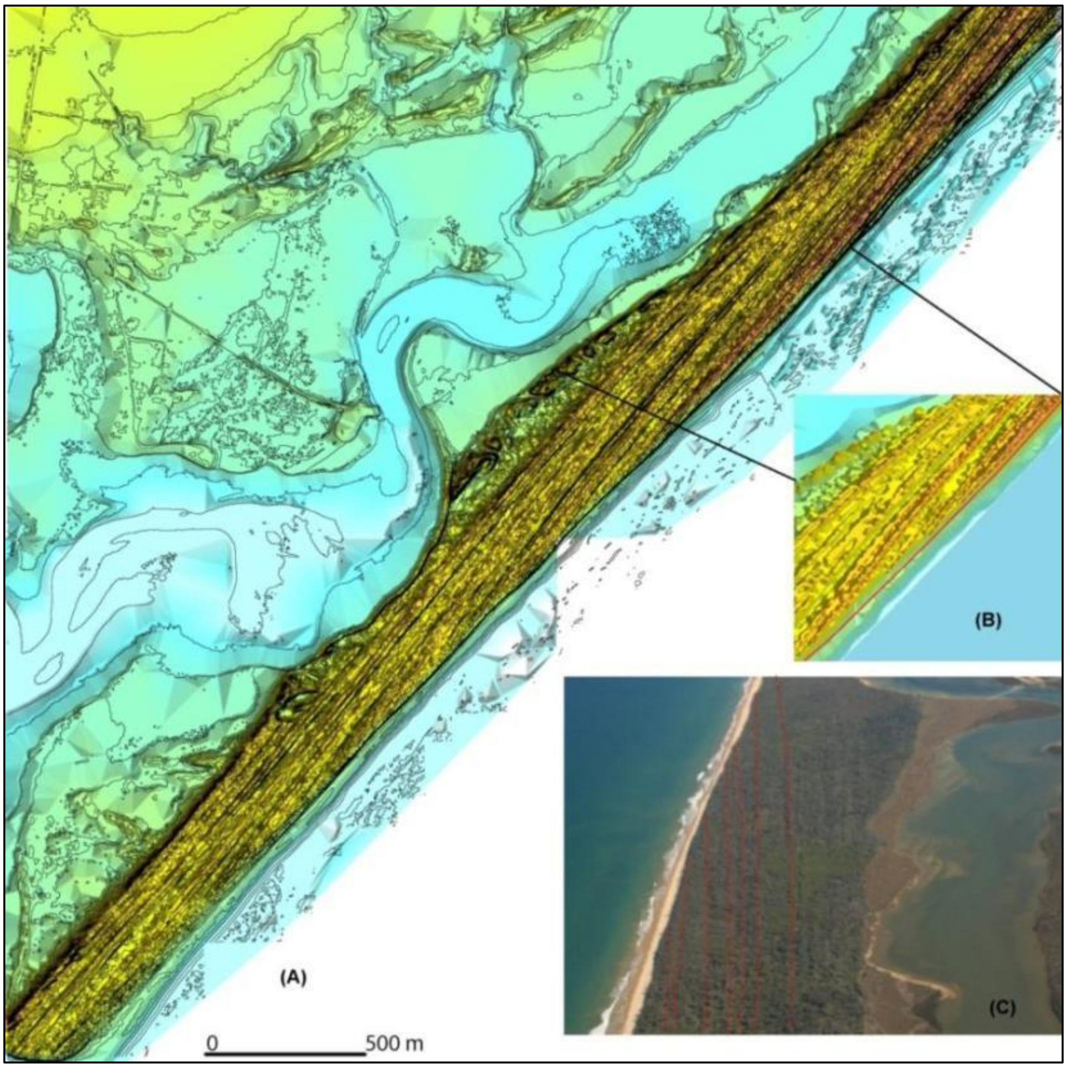


Figure 2-9 Truncation of Parallel Ridges by Ninety Mile Beach Alignment, McLoughlins Beach. ((A), (B) Lidar images DSE Vic; (C) oblique aerial photograph Neville Rosengren Aug 2009).

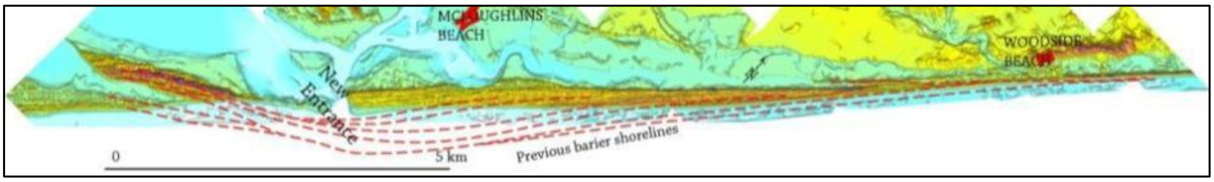


Figure 2-10 Proposed Ninety Mile Beach Realignment and Barrier Recession New Entrance to Woodside Beach

Between McLaughlins and Woodside the number of ridges decreases as the shoreline orientation has changed and the outer ridges have been eroded. At Woodside Beach a 4 m high bluff defines the limit of the mid-Holocene higher sea-level and in front of this is an old tidal channel, an inner barrier and two narrow seaward barriers at a different orientation from the older sand body and the present beach alignment (Figure 2-11). It is from here to the south that there has been substantial late-Holocene beach realignment.

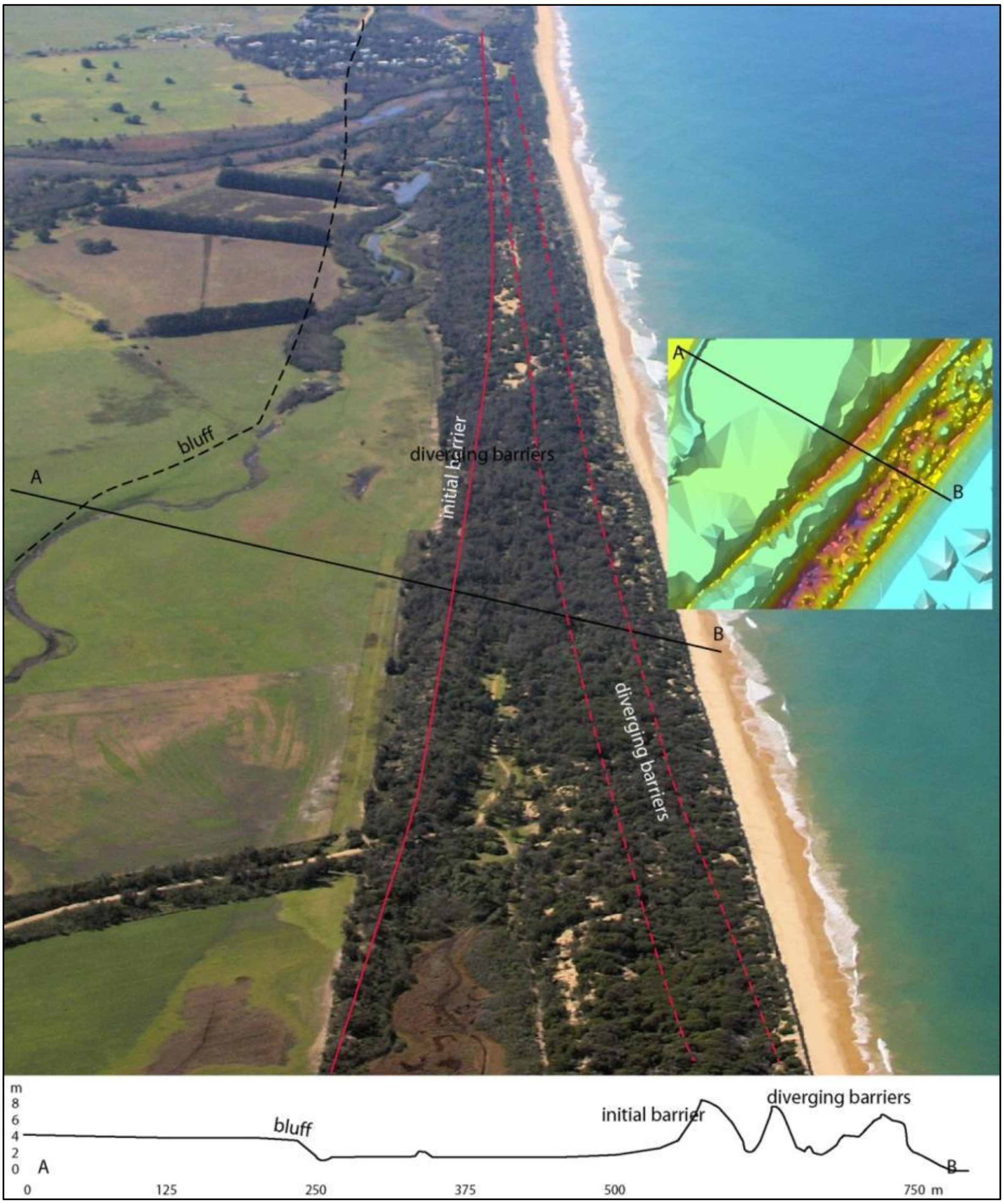


Figure 2-11 Bluff, Initial and Diverging Barriers at Woodside Beach (Lidar image DSE Vic; oblique aerial photograph Neville Rosengren Aug 2009).

2.2.5 Unit 3: Woodside Beach to Glomar Beach

This unit extends for 35 km from Woodside Beach to Glomar Beach northeast of Seaspray (Figure 2-12). It is a relatively straight coastline with a slight lobate protrusion in the Lake Denison sector from McGaurans Beach to south of Seaspray (Figure 2-12). The beach is backed by a single narrow barrier ridge with a backbarrier terrace, lagoons and a palaeo-tidal channel. A well-defined bluff marks the landward limit of Holocene higher sea-levels and in places is high enough to be a stranded Last Interglacial marine cliff. There is a single barrier ridge along this section with several low points where flood overflow and storm washover occur.

Figure 2-12 Single Barrier Ridge Northeast of Woodside (photograph Neville Rosengren Aug 2009)

The areas behind the barriers are the former embayment of Jack Smith Lake and Lake Denison, now closed by the barrier ridge but with several low points where flood outflow and storm washover occur. Behind the barrier ridge are lagoons and lakes, either occupying former tidal channels or the lower reaches of small creeks blocked by dune ridges. The core of the barrier is a young landform and must be less than 6000 years old and much is probably younger than 3000 years. The higher ridged dune that caps the barrier to both the northeast and southwest of Seaspray may only have developed since the arrival of marram grass inside the last 120 years. The low and narrow sectors of the barrier are vulnerable to storm overwash. At McGaurans Beach and in front of Lake Denison the barrier is a low terrace and discontinuous ridge 1.5 m to 3.5 m high (Figure 2-13).

Figure 2-13 McGaurans Beach 2001 Washover Site (photograph Neville Rosengren, August 2009)

A consistent feature of the backbarrier terrain in this unit is a broad sandy terrace - an occasionally active washover deposit 1.0 to 1.5 m above present sea-level - that lies between the barrier ridge and remnant tidal channels. The terrace pre-dates the modern barrier. Figure 2-14 displays former backbarrier lagoon peats exposed on the shoreward face of the barrier in this unit following a storm event in August 2001.

Figure 2-14 Former Backbarrier Lagoonal Peat Exposed due to Barrier Erosion, (photograph Neville Rosengren, August 2001)

East of Merriman Creek at Seaspray the single barrier ridge, less than 100 m wide at Seaspray and over 500 m wide at the Honeysuckles, continues to Glomar Beach. The volume of the Outer Barrier in the vicinity of Seaspray and the Honeysuckles are relatively small and of the order of only 250 m^3/m. The backbarrier terrain is complex with a sector of abandoned floodplain of Merriman Creek with a remnant leveed channel (Figure 2-15).

Cores across the backbarrier show the limited development of the dune and nearshore sand zone compared with the wide washover and lagoon zone (Figure 2-16). The latter are rich in estuarine shells with some marine species ((Gill, 1970); (Donner & Jungner, 1981)) indicating a long period of backbarrier lagoon development with freshwater inflow and occasional marine incursions. Intermittent marine connection implies partial barrier development rather than an extended closed barrier and the narrow modern barrier overlying estuarine facies indicates substantial barrier recession in the late Holocene.

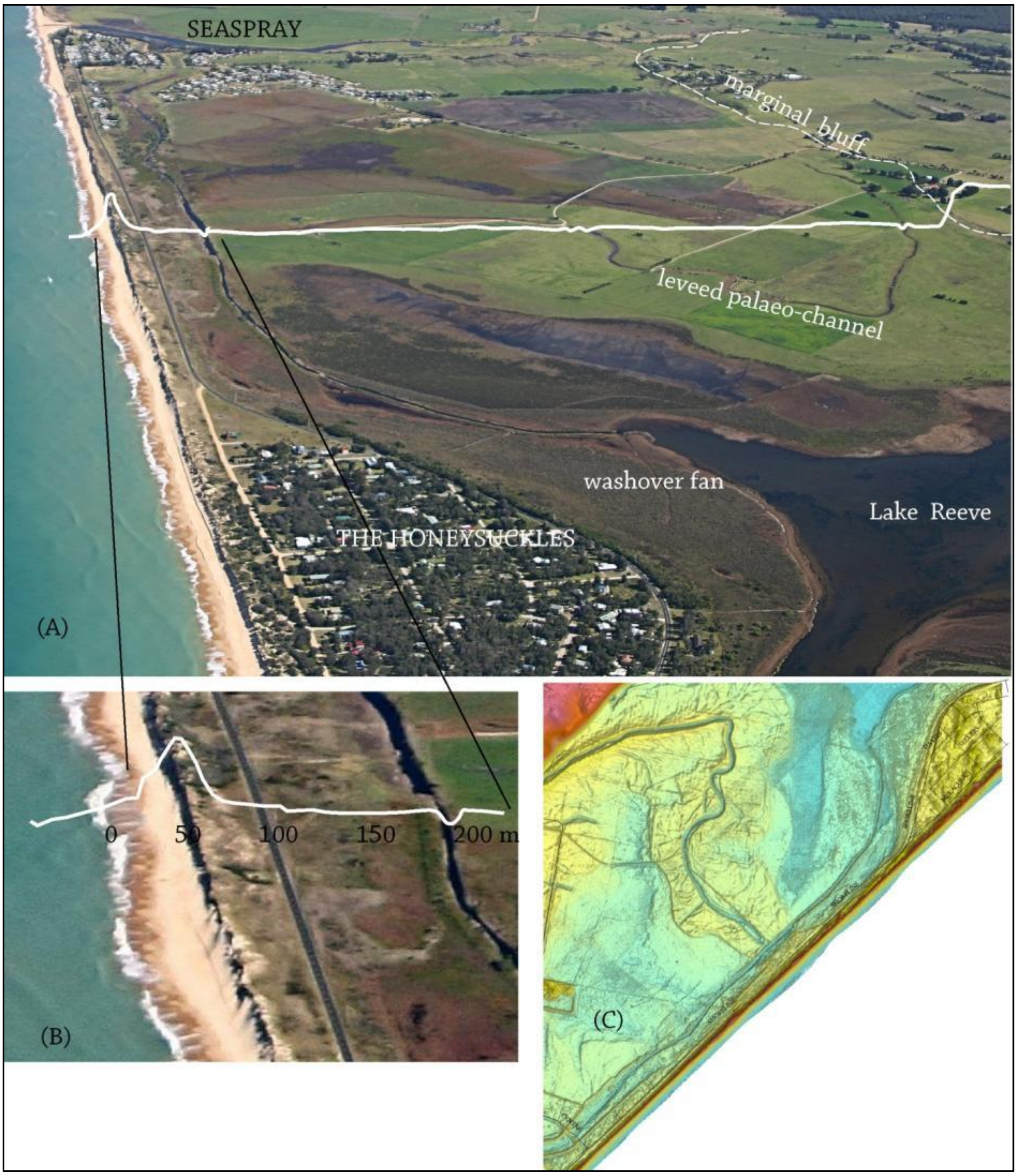


Figure 2-15 Barrier and Backbarrier Geomorphology – Seaspray to Honeysuckles. (Lidar image DSE Vic; photograph Neville Rosengren Aug 2009)

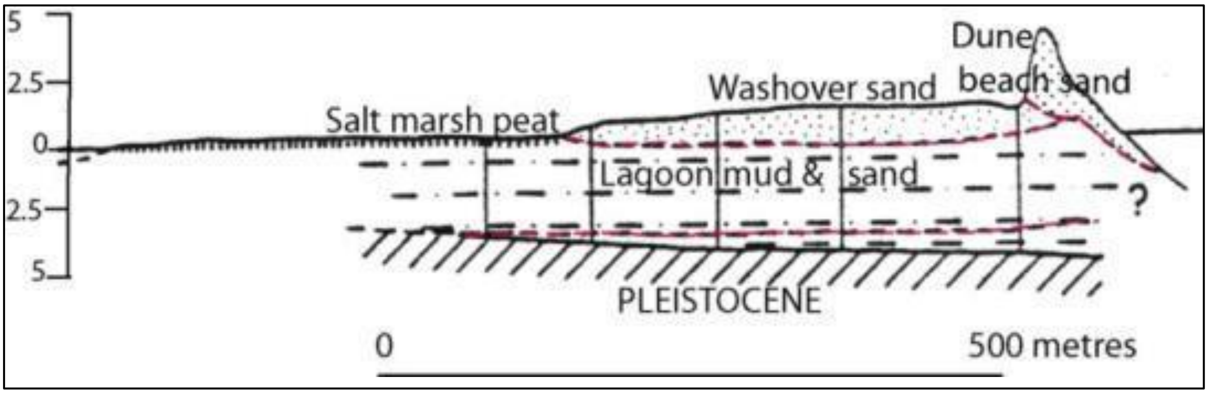


Figure 2-16 Stratigraphy of Coastal and Backbarrier Sediments at Honeysuckle (after Thom *et al.* 1983).

2.2.6 Unit 4: Glomar Beach to Paradise Beach

This unit extends 25 km from Glomar Beach to Paradise Beach. It is characterised by a wide barrier zone of multiple parallel ridges and broad sand terraces with a generally continuous cover of EVC 1 (Coastal Dune Scrub, low shrubland of *Acacia longifolia* and closed scrub of *Leptospermum laevigatum*). The sand complex includes foredunes, parallel ridges, small areas of transgressive dunes and broad sand terraces and flats. At Letts Beach (Golden Beach) there are 13 well-defined closely spaced ridges up to 10 metres high in a zone almost 500 m wide (Figure 2-17). More commonly there are only two to four ridges, the inner ridge rising in places to 15 m high. The volume of the barrier increases rapidly from the north east of the Honeysuckles such that at Golden Beach, the barrier volume can exceed 4000 m^3/m.

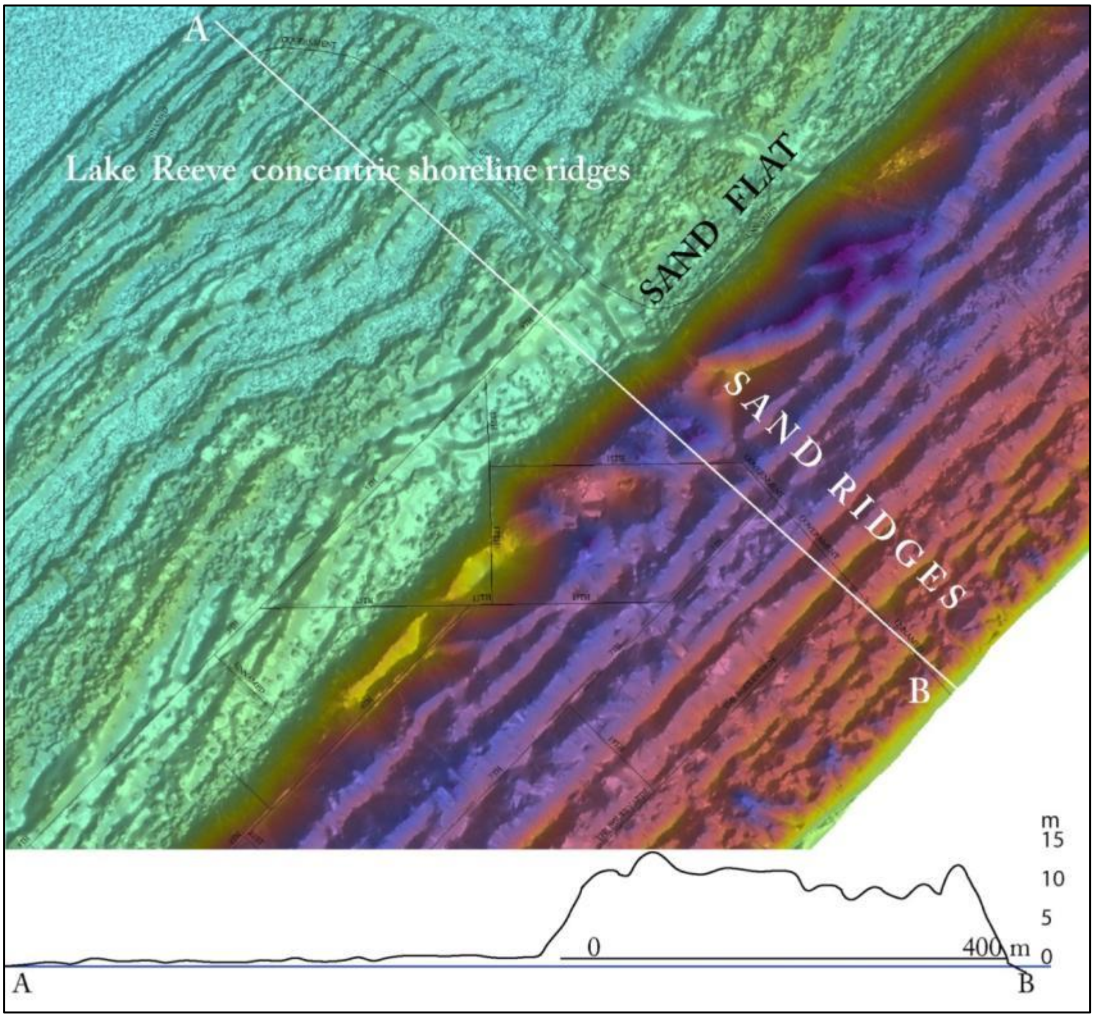


Figure 2-17 Multiple Barrier Ridge Profile at Letts Beach – Golden Beach

This stratigraphy of this barrier unit (Figure 2-18) shows the characteristics of a stationary barrier that has experienced a long (3,000+yrs) period of marine accretion and upward growth by wind action. The muddy and sandy mud sediments that lie below Lake Reeve and the inner washover sands of the barrier indicate a gradual enclosure of Lake Reeve and it transformation from a tidal lagoon to a semi-isolated saline flat (Thom 1984).

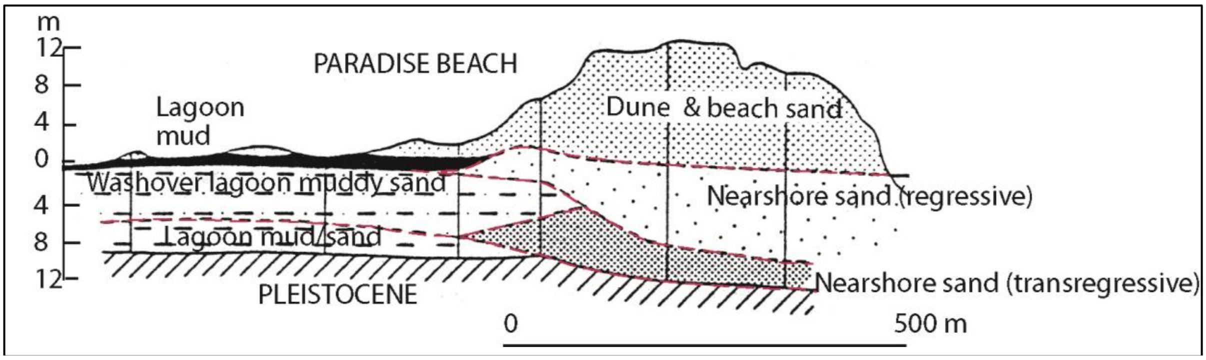


Figure 2-18 Stratigraphy at Paradise Beach (after Thom *et al.* 1983).

2.2.7 Unit 5: Paradise Beach to Loch Sport Ocean Beach

This unit is 22 km long and is similar to Unit 4 with two clear differences: (a) there are two groups of parallel ridges of different height; and (b) the rearmost dunes have been partly rearranged by transgressive dune development (Figure 2-19).

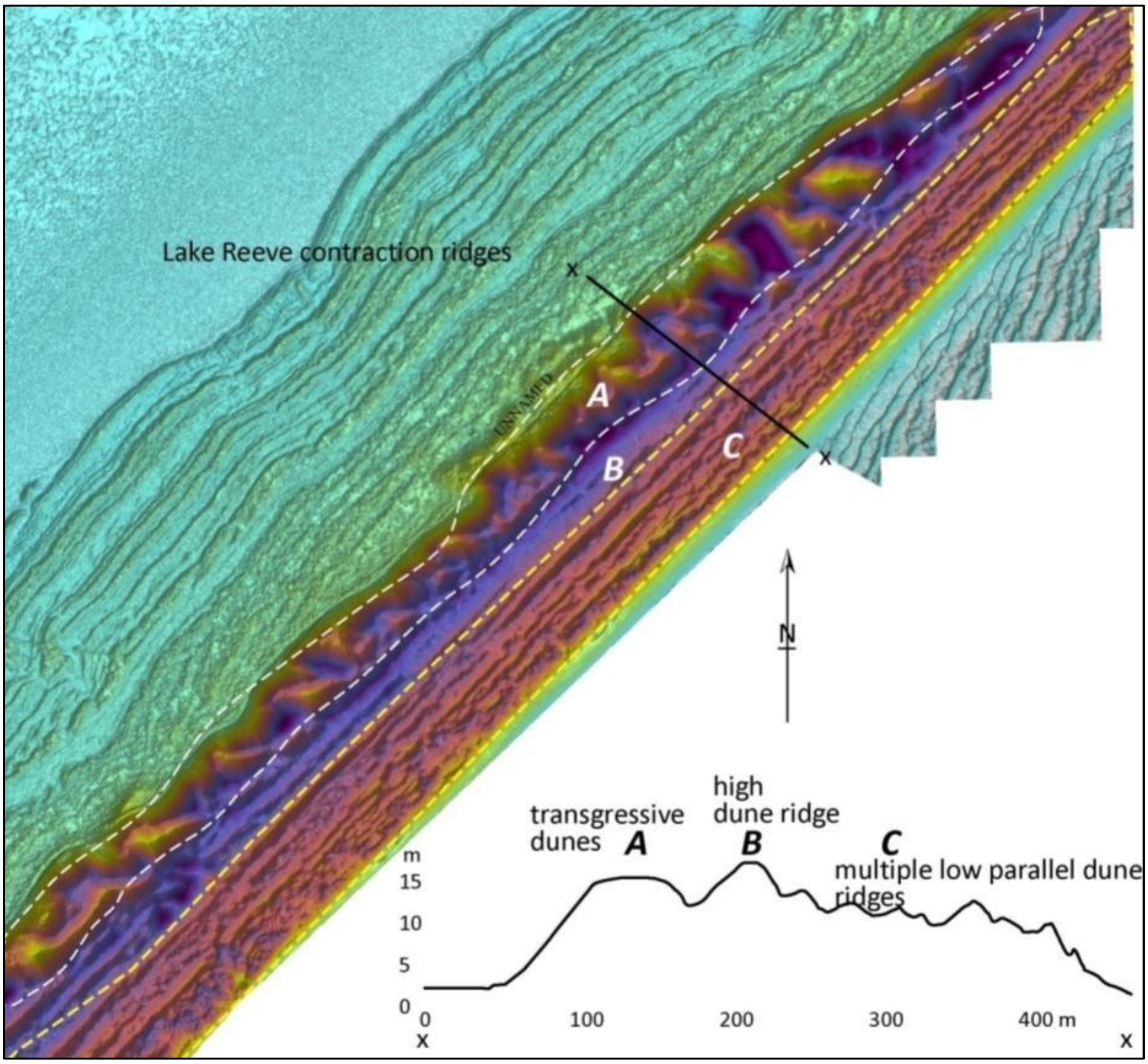


Figure 2-19 Lidar Image and Profile (A –B) of Dune Sets East of Paradise Beach

The frontal dunes are regularly spaced symmetrical parallel ridges numbering up to 10 in places and decreasing in height towards the shore. Behind these is a single or double ridge up to 5 m higher and with steeper slopes. The back of the sand body is a series of ridges and elongate depressions with a broadly west-east orientation that has the appearance of blowouts or U-shaped dunes. They are large structures with internal relief of 10 to 12 m and steep slopes, and are of much greater dimension than the areas of blowing sand in the frontal dunes. As the predominant wind direction along this coast is from the west, the resultant movement direction of wind-blown sand would be towards the east i.e. offshore. It is speculated here that these are “reverse” U-dunes in the sense that the direction of movement has been *towards* the shoreline and that masses of unconsolidated sand or previously developed parallel shoreline ridges or broad areas of washover sands have been reactivated as transgressive dunes. It is also likely that some blowouts have been initiated by onshore easterly to south-easterly winds.

Figure 2-20 **Dune Systems North-east of Paradise Beach Showing Apparent Directions of Movement of Transgressive Sand Movement (arrows). (Vertical aerial photograph 2006)**

2.2.8 Unit 6: Loch Sport Ocean Beach to Ocean Grange

This unit extends for 19 km from the Loch Sport Ocean Beach to Ocean Grange. It is distinguished by the backbarrier terrain of sub-parallel curving ridges, islands and subaqueous banks separated by well-defined channels that trend at right angles to the coast (Figure 2-21). This backshore topography ends at Ocean Grange where the islands and channels extend into Lake Victoria. The site is the clearest example of multiple washover channels developing a long-lived tidal inlet with a delta island and channel complex forming between the Boole Poole Peninsula and Rotamah Island. The curvature of the forms is a result of alongshore drift deflecting the ebb tidal currents towards the east and northeast, therefore defining the orientation of the channels and tidal depositional banks.

The sand on Rotamah Island pre-dates the tidal incursions that developed the channels as they truncate the western margin of the island. The barrier sequence that overlies and enclosed these inlets is a narrow series of 2 to 5 parallel ridges. The stratigraphy established by drilling at Stockyard Hill (Figure 2-22) shows the barriers to be less than 4000 years old overlying sands and mud of abandoned tidal channels filled with organic mud (Thom, Short, & Hobday, 1983).

North-east from Stockyard Hill the barrier ridge set gradually narrows from over 200 to 75 m width and ridge numbers decrease to be a single lower ridge. The volume of the barrier similarly declines north-east from Stockyard Hill to be less than approximately 1,000 m^3/m. The number of blowouts also increases as the changing orientation of the coastline increases the influence of onshore southerly to south-westerly winds.

Figure 2-21 Former Tidal Inlet Channels and Delta Islands West of Rotamah Island. (Photograph Neville Rosengren Aug 2009).

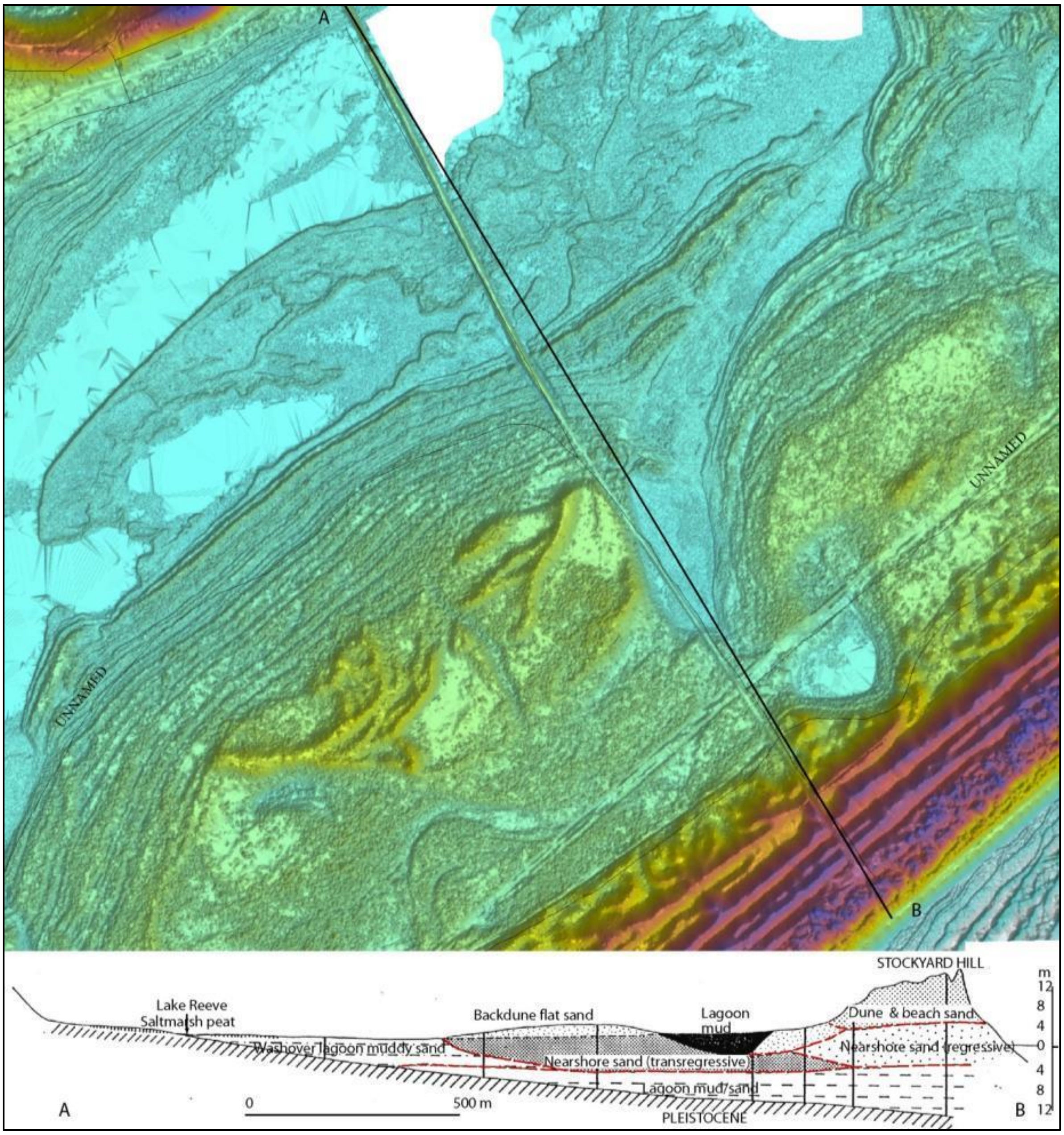


Figure 2-22 Lidar Image, Stratigraphy Stockyard Hill. (Lidar image: DSE Victoria; stratigraphy: Thom *et al.* 1983).

2.2.9 Unit 7: Bunga Arm

This unit extends 13 km from Steamer Landing at Ocean Grange to the eastern end of Bunga Arm. It is a single irregular barrier ridge 50 to 150 m wide and 4 to 8 m high with occasional higher crests greater than 12 m (Figure 2-23). The barrier volume declines north-eastward along Bunga Arm to approximately 300 m^3/m. The ridge crest is interrupted by numerous blowouts forming shallow U-dunes and sand flats adjacent to Bunga Arm.

Bunga Arm is an extension of Lake Victoria between Rotamah Island and the outer barrier. It is closed by sand and marsh at the eastern end. A number of sandy lobate features extend from the inner edge of the barrier ridge into Bunga Arm. These originate either as storm washover fans, dune blowout splays or cuspate shoreline segmentation spits and many are probably of compound origin. They develop almost exclusively on the barrier shore of Bunga Arm with poor development on the

Rotamah Island shoreline. Although similar in some respects to the tidal delta islands and banks at Ocean Grange, these originate from short-lived breaches of the outer barrier and have not had time to develop as tidal deltas.

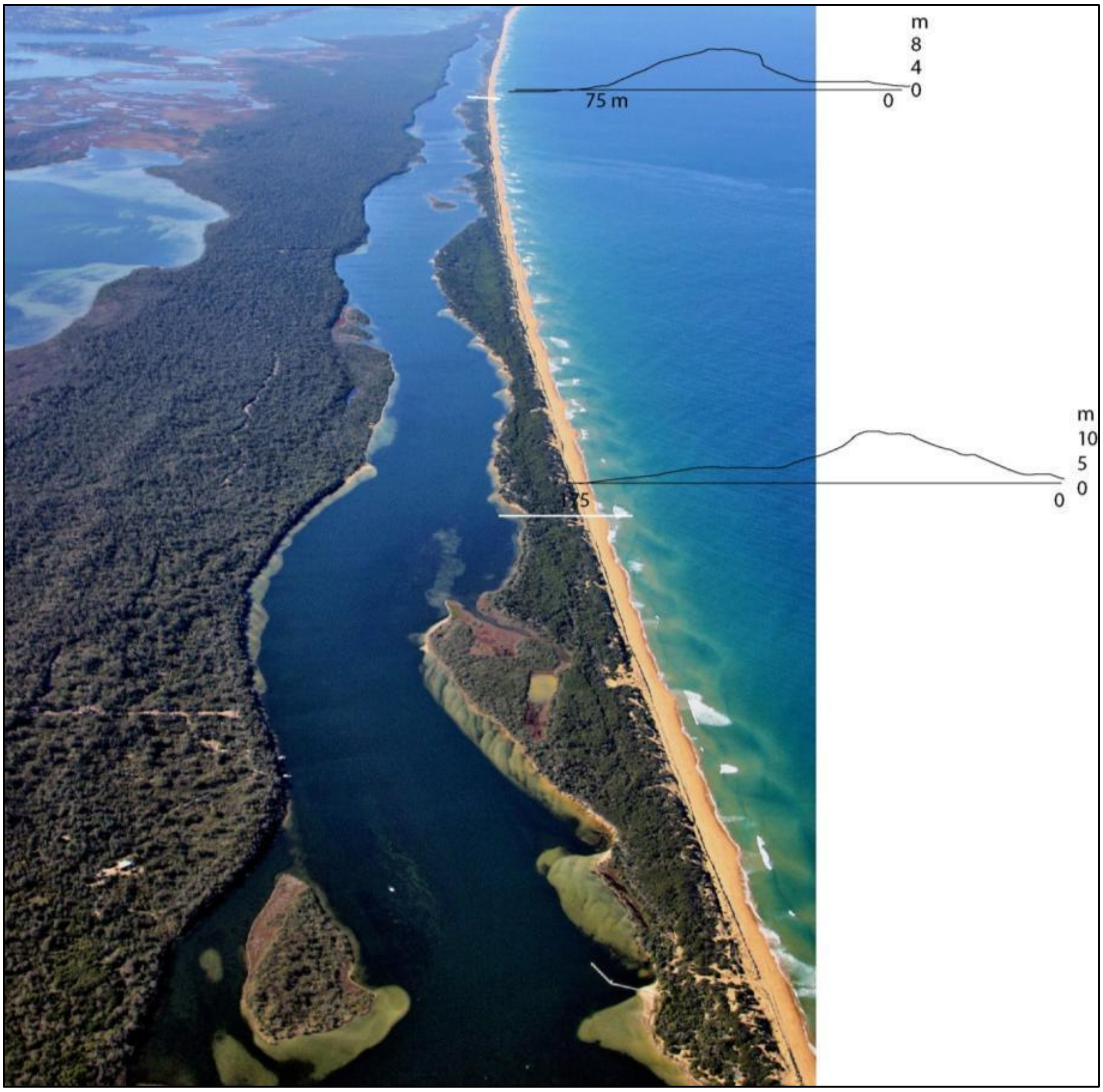


Figure 2-23 **Barrier Adjacent to Bunga Arm and Representative Profiles (Photograph Neville Rosengren Aug 2009).**

2.2.10 Unit 8: Barrier Landing

This short sector extends from the eastern end of Bunga Arm for 4.5 km to Barrier Landing and is backed by the infilled former eastern end of Bunga Arm. The barrier has similar dimensions to Unit 7 but has a sandy backbarrier flat with low sand ridges (Figure 2-24).

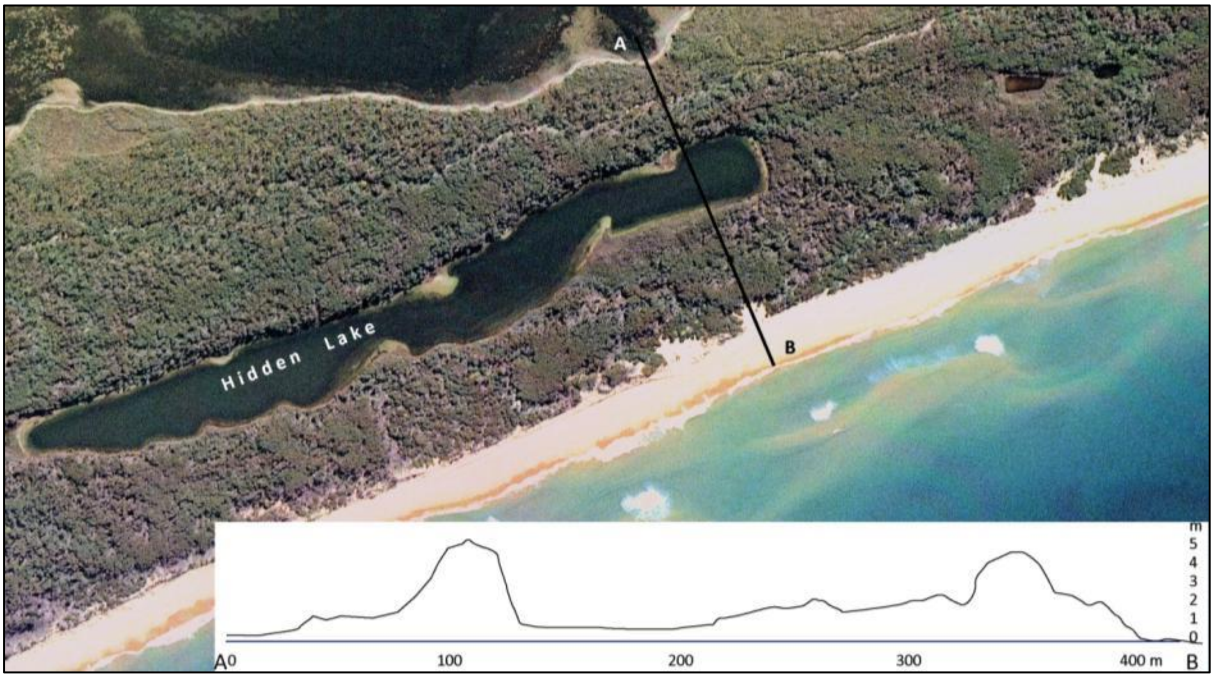


Figure 2-24 Low, Narrow Barrier and Backbarrier Sand Ridges at Hidden Lake. (Vertical air photo 2006).

2.2.11 Unit 9: Lakes Entrance

This unit extends 6.5 km east from opposite Barrier Landing, across Lakes Entrance to the eastern end of Cunninghame Arm (formerly known as Reeves River). It includes the artificial and dredged entrance to the Gippsland Lakes opened in 1889. Apart from the recovery of the barrier east of the New Entrance at McLauglins Beach (Unit 2), this is one of the few sectors of the outer barrier displaying sustained foredune and barrier ridge accretion and is a consequence of the stone jetties and concrete breakwaters that define and extend seaward of the cut entrance. These trap sand from longshore drifting either east or west and also delivered by the ebb tide and through the entrance (Bird E. C., Historical changes on sandy shorelines in Victoria, 1980). Constructive wave action has built two broad forelands extending up to 300 m beyond the pre-entrance shoreline (Figure 2-25).

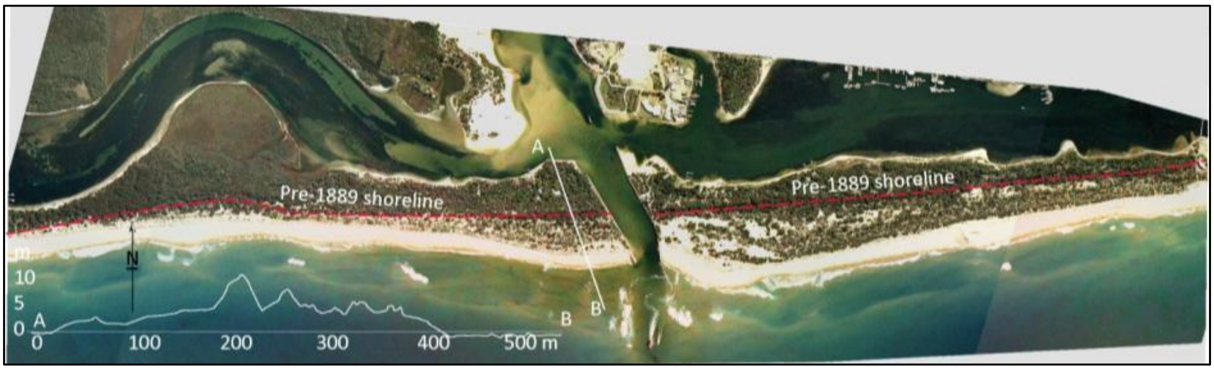


Figure 2-25 Forelands Extending Adjacent to Breakwaters, Lakes Entrance. (Vertical air photo 2006)

2.2.12 Unit 10: Eastern Beach to Lake Bunga

This unit commences at the eastern limit of the shoreline progradation developed adjacent to the entrance breakwaters and extends 2.9 km to the entrance of Lake Bunga. It is a unit with narrow (30 to 70 m wide), low (4 to 7 m with occasional 10 m height) barrier dunes as single or in places multiple ridges. The backshore is the mainly infilled remnant of the former Reeve's River, the easternmost expression of the Gippsland Lake system. Reeve's River was a channel that opened to the sea across the sand barrier near Lake Bunga. The position of the entrance moved east-west according to wave and sand drift and was frequently shallow or closed by a sand bar and berm. After the cutting of the artificial entrance in 1889, the eastern part of Reeve's river rapidly filled with overwashed and wind-blown sand (Bird & Lennon, 1973). Several elongate parabolic dunes that lie almost shore-parallel and contain the fairways of the Lakes Entrance Golf Club therefore post-date the opening of the entrance. Based on radiocarbon dating of shells, Thom (1984) recognised two episodes of barrier formation: (a) a mid-Holocene (~ 6,000 years ago) deposit on the northern side of Reeve's River (Cunninghame Arm) and a younger (~3,000 years ago) modern beach and barrier.

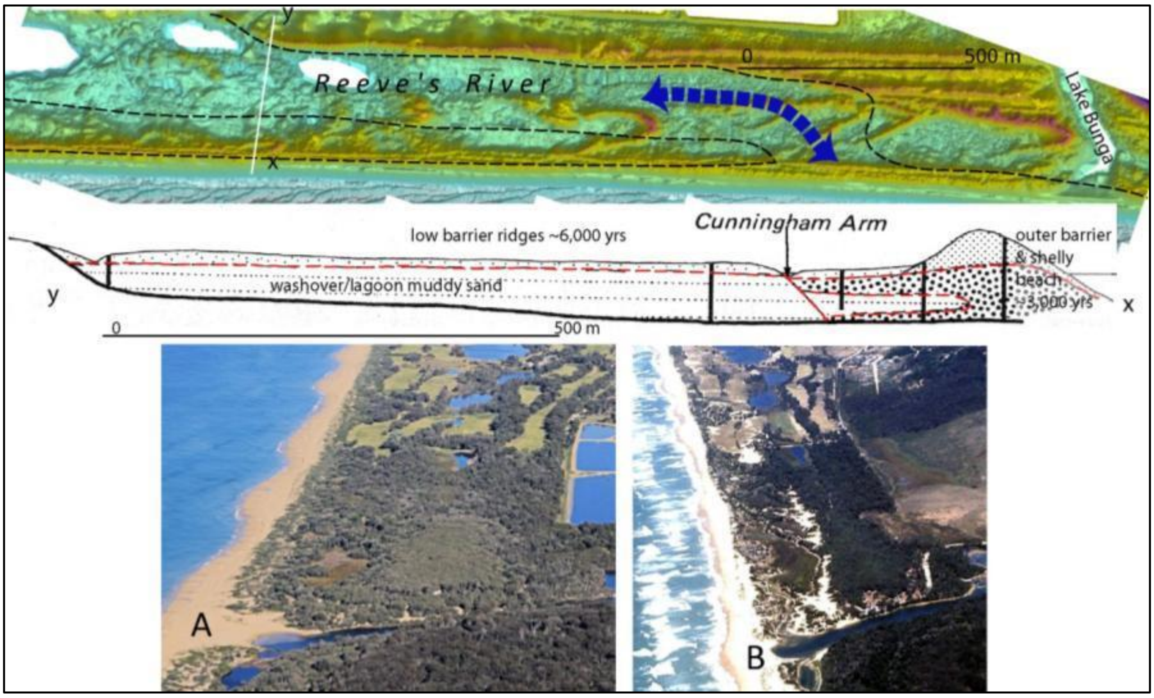


Figure 2-26 Eastern Beach and Lake Bunga showing former Reeve's River and Pre-1889 Entrance to Gippsland Lakes (broken blue line)

Stratigraphy from Thom (1984). Aerial oblique photographs 2010 (A) and 1972 (B) show increase in vegetation cover of dunes. (Photographs Neville Rosengren, Oct. 2010 and Nov. 1972).

2.2.13 Unit 11: Lake Bunga to Red Bluff

This unit extends from the intermittent opening of Lake Bunga for 1.4 km to the seacliff that defines the eastern margin of the Ninety Mile Beach at Red Bluff. Red Bluff is the only active marine component of the marginal bluff, the former seacliff cut by Pleistocene higher sea-levels into the Cainozoic sedimentary rocks that form the hinterland and basement of the Gippsland Lakes embayment. The barrier is a series of irregular ridges and hummocks at the base of the bluff east of Lake Bunga (Figure 2-27). There are two groups of ridges - a single 5 to 6 m high ridge extends 200 m east from an enclosed remnant of Lake Bunga and reoccurs at the base of the bluff 500 m east. There are two well-defined lower ridges in front of this separated by a well-defined swale.

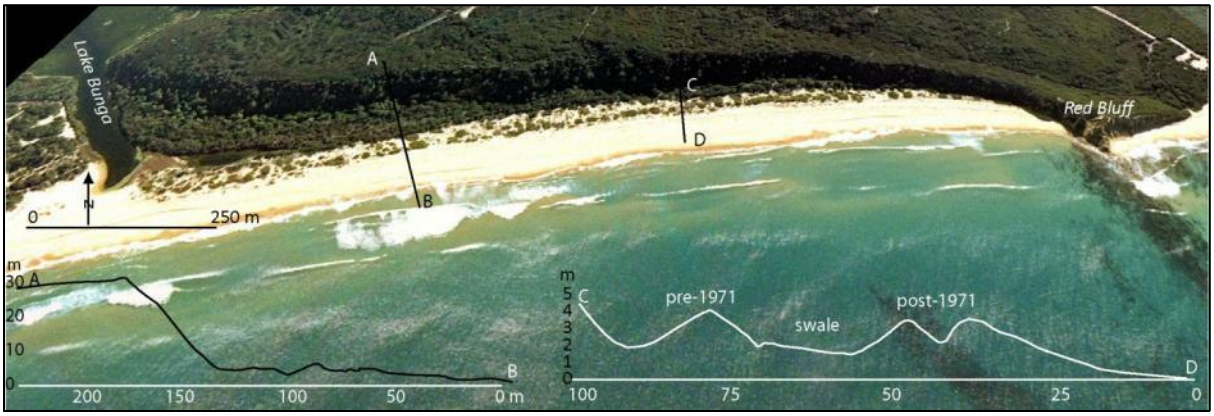


Figure 2-27 Ridges between Lake Bunga and Red Bluff. Profiles are at different scales. (Photo base 2006)

2.3 Summary

The analysis of the geomorphology of the Outer Barrier has highlighted the extent of the variation in the origin, evolution and contemporary morphology of this landform along the length of the study area. The review of the geomorphology of the Outer Barrier is considered to have identified the following key points relating to the assessment of coastal hazards along the Outer Barrier:

- Due to the extent of the variation in the origin, evolution and contemporary morphology of the Outer Barrier, the type and extent of coastal hazards could be expected to also vary significantly along the length of the Outer Barrier;
- The extent of the late Holocene evolution and rearrangement of the Outer Barrier highlights the susceptibility of this landform to relatively rapid morphological change and associated coastal hazards associated with changes to sea levels and/or sediment supply.

The characteristics of the geomorphic units within the study area in terms of the volume, number of ridges, height and back barrier terrain discussed in the previous sections have been summarised below in Table 2-1. The delineation of the Outer Barrier into the geomorphic units summarised in Table 2-1 provides the basis for the assessments of the sea level rise response mechanism, variability and subsequent extent of coastal hazards along this landform.

Table 2-1 Summary of the Geomorphologic Units of the Outer Barrier

Unit	Barrier Morphology	Back Barrier Morphology	Max. Dune Crest Height Range (m AHD)	Barrier Volume Range (m^3/m)	Barrier Type
Unit 3: Woodside Beach to Glomar Beach	Single narrow barrier ridge	Backbarrier terrace, lagoons and palaeo-tidal channels.	2.5 – 10	250 – 1,000	Transgressive
Unit 4: Glomar Beach to Paradise Beach	Multiple parallel ridges. Typically 2-4 ridges, but 13 closely spaced ridges identified at Golden Beach	Lake Reeve	6.5 - 20	800 – 4,500	Stationary/Regressive
Unit 5: Paradise Beach to Loch Sport	Multiple parallel ridges.	Lake Reeve	10 - 18	2,100 – 4,700	Stationary/Regressive
Unit 6: Loch Sport to Ocean Grange	Multiple barrier ridges declining to a single ridge towards Ocean Grange	Lake Reeve and sub-parallel curving ridges, island and subaqueous banks extending into Lake Victoria	11 - 18	2,500 - 900	Stationary/Regressive
Unit 7: Bunga Arm	Single irregular barrier ridge	Bunga Arm lagoon	4 - 15	110 – 1,000	Stationary
Unit 8: Barrier Landing	Single irregular barrier ridge	The infilled former eastern end of Lake Bunga – a sandy backbarrier with flat low sand ridges	5 - 10	250 - 850	Stationary
Unit 9: Lakes Entrance	Multiple irregular barrier ridges	Cunninghame Arm	6 - 12	370 - 1,600	Regressive
Unit 10: Eastern Beach to Lake Bunga	Narrow, low barrier dunes as single or in places multiple ridges	Infilled remnant of the former Reeve's River	5 - 12	200 – 1,700	Regressive
Unit 11: Lake Bunga to Red Bluff	Series of Irregular ridges and hummocks	Marginal Bluff	5 – 15+		Stationary

3. METOCEAN CONDITIONS

The magnitude, frequency and variability of the main meteorological and oceanographic processes that impact the Outer Barrier have been analysed and reviewed. The physical oceanographic and meteorological processes of Eastern Bass Strait have strongly influenced the late Pleistocene and Holocene evolution and contemporary coastal processes of the Outer Barrier. Review and analysis of these processes provides the foundation for understanding historical coastal change. This in turn enables the assessment of potential coastal hazards along the Outer Barrier, due sea level rise this century, to be undertaken.

3.1 Wind Climate

Along the Outer Barrier, winds are predominantly westerly, with minor southerly and easterly components. As the broad orientation of the Outer Barrier is to the NE, the majority of the strongest and most persistent winds blow offshore, however, there is some variation along the study area.

Figure 3-1 displays the wind climate in the south west of the study area, relative to the shoreline orientation at Seaspray. From Figure 3-1 it can be seen that the shoreline is aligned to the NE (45^0) such that only winds from the south to east have appreciable onshore components at Seaspray. However from Figure 3-1 it can be seen that at Lakes Entrance, the shoreline is aligned more closely to the ENE (70^0) and winds from the south-west generate a slight onshore component.

The limited exposure of the Outer Barrier in the study area to the prevailing west to south westerly winds limits the influence of aeolian transport processes on backshore dune formation and transgressive dune field development.

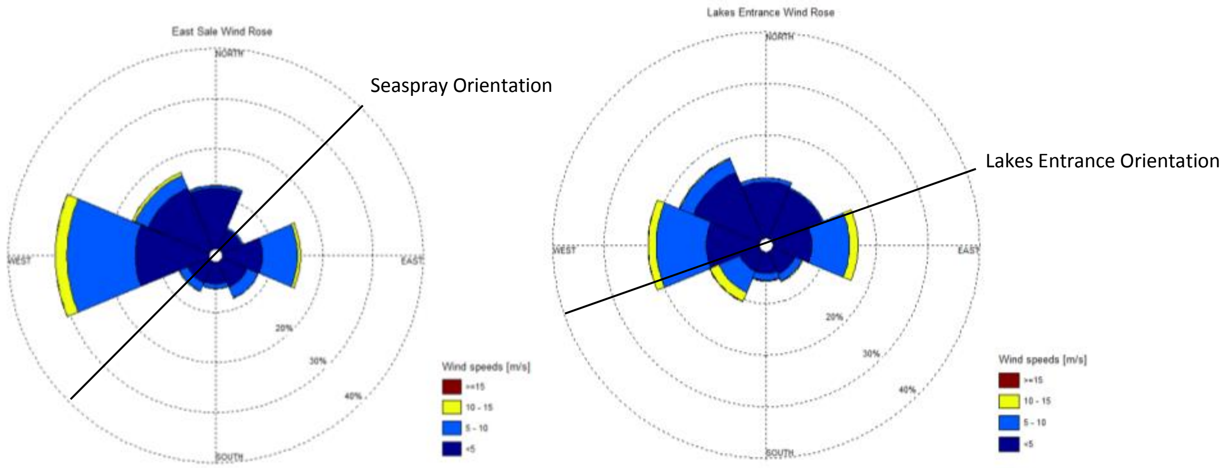


Figure 3-1 Wind Climate Relative to Shoreline Orientation along the Outer Barrier

3.2 Wave Climate

Waves and the variability associated with their height, period and direction comprise the principle source of energy for mobilising the sediments of the Outer Barrier. Waves and wave driven processes (such as sediment mobilisation and alongshore currents) both result in constructive barrier building and destructive barrier erosion processes. The relative difference between these two opposing processes subsequently influences coastal evolution and the potential extents of coastal hazards along the Outer Barrier.

To develop a long term understanding of the wave climate and its variability in Eastern Bass Strait for the study area, a 63 year (1948-2011) wave hindcast has been simulated with a calibrated spectral wave model as described in Appendix A.

The wave climate of the East Gippsland coast is largely sheltered from direct exposure to the highly energetic wave climate of the Southern Ocean by the Tasmanian landmass, although waves from this source do refract around the eastern side of the Tasmania. Larger waves are therefore principally generated within eastern Bass Strait by south westerly to southerly winds and in the South Tasman Sea by east to south-easterly winds.

The percentage exceedance of significant wave heights from the 63 year wave hindcast at Lakes Entrance is displayed below in Figure 3-2. From Figure 3-3 it can be seen that significant wave heights are generally between 0.5 and 1.0 m. Significant wave heights exceed 2.0 m less than approximately 2% of the time at Lakes Entrance. A slightly higher percentage of larger waves are observed at Lakes Entrance than the south-western end of the study area at Seaspray. This variation is attributed to the greater attenuation of waves by bed friction across the widening continental shelf towards the south-west of the study area.

Figure 3-3 displays the variation in the directional distribution of significant wave heights at Seapsray and Lakes Entrance over the 63 year wave hindcast. From Figure 3-3 it can be seen that mean wave directions are principally from the south and south-east with minor contribution from south-westerly and easterly waves. Towards the south-west at Seaspray, the slightly greater easterly aspect of the coastline results in a slightly greater percentage of waves arriving from the east compared to the more south-east facing coastline at Lakes Entrance.

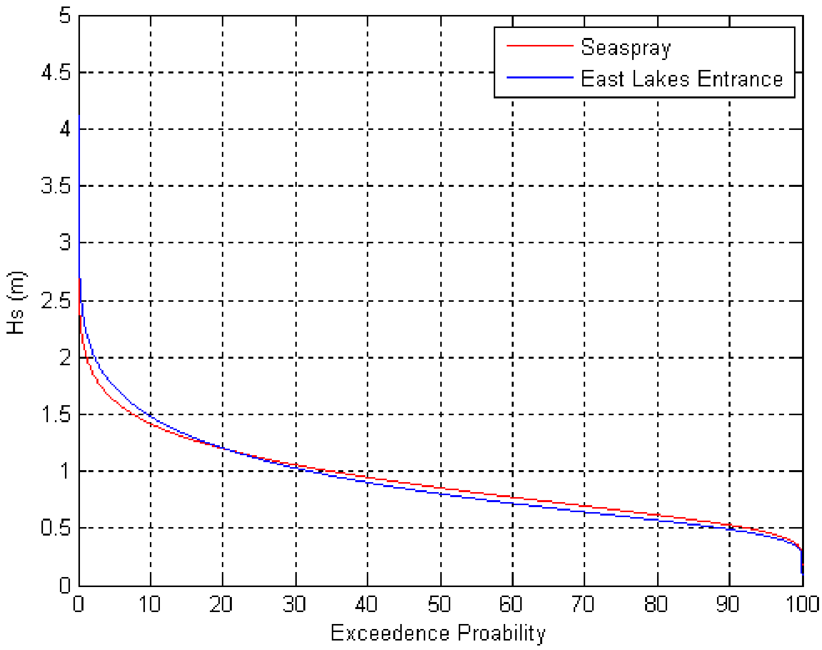


Figure 3-2 Significant Wave Height Percentage Exceedance (1948-2011)

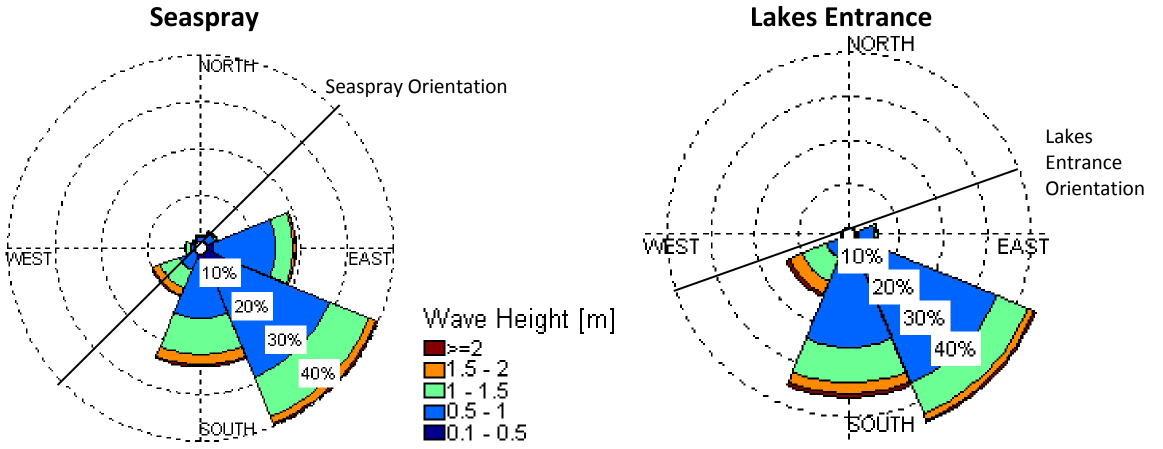


Figure 3-3 Rose Plots of Significant Wave Height 1948 - 2011 at Seaspray and Lakes Entrance

3.2.1 Storm Wave Climate

The long-term hindcast wave climate has been analysed to characterise the storm wave climate of the study area. The development of an understanding of the magnitude, duration and frequency characteristics of the storm wave climate is important for understanding the coastal hazards along the Outer Barrier.

Individual storm events were identified from the wave hindcast using a peak-over-threshold (POT) method. A significant wave height threshold of 3.0 m was used and a minimum storm duration of 6 hours was adopted. Individual storm events within 48 hours of each other were assumed to be generated by the same meteorological system and were combined. To integrate both the storm intensity (wave height) and duration to provide a measure of overall storm severity, the cumulative storm energy was calculated for each of the storm wave events identified from the hindcast wave climate after the method described by Harley, Turner, Short, & Ranasinghe (1992). The weighted mean wave direction was also calculated for each storm wave event in the hindcast data.

The cumulative storm wave energy for each POT event was calculated using the following equation:

$$E = \frac{1}{16}\rho g \Delta t \sum_{i=1}^{N} H_i^2$$

Where

N is the number of hourly data points *i* in the event duration

p is the mass density of sea water

g is the acceleration due to gravity

Δt is the temporal resolution of the dataset

H is the significant wave height

The above analysis yielded a total of 78 storm wave events from a total of 63 years of wave hindcast. Figure 3-5 displays the identified storm wave events as a function of their estimated cumulative wave energy.

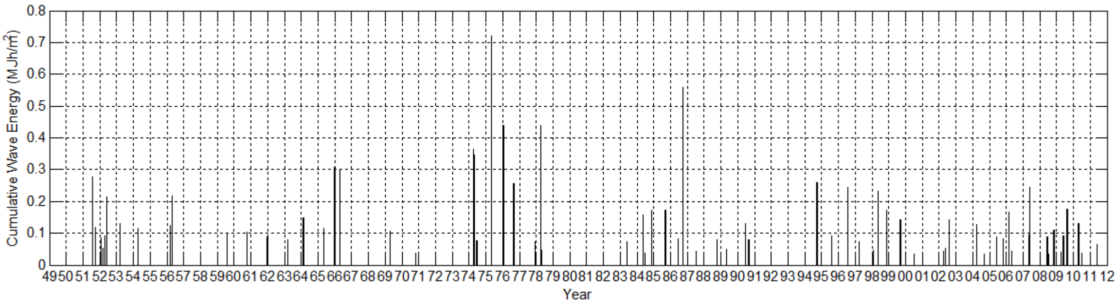


Figure 3-4 Historical Series of Storm Wave Events at Lakes Entrance

From Figure 3-5 it can be seen that the storm wave events are not distributed evenly over the historical record but display significant clustering on an approximate decadal scale. Relationships between storm intensity and frequencies on the east coast of Australia have been identified as potentially being modulated by the Interdecadal Pacific Oscillation (IPO) and El Niño-Southern Oscillation (ENSO) by You & Lord (2008) and Shand et al. (2010).

From the clustering of storm wave events displayed in Figure 3-5, periods of heightened wave storminess were interpreted as displayed in Figure 3-5 and listed below:

- 1950-1956;
- 1964-1967;
- 1974-1978;
- 1984-1987;
- 1995-2001; and
- 2007-2011;

The approximate periods identified in Figure 3-5 and listed above correspond remarkably well with documented periods of significant storminess and coastal hazard impacts on the NSW coastline (Hanslow & Gissing, 2010).

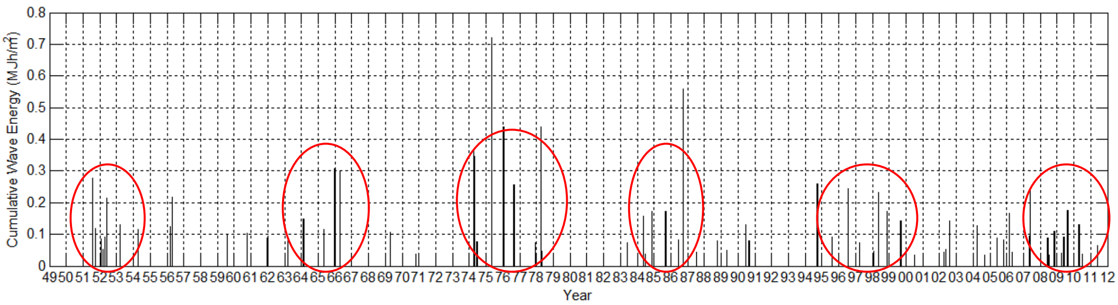


Figure 3-5 Clustering of Storm Wave Events from the Historical Wave Record at Lakes Entrance

To provide an estimate of the expected recurrence interval of large storm wave energy events along the study area, statistical analysis of the population of cumulative wave energy events identified from the POT method was undertaken.

Initially, an annual series of maximum wave energy events from each of the 63 years of wave hindcast was fitted to various extreme value distributions. However, the clustering of the large storm wave events in the historical record resulted in the annual maxima excluding significantly large events when two, or more, occurred within the same year. Conversely, annual maxima analysis resulted in the inclusion of numerous relatively small events from the periods between large event clusters. These characteristics of the storm wave climate resulted in the annual maxima series producing a poor fit to extreme value distributions and an apparent significant underestimate of the recurrence interval of large storm wave events.

To overcome this limitation, a partial series analysis was performed on the cumulative wave energy event series. A negative exponential distribution was fitted to the 58 largest events to estimate the average recurrence interval between events of a given magnitude, as shown in Figure 3-6. Figure 3-6 demonstrates the strong fit achieved between the statistical distribution and the cumulative wave energy event series.

From Figure 3-6 it can be seen that the largest event is estimated as slightly exceeding a 1 in 100 year ARI. It can also be seen that four of the top five events occurred within a 5 year space of time during the mid to late 1970's, highlighting the intensity of the clustering of extreme storm wave events apparent in the historical record.

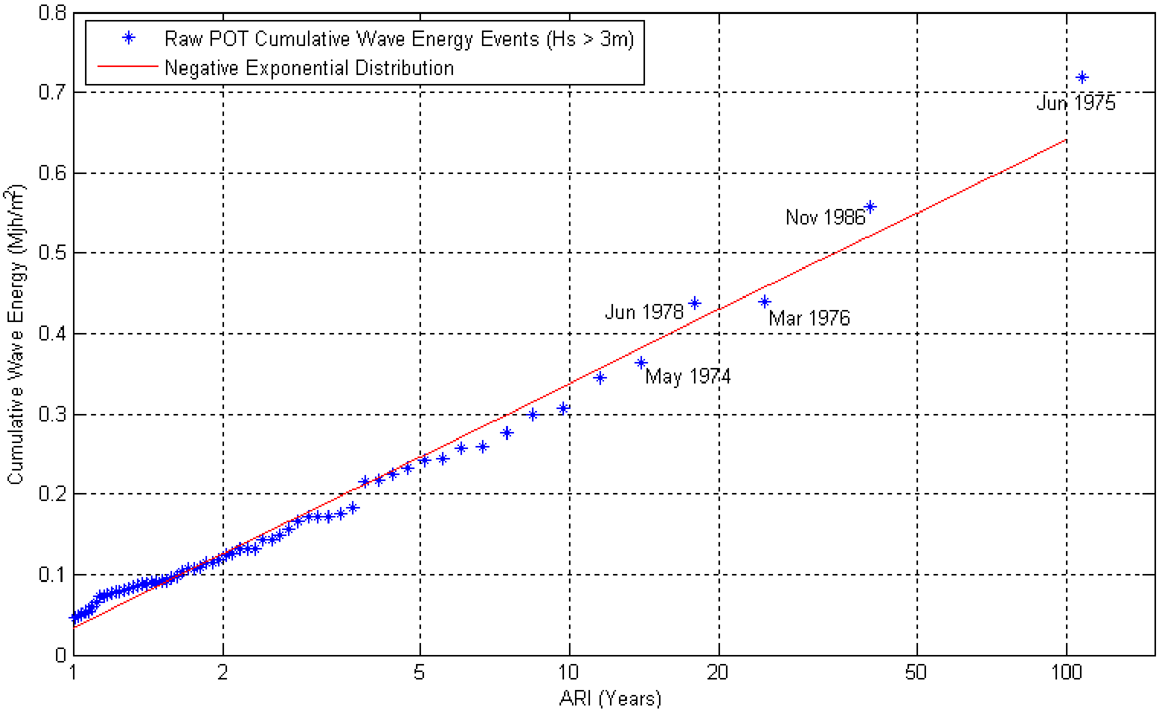


Figure 3-6 **Average Recurrence Interval Distribution of Cumulative Wave Energy for Storm Events Greater than 3m at Lakes Entrance**

Analysis of the relationship between the characteristics of the storm wave events and the weighted mean wave directions has also been undertaken. Figure 3-7 (left) displays the storm wave event durations as a function of weighted mean wave direction. It can be seen from the left hand figure that the longest duration storm events occur from the south-easterly direction and have durations generally between 48 and 72 hours. Figure 3-7 (right) displays the cumulative wave energy as a function of the weighted mean wave direction and shows a similar pattern with the largest storm wave events impacting the study area from the south-east.

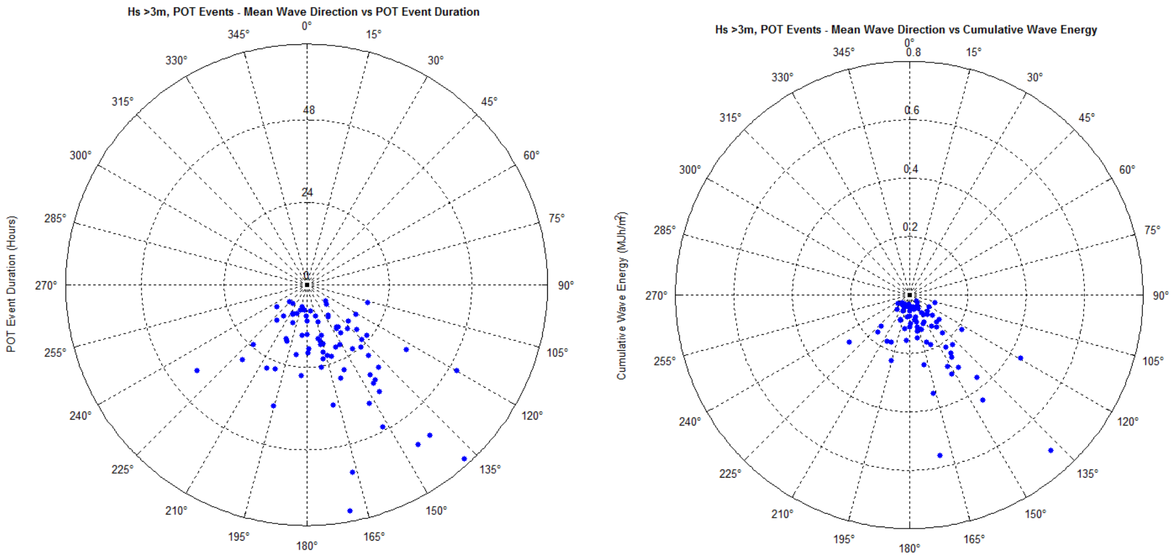


Figure 3-7 Storm Wave Event Characteristics as a Function of Weighted Mean Wave Direction

The synoptic weather systems generating sustained and large south-easterly wave events on the eastern seaboard that have been identified from the analysis of the wave climate are generally associated with East Coast Low (ECL) extra-tropical cyclones (Dowdy, Kuleshov, De Wit, Schweitzer, Phan, & Jones, 2011). Figure 3-8 displays an example of the typical synoptic pattern associated with an ECL that results in a tight pressure gradient and strong anti-clockwise circulation and subsequent generation of sustained, storm-force south-easterly winds and waves along the study area coastline.

The clustering of ECL storm wave events in the study area, most likely in response to decadal scale climate variability, is considered significant for assessing the potential extent of coastal hazards along the study coast. The cumulative nature of the physical impacts of these storm events is expected to be such that the relationship between the magnitude of an individual storm event and corresponding magnitude of the coastal hazard impact, are likely to vary considerably as a function of the antecedent storm events and subsequent physical state of the Outer Barrier. For these reasons, the assessment of the potential extent of coastal hazards from storm related erosion is most appropriately estimated by considering a sequence of large ECL storm events.

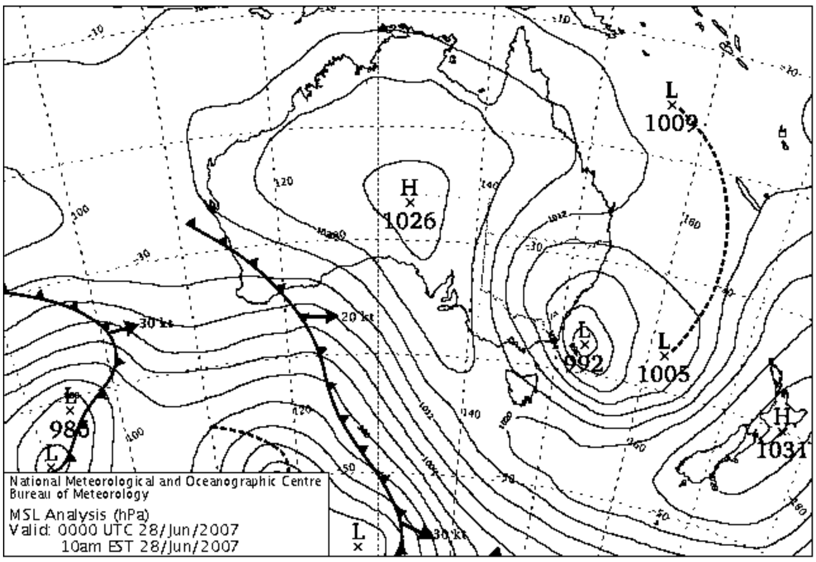


Figure 3-8 Typical East Coast Low MSLP Pattern Resulting in Large South Easterly Wave Events

3.3 Coastal Water Levels

Along the seaward side of the Outer Barrier, water level variations are primarily caused by a combination of the inverse barometric pressure affect, coastally trapped waves and astronomical tides.

3.3.1 Astronomical Tides

The gravitational interactions associated with the sun and moon on the earth's oceans generate regular water level variations commonly referred to as the tide. The Eastern Bass Strait coastline experiences a micro-tidal climate with the tidal range increasing slightly towards the south-west of the study area due to resonance of the tide within Bass Strait. Table 3-1 displays the main astronomical tidal planes at Lakes Entrance relative to Lowest Astronomical Tide (LAT).

Table 3-1 Astronomical Tidal Planes for Lakes Entrance (Outer) and Seaspray (ref. to LAT)

	HAT (m)	MHHW (m)	MLHW (m)	MSL (m)	MHLW (m)	MLLW (m)
Lakes Entrance (Outer)	1.4	1.2	0.8	0.8	0.7	0.3
Seaspray[1]	1.6	1.4	1.0	0.9	0.8	0.2

[1] Approximated from tidal constituents at McGauran's Beach (Hinwood, 1986)

3.3.2 Storm Surges

Storm surge is the common term used to describe variations in coastal water levels that exceed that which can be attributed to the astronomical tide. Storm surges are generated by a combination of the inverse barometric pressure affect, coastally trapped waves and wind setup.

Estimated recurrence intervals of peak storm surge and storm tide levels for the open coast at Seaspray for relevant sea level rise scenarios have been developed by the CSIRO and are displayed in Table 3-2. CSIRO estimates at Lakes Entrance are for inside the entrance and not applicable to the open coast as the data is influenced by flooding.

Table 3-2 Estimated Storm Surge and Storm Tide Recurrence Intervals for Open Coast at Seaspray, based on the IPCC 2007 A1FI Scenario – Hunter (2009). Taken from McInnes, et al. (2009)

Period (years)	Storm Surge (m)			
	Current Climate	+0.15 m SLR	+0.47 m SLR	+0.82 m SLR
10	1.22 ±0.12	1.37	1.69	2.04
20	1.32 ±0.12	1.47	1.79	2.14
50	1.43 ±0.12	1.58	1.9	2.25
100	1.50 ±0.14	1.65	1.97	2.32

The synoptic weather systems responsible for significant storm surge events on the East Gippsland coast were investigated by the CSIRO (2005). A synoptic typing technique was utilised that generated three generic weather systems giving rise to storm surges on the East Gippsland Coast. The three generic weather systems were termed Cold Fronts, Tasman Lows and East Coast Lows.

The study determined that from a population of storm surges greater than 0.4 m at Lakes Entrance, 77% were associated with cold fronts at various stages of progression across Bass Strait. Only around 23% of significant storm surges were identified as being generated from either Tasman Low or East Coast Low weather systems (and of these, the residual water level was most likely influenced by flood flows in the Gippsland Lakes).

As discussed in Section 3.2.1, the storm wave climate is dominated by East Coast Low systems and the relationship between large wave events and storm surges are an important consideration for assessing storm erosion hazard impacts along the Outer Barrier.

To assess the relationship between the cumulative storm wave events identified from the wave hindcast and storm surges, the maximum tidal residual water level from the available gauge record at Bullock Island was determined for concurrent cumulative storm wave events. Concurrent water level records existed for 32 out of a total of 78 cumulative storm wave events identified from the wave hindcast. Figure 3-9 displays the relationship between cumulate storm wave events and maximum storm surge level as a function of the weighted mean direction of the storm wave events. From Figure 3-9 it can be seen that, from the available concurrent records, the largest storm surges are correlated with south-westerly storm wave events. No storm surge greater than 0.2 m was identified for any of the south-easterly storm wave events. The lack of apparent correlation between the largest storm wave events and elevated water levels is considered significant to the assessment of coastal hazards to the Outer Barrier.

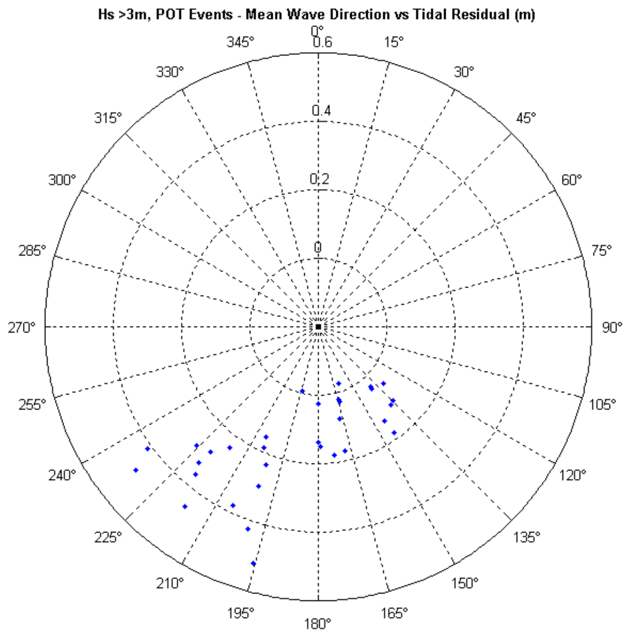


Figure 3-9 Correlation between Storm Wave Event Mean Wave Direction vs Maximum Tidal Residual at Lakes Entrance

4. COASTAL DYNAMICS AND GEOMORPHOLOGICAL CHANGES

Analysis and review of the sediment budgets, contemporary coastal processes and historical coastal hazard impacts along the Outer Barrier has been undertaken. The analysis provides a synthesis of the contemporary coastal processes and coastal hazard impacts along the Outer Barrier. The analysis has been undertaken to develop, refine and validate subsequent assessments of the potential extent of future coastal hazard impacts due to sea level rise along the Outer Barrier.

4.1 Sediment Budgets

The relative sources, sinks and fluxes of sediment along and across the Outer Barrier influence the morphology and evolution of this landform. The following sections provide an overview of the understanding that exists of the sediment budgets and magnitude of the sediment fluxes along the Outer Barrier.

4.1.1 Nearshore Geology

There is relatively limited information about the nearshore geology compared with onshore and offshore exploration areas. The exploration bores and production wells associated with the oil and gas industry are generally too far offshore to be of value for understanding nearshore sediment characteristics and budgets for this study.

Nearshore seafloor investigations conducted for the Latrobe Valley Water and Sewerage Board (LVWSB) in 1991 for the Latrobe Valley Ocean Outfall do provide details of bathymetry and seabed features at five sampled sites between Woodside Beach and north of Paradise Beach. Multiple traverses at 500 m spacing extended from the nearshore (approximately 8 m water depth for 5 km offshore to water depths of 20+ m. The results are summarized here by presenting the bathymetric profiles, interpreted seafloor and sub-bottom geology for McGaurans Beach, North of Seaspray, Glomar Beach and North Paradise Beach in Figure 4-1 through to Figure 4-4 respectively.

Review of the characteristics of the nearshore geology provided in Figure 4-1 through to Figure 4-4 provides useful insight into the characteristics of the offshore sediment sources and processes in the study area, including the following key observations:

- The barrier sand and silty sands extend approximately 1.0 – 1.5 km offshore to depths of approximately 15-20 m;
- The barrier sands overlay consolidated sediments interpreted as either Haunted Hills Formation sand or Pleistocene gravels cemented by silica and/or iron, and calcareous sediment;
- Across all sections, the consolidated sediments outcrop between approximately 1.5 – 3.0 km offshore in depths of approximately 15-20 m. The offshore outcroppings of consolidated sediments are interpreted to define the maximum depths at which wave action has mobilised and transported sand onshore to the Outer Barrier;
- At depths beyond approximately 15-20 m, unconsolidated sandy sediments to approximately 5 m thickness occur, however the surface geology suggests that they exist at depths too great to be mobilised onshore by wave action in significant quantities; and
- The thickness to unconsolidated sand offshore of McGaurans Beach, to the south-west of the study area, is considerably smaller than all locations to the north east along the Outer Barrier.

Additional surveys and analysis of nearshore sediment characteristics undertaken by (Wright, Nielsen, Short, Coffey, & Green, 1982) off of East Beach, Lakes Entrance also identified an abrupt change in sediment size and characteristics at approximately 15 m. Median grain size approximately doubled from 10 m to 15 m and beyond 15 m, the sediments were heavily iron stained and numerous whole shells and cobbles were scattered on the bed. Wright interpreted this discontinuity in sediment characteristics as indicating that beyond 15 m, the outer nearshore plain is morphodynamically discontinuous from the inner nearshore zone and composed of pre-Holocene sediments which are not in active shore-normal exchange with the inner nearshore zone.

The identification of an outer limit to active shore-normal sediment exchange with the inner nearshore zone (i.e. the Outer Barrier) is an important parameter for estimating the potential response of the Outer Barrier to sea level rise and is discussed further in Section 5.2.

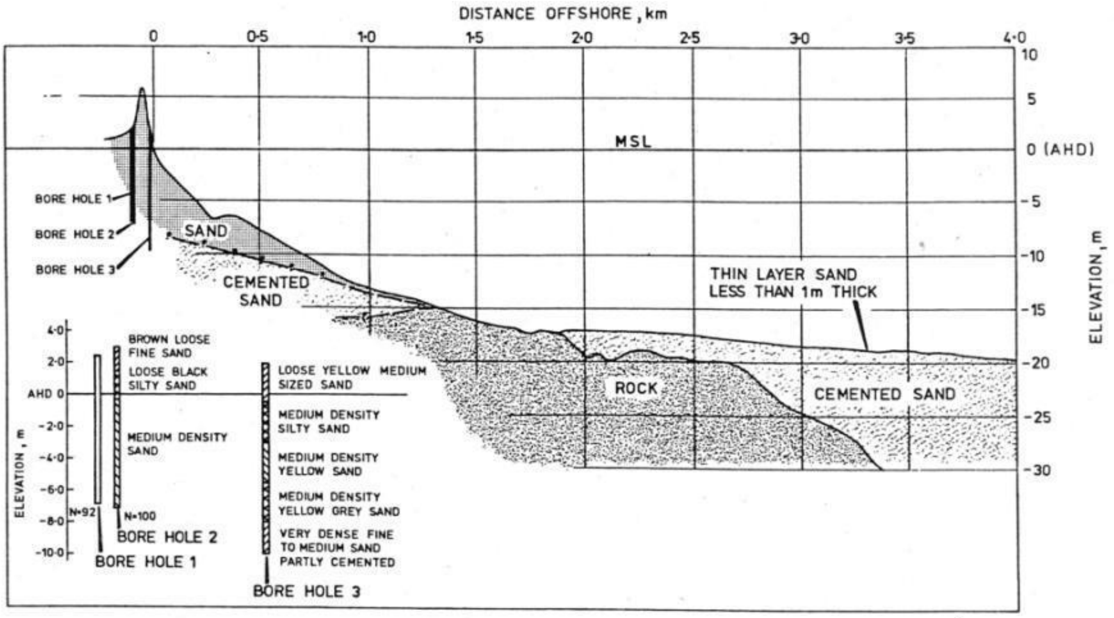


Figure 4-1 **Interpreted Section Offshore from McGaurans Beach (Latrobe Valley Water and Sewerage Board, 1991)**

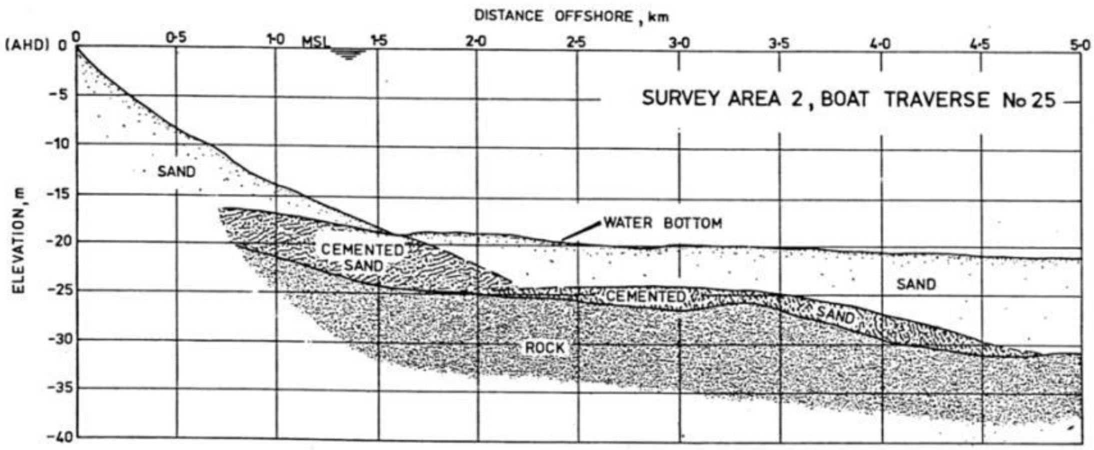


Figure 4-2 **Interpreted Section Offshore from North of Seaspray (Latrobe Valley Water and Sewerage Board, 1991)**

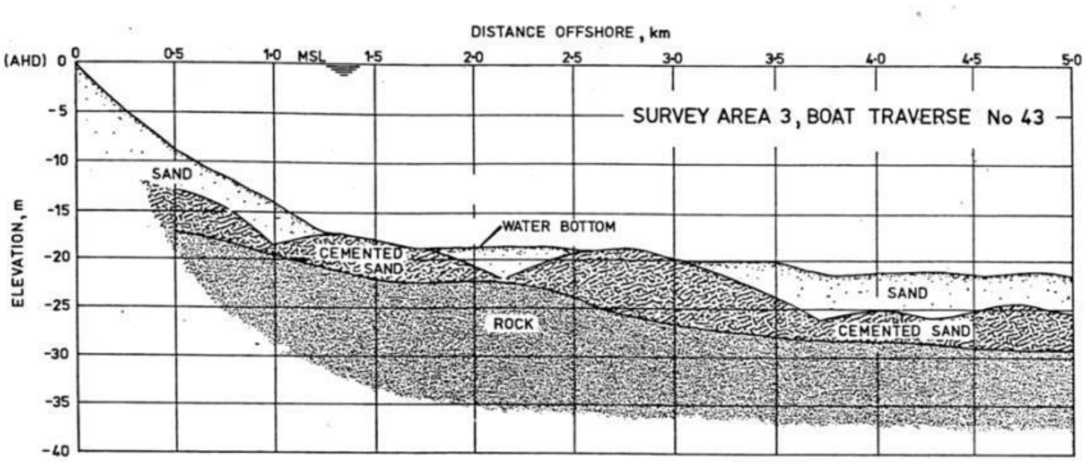


Figure 4-3 **Interpreted Section Offshore from Glomar Beach (Latrobe Valley Water and Sewerage Board, 1991)**

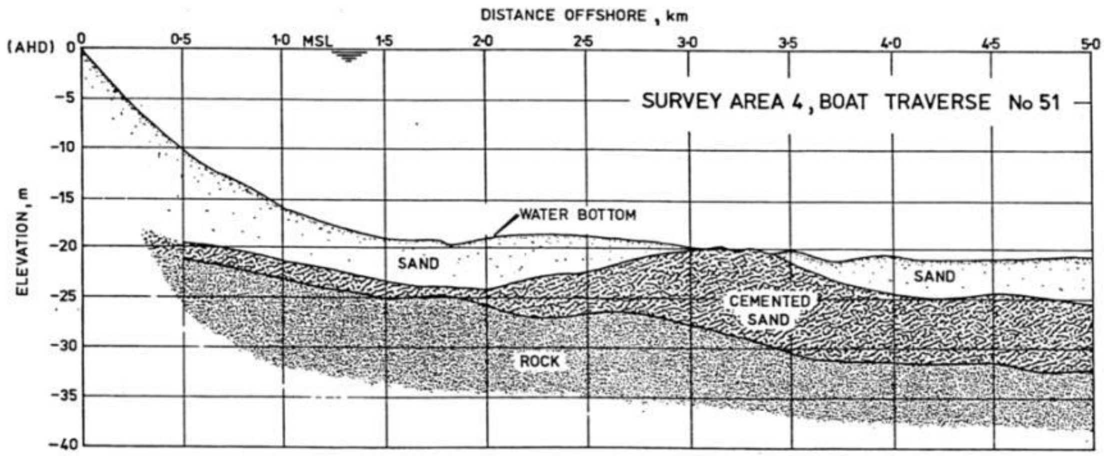


Figure 4-4 **Interpreted Section Offshore from North Paradise Beach (Latrobe Valley Water and Sewerage Board, 1991)**

4.1.2 Sediment Sources and Sinks

The sediments comprising the Outer Barrier are principally derived from the onshore migration of siliceous sediments transported by wave and current action as the ocean transgressed across the emerged continental shelf during the Late Pleistocene and early Holocene. Major progradation of the outer barrier due to onshore sediment supply is conventionally considered to have commenced 7,000 years bp, while sea levels were still slowly rising towards the end of the post glacial marine transgression. Based on C^{14} dating of sediments of the Collaroy/Narrabeen barrier on the Northern Sydney coastline, quartzose sediment delivery from the continental shelf is generally considered to have ceased approximately 2,000 – 3,000 years bp (Woodroffe, 2012)in that region, however, it is not known if these estimates are applicable to the East Gippsland coastline. In the absence of site specific detailed analysis in the study area, it is now generally considered that primary sediment supply from offshore has been exhausted and/or remaining sediment is located at depths too great to be mobilised and transported onshore in significant quantities along the Outer Barrier. It is also noted that no primary terrestrial cliff sources of sediment exist as no hard rock material is exposed along the coastline or inland for some hundreds of metres.

Carbonate sediments (sea shells etc) generally comprise a minor fraction of the beach sediments (between 5% and 10% locally) but only very minor traces are found in the dunes of the Outer Barrier.

Contemporary sediment supply from biogenic production are not expected to constitute a significant source of sediment to the Outer Barrier, however little data exists to quantify the magnitude of this sediment source in East Gippsland.

It is possible that in some locations along the Outer Barrier, prevailing westerly winds resulted in aeolian transport of sediments from the earlier, landward Pleistocene barriers, towards the Outer Barrier during drier and windier climatic conditions. In particular, sections of the inner barrier in the vicinity of Loch Sport show evidence of large parabolic dune features oriented west-east, indicating active aeolian sediment transport occurred across this earlier barrier in the past. This potential source of sediment to the Outer Barrier has however now been prevented by the stabilising effects of vegetation growth.

Coastal reconfiguration of a paleo-shoreline barrier complex that existed south west of Woodside Beach may have potentially supplied large quantities of sediment to the Outer Barrier to the north east via longshore transport in the early Holocene. Reconfiguration of this shoreline is however now apparently complete or inactive and is not expected to be supplying significant quantities of sediment to the Outer Barrier further to the north east.

Fluvial sources are also not considered a significant source of sediment to the Outer Barrier. Much of the sediment delivered by the major rivers that discharge into the Gippsland Lakes is trapped and deposited within the lakes basin and/or is too fine grained to be retained as beach sediments. During large flood events, appreciable quantities of the flood tide delta deposits that have accumulated in the channel and surrounding shoals at Lakes Entrance are mobilised and discharged into the littoral zone on the seaward side of the Outer Barrier. These sediments however do not comprise a net source of sediment to the Outer Barrier.

Pronounced north-east/east longshore sediment drift is evident in the morphology of the Outer Barrier within the study area with the easterly deflection of paleo entrances at Bunga Arm and Cunninghame Arm. Easterly longshore drift continues along the East Gippsland coast where extensive transgressive dune fields have developed in bedrock sediment traps such as Point Hicks. At Cape Howe, on the eastern most tip of the East Gippsland Coast, these dunes spill across the Cape onto the southern coast of NSW where longshore drift transports sediments northwards (Bird E. C., 1993).

To the south-west of the study area towards Corner Inlet, Wilsons Promontory increasingly shelters the coastline from south westerly wind and waves, whilst the exposure to waves from the east remains relatively unlimited. Corner Inlet therefore functions as a large sediment trap for sediment that is drifted south-westerly into the lee of Wilsons Promontory.

The regional sediment transport processes of the East Gippsland coast therefore suggest that once the onshore transport of sediment ceased some 2,000-3,000 years ago, net transport of sediment by longshore drifting is suspected of resulting in an underlying deficit in the sediment budgets in the south-west end of the East Gippsland coast, as sediment is transported primarily to the north east but also to the south west, where it is trapped in Corner Inlet in the lee of Wilson Promontory.

The contemporary sediment budget of the Outer Barrier is therefore characterised by a relatively finite volume of sediment with only very minor contemporary sources of sediment adding to the littoral volumes. The contemporary sediment budgets along the Outer Barrier are subsequently considered largely a function of the longshore and cross-shore transport fluxes of this essentially finite sediment volume. The magnitude and variability of theses fluxes and the extent to which variations in these fluxes can be attributed to contemporary shoreline change are discussed in the following sections.

4.2 Aeolian and Biological Processes and Dune Morphology

Aeolian processes have been, and continue to be, a significant factor in the morphology of the Gippsland coastal barriers, by shaping and subsequently modifying the initial forms of sand dunes. The essential character of dunes is that wind is the primary factor in mobilising and moving sand and changes in the wind regime – either by inherent physical or ambient meteorological processes or interception, deflection, absorption by other features — reduces or increases the local wind velocity resulting in grain deposition or erosion respectively. All vegetated dunes are initially *backshore* features in that they develop beyond the reach of normal wave swash.

The following sections summarise the morphology of dunes and the role of vegetation in aeolian sand transport and deposition along the Outer Barrier.

4.2.1 Incipient Foredunes

A foredune is an isolated mound or sheet of unconsolidated sand formed where sand grains have been lifted or rolled from the beach face by wind and deposited beyond the reach of high tide swash, thus forming a dune that will persist beyond the tidal regime. Deposition occurs as wind velocity and/or turbulence decreases as wind encounters obstacles such as existing topography, outcrop, strand e.g. driftwood or vegetation. Small, localised deposition on upwind and lee sides of these objects forms mounds or linear ridges termed rudimentary dunes (Cooper W. S., 1958) and incipient foredunes (Hesp, 1984). The rudimentary dune then becomes an agent in sand deposition, so accretion will continue on both upwind and lee sides. The dune initially increases in dimension but will also lose sand as wind velocity increases or changes direction. At this stage the processes that anchor dunes and the morphology of the dune become strongly influenced by the establishment of sand and salt tolerant vegetation along the strand and backshore.

4.2.2 Established Foredunes

Established foredunes develop from incipient foredunes and either occupies the seaward-most position at the rear of the beach or is situated behind an incipient foredune. They are commonly distinguished from incipient foredunes by the growth of intermediate, sometimes woody plant species, and by their greater morphological complexity, height, width, age, and geographical position (Hesp, 2002).

On the Gippsland coast, both incipient and established foredunes are formed typically within or adjacent to discrete annual or perennial plants established from seed, either wind-dispersed or deposited by swash, or from plant fragments. Incipient foredunes develop into established foredunes as vegetation becomes laterally extensive and continuous, forming a ridge rather than separated mounds or hummocks. On accreting shores with appropriate wind and vegetation, a sequence of incipient and established (older incipient foredunes) will develop, resulting in multiple shore-parallel ridges increasing in height landward as development of woody vegetation increases the capacity to trap aeolian material.

The morphology of the foredune may in part be determined by the vigour and growth form of the colonising plants. There are varied views on the influence of vegetation on foredune morphology (McKenzie, 1958) (Bird E. C., 1960) (Bird E. C., 1985) (Hesp, 1984) (Hesp, 1999). Although there are likely to be different responses determined by local wind and sand supply and existing topography, clear relationships have been observed between colonising vegetation and foredune morphology in Gippsland (Rosengren, 1978).

4.2.3 Foredune Vegetation

The model accepted in this report for the origin of the foredune ridges that comprise the terrain backing the Ninety Mile Beach, follows that proposed by Hesp (2006), (2012), where vegetation is the critical factor in providing a nucleus for aeolian sand deposition. The alignment of the foredune is determined by the establishment of vegetation as an original incipient foredune, and this in turn was a result of the initial wash-aligned stranding of seeds or vegetative material for plant establishment on the backshore.

Prior to the introduction of exotic sand-binding species, *Spinifex sericeus* (hairy spinifex and *Austrofestuca littoralis* (coast fescue) along with *Leucophyta brownii* (cushion bush) would have been the principal strand line plants building incipient foredunes. As these became established foredunes, isolated by the establishment of a new incipient foredune, the scrub and heath plant succession consolidated the sand body and facilitated upward growth. The existence of multiple sand ridges of foredune origin along the Outer Barrier, indicates the sand trapping ability of these plants.

There is an extensive literature generated by geomorphologists and ecologists investigating the establishment and succession of vegetation on coastal dunes and assessing the influence of different species on dune morphology e.g. (Rosengren, 1978). A number of studies in the USA, South Africa, Australia, and New Zealand extending from (Cooper W. S., 1958) to (Hilton & Konlechner, 2011) have examined the role of introduced plants with a focus on *Ammophila arenar*ia (European Marram Grass). Heyligers (1985) recognised that the foredunes of south-eastern Australia carried at least 50 different plant species of which 25% were alien and have become naturalised. The alien species have become so widespread that it is now difficult to find any extensive stretch of sandy coast with foredunes containing only native species. Four major introduced foredune species are now present in the study area and at least two of these (cakile and marram) have adopted the role of principal beach ridge and foredune (backshore dune) pioneers. Recently *Euphorbia paralias* (sea spurge) has also become more widespread.

Marram Grass (Ammophila Arenaria)

European Marram Grass [*Ammophila arenaria*], also known as European Beachgrass, is native to the coastlines of Europe and North Africa where it is widespread on beach and dune sands. Marram Grass has been introduced beyond Europe as a sand-binding agent in coastal dune management projects and is now widespread in temperate climates in both hemispheres. Following its introduction at several locations in the late 1800's and early 1900's, Marram Grass has become a naturalized plant around the coast of southern Australia including Tasmania

Many authors have commented on the role of *Marram Grass* in intercepting blowing sand and promoting the accretion of sand in mounds and ridges (Bird E. C., 1985) (Heyligers, 1985) (Hesp, 1999) (Kent, Owen, Dale, Newnham, & Giles, 2005) (Hilton, Duncan, & Jul, 2005) (Maun, 2009). When Marram becomes established, wind velocities experience rapid deceleration on reaching the plants, local acceleration around the plants, and flow separation behind the plants resulting in sand deposition. Marram has high aerodynamic roughness, significantly greater vertical growth capabilities following sediment deposition and, therefore, traps greater quantities of sand than other native plant forms (Hesp, 2012). Marram also traps sand and builds dune at rates that exceed the threshold of tolerance of native species (Hilton, Duncan, & Jul, 2005).

The occurrence and density of stands of Marram Grass varies considerably along foredunes backing the Ninety Mile Beach. The greatest concentrations occur on the single ridge at Seaspray extending to the northeast of The Honeysuckles and east of Lakes Entrance where there were extensive plantings in the 1890's. It is also common on the dunes at the eastern end of Bunga Arm, to the west of Seaspray on areas of newly deposited sand e.g. the overwash at McGaurans Beach and on freshly exposed sand faces elsewhere where wave scarps occur on established foredunes.

There is no doubt that Marram Grass has significantly influenced the position and form of the Seaspray - The Honeysuckles foredune, allowing the ridge to build vertically much higher than would occur with native species. In 1894 it is recorded that the Reserve was subject to drifting sand and on spring tides the dunes were flooded. This was attributed to destruction of vegetation by clearing (including tree ringbarking) and grazing in the previous twenty years. Alf Futcher, then lessee of the Reserve built a brush and Ti-Tree fence, over 1 km long and 2 m high and planted Marram Grass in rows 1 m apart in front of the fence. This apparently was successful in reducing sand drift and storm overwash. Marram Grass at that time was also being used at Lakes Entrance.

Photographs in the State Library of Victoria Historical Pictures Collection show beach scenes at Seaspray between 1930 and 1950 (Figure 4-5) with variable cover of grass and extensive areas of bare sand.

Jenkin (1968) also discusses the apparent youthful nature of the ridge at Seaspray and attributes this to the planting of Marram Grass since the 1890's. He mentions (page 27) that the irregular plan form of the ridge is "…partly natural but accentuated by erosion initiated by human agency". This apparently refers to trampling and lowering of the crest by people accessing the beach, an effect that is apparent today.

Marram has also been planted extensively on either side of the entrance at Lakes Entrance resulting in hummocky dunes and ridges (Figure 4-6).

Figure 4-5 Seaspray Foredunes A = ~1935, B = ~1950 (State Library of Victoria).

Figure 4-6 Hummocky and Linear Dunes with Marram Grass, Lakes Entrance ~1940's (State Library of Victoria)

4.2.4 Transgressive Dunes

Environmental changes, such as augmented wave action across the backshore due to rising sea levels or increased storm duration and intensity, changes in wind vector (direction, frequency and velocity) and reduction in vegetation cover (possibly as a consequence of reduced rainfall) and structure may allow remobilisation of sand from established foredunes (or other dune types) producing new landforms at the removal/deflation (erosion) and re-deposition (accretion) sites. These landforms, are referred to here as transgressive dunes as they extend across existing dunes and/or other hinterland landforms.

The type, spatial extent and prevalence of transgressive dunes along the Outer Barrier are considered significant to the assessment of the total extent of the coastal hazards due to sea level rise this century. Transgressive dunes can influence the extent and/or rate of coastal hazards by the following:

- Transgressive dunes can result in the relatively rapid mobilisation of sand at distances and elevations well beyond that which can occur due to hydrodynamic processes of tides, surges and waves. The erosion and accretion associated with transgressive dunes can therefore be considered to contribute to the total extent of coastal hazards along the Outer Barrier;
- Transgressive dunes can take the form of "blowouts' which describe a variety of trough-shaped depressions or hollows that transgress across existing foredune ridges and may extend into backbarrier areas creating depressions across the barrier which may form locally vulnerable areas to overwash processes; and
- The rate at which sand is mobilised and transported landward within transgressive dunes forms a critical control on the overall rate at which coastal barriers are translated landward in response to sea level rise.

The nature and present extent of active and relict transgressive dunes backing the Ninety Mile beach was determined from vertical aerial photography, 2009 and 2013 oblique aerial surveys, site photographs and LiDAR survey data supplemented by limited ground observations. The combination of these methods provides record of contemporary transgressive dune activity. Several different modes of active, inactive and relict transgressive sand bodies were identified related to different stages in barrier development. Their characteristics and distribution are listed in the following sections below. Only the transgressive dunes developed from or over the outermost younger Holocene foredunes are detailed. The older, inner ridges and other sand bodies are not included because:

- the dune features were developed under different climatic, vegetation and sea-level conditions;
- they are inactive and carry a generally dense vegetation cover; and
- they are not seen to be at risk of reactivation due to projected storm wave or sea-level rise over a century time scale.

4.2.5 Climbing Dunes

These are unusual transgressive dunes in the context of the Ninety Mile Beach as they are developed at the back of the beach at the base of a scarped foredune. They may have initiated quickly as protodunes on wet backshore sand during strong wind at low tide and migrated across the backbeach to the foredune scarp. Continuing strong winds at all tides continue to move sand onto the scarp building a ramp ascending the scarp face to the crest and spilling onto the backbarrier slope forming a broad apron. The rate of sand transport is too rapid to allow primary colonisers to establish.

Table 4-1 Summary of Climbing Transgressive Dune Characteristics and Extents

Position	Morphology	Active/Relict	Distribution	Landward Hazard Extent
Base of scarped foredune.	Cone-shaped broad at base.	Active – climbing face of established foredune and spilling over crest.	Base of incipient foredune Seaspray to Honeysuckles is the most extensive development noted with smaller areas near Ocean Grange.	Limited to seaward face of foredune scarp

Figure 4-7 Climbing Transgressive Dune at the Honeysuckles

4.2.6 Backscarp Sand Apron

These have developed from the landward extension of the climbing dunes above or local disturbances of the foredune scarp. They form as lobes and broad aprons with occasional high hummocks. At the Honeysuckles, an active backscarp sand apron is transgressing across Shoreline Drive, approximately 40 m landward of the foredune scarp (Figure 4-8).

Another active backscarp sand apron was identified at Bunga Arm (Figure 4-9). Comparisons of the foredune profile at this location between 2007 LiDAR survey and 2012 survey demonstrates the rate and extent of active landward aeolian sand transport (~30 m) and deflation of the foredune crest between these two surveys.

Table 4-2 Summary of Backscarp Sand Apron Characteristics and Extents

Position	Morphology	Active/Relict	Distribution	Landward Hazard Extent
Landward slopes of established foredune.	Broad – irregular sand sheet.	Mainly relict with localised active areas.	A recently active feature behind the single foredune ridge at The Honeysuckles to Seaspray and Bunga Arm Probably widespread in relict scarped foredunes but mantled by vegetation growth.	30-50 m landward of foredune scarp

Figure 4-8 Backscarp Sand Apron Developed from Climbing Dunes and Blowouts, The Honeysuckles.

Figure 4-9 Active Backscarp Dune Apron and Blowout, Bunga Arm (Photographer: Warwick Bishop, Feb, 2013)

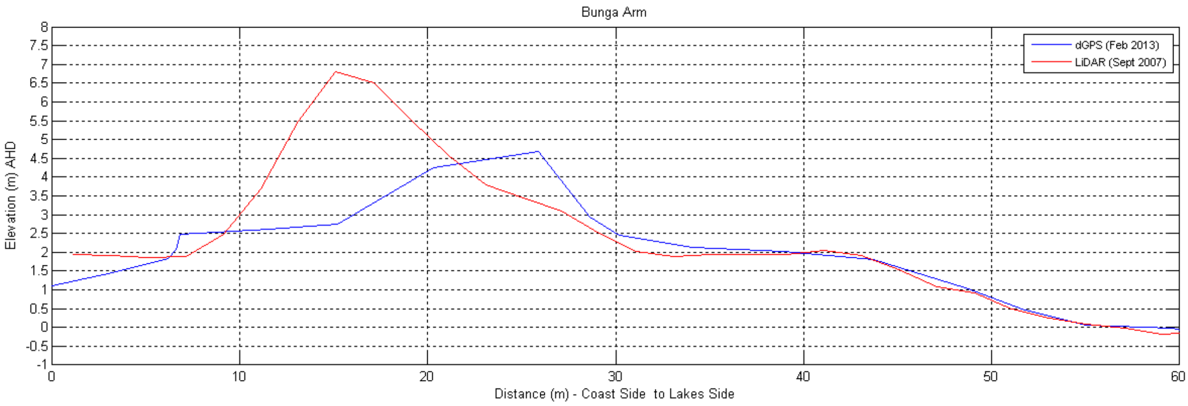


Figure 4-10 Comparison of Coastal Profiles at Active Backscarp Dune Apron, Bunga Arm

4.2.7 Elongate Blowout – Shore-Normal and Oblique

Narrow, generally trough shaped transgressive dunes cutting shore normal or at oblique angles are widespread on the multiple dune sequence crests from Paradise Beach (Figure 4-11) to Ocean Grange (Figure 4-12). At Ocean Grange, active blowout troughs cut across all established foredune crests and into back barrier areas. Figures Figure 4-11,Figure 4-12 and Figure 4-13 provide photographic (top) and topographic (bottom) examples of such elongate dune blowouts. These elongate dune blowouts represent the landward movement of an isolated section of duneline primarily due to Aeolian (wind) transport.

Along Bunga Arm at several sites where there is only a single established foredune ridge, blowout troughs extend across the barrier and spill into the Bunga Arm lagoon (Figure 4-13).

These are large scale transgressive dune features that can extend from the foredune scarp to up to 100 m landward.

Table 4-3 Summary of Elongate Blowout Characteristics and Extents

Position	Morphology	Active/Relict	Distribution	Landward Hazard Extent
Seaward slope and crest of established foredunes.	Narrow, generally shallow trough cutting across established foredune(s) perpendicular to shore or at high oblique angle.	Many small active blowouts of this type occur. Larger occurrences are inactive or relict. Near Ocean Grange and Bunga Arm active blowouts cross all established foredunes.	Widespread on the broad dune sequence crests from Paradise Beach to Ocean Grange.	50 – 60 m landward of foredune scarp

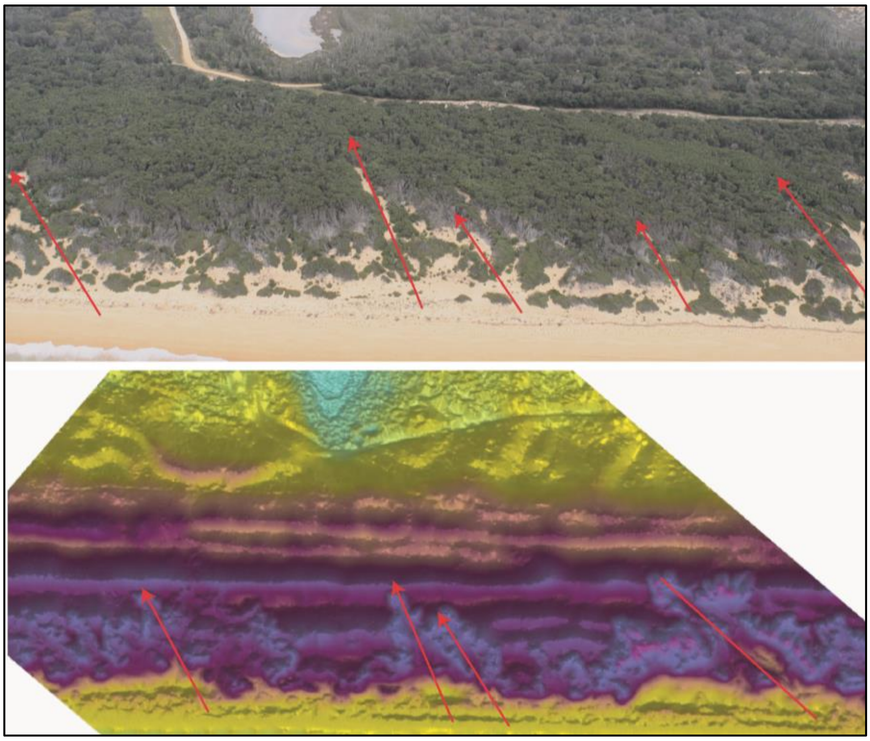


Figure 4-11 Multiple Blowouts from Incipient Foredune Crossing Relict Established Foredunes NE of Stockyard Hill

Lidar Image (lower) and Oblique Aerial Photograph (Neville Rosengren Jan 2013).

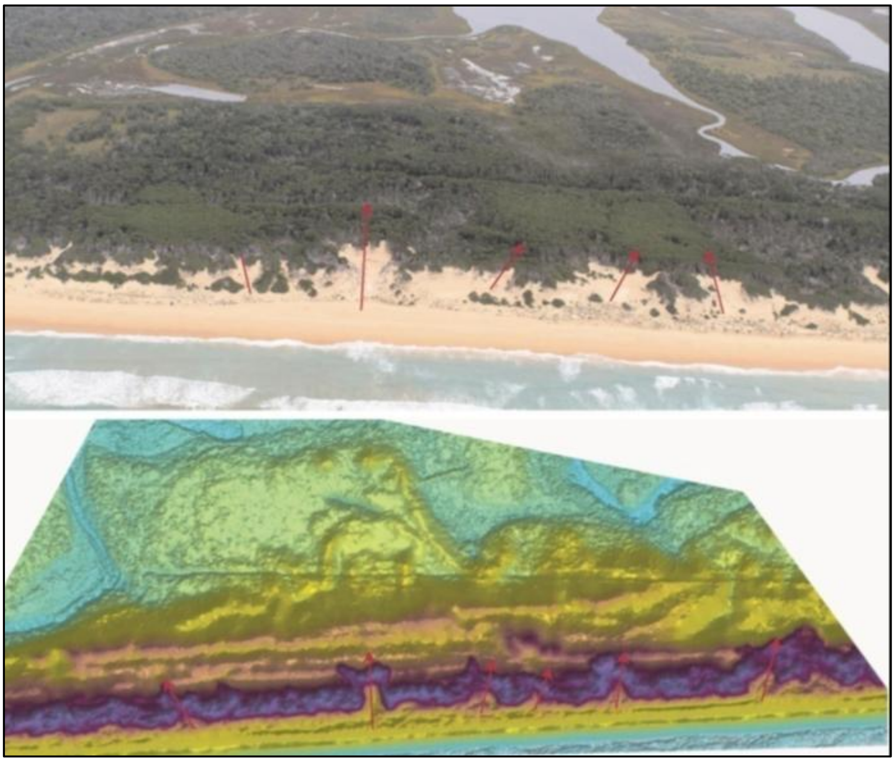


Figure 4-12 Multiple Blowouts from Incipient Foredune Crossing Relict Established Foredunes near Ocean Grange

Lidar Image (lower) and Oblique Aerial Photograph (Neville Rosengren Jan 2013).

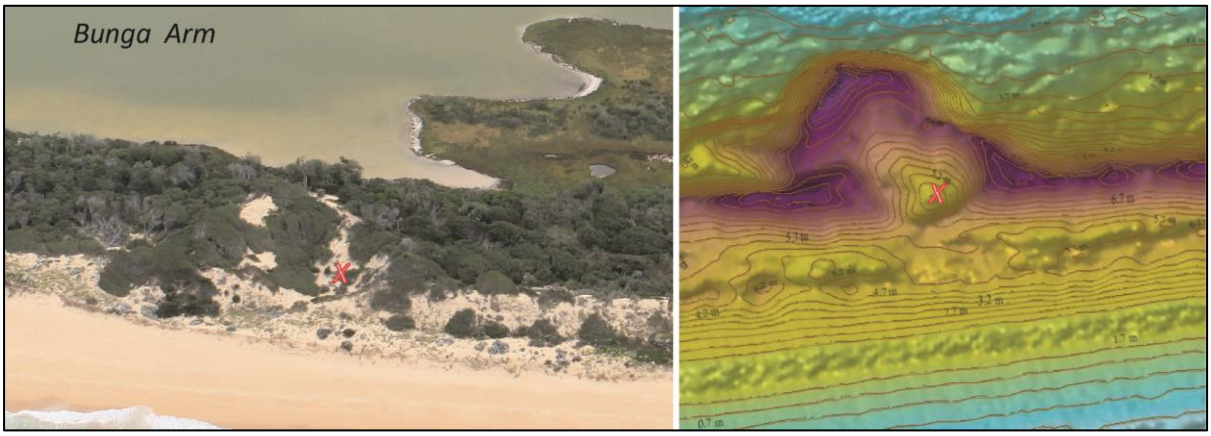


Figure 4-13 Deep Blowout Extending from Incipient Foredune Crossing Established Foredunes to Edge of Bunga Arm (Photograph Neville Rosengren Jan 2013).

4.2.8 Shore-Parallel Depression Complex

This is a distinctive coastal sand body where multiple processes have developed a now partly active blowout group following an episode of locally enhanced shoreline wave erosion. This sequence of scarped foredune, deep elongate depression with irregular blowout surfaces and sparse vegetation backed by a higher scarped dune face occurs along several sectors of coast northeast of the Honeysuckles to near Golden Beach (Figure 4-14). In some locations they occur as relatively isolated depression complexes bound by higher scarped dunes and in other locations they occur as relatively continuous depression sequences over distances of several kilometres.

These landforms are interpreted to be a rebuilt established foredune following an episode of shoreline erosion that cut back into the established foredune. Wind action further deepened this cut prior to the redevelopment of an incipient and established foredune across the breached sector. The re-established foredunes and vegetation recovery reduced the rate of blowout development leaving a defined shore-parallel corridor wider than that developed as a swale between an incipient foredune and established foredune.

Where these depression complexes occur in isolated locations over lengths of shoreline of several hundred metres, they are interpreted as most likely associated with large rip cell embayments that caused a localised increase in short term, storm related erosion extents along the barrier.

However, where a relatively continuous sequence of depression complexes occur along the barrier for several kilometres or more, it is likely that they relate to a prolonged period of historical shoreline recession, possibly associated with variations in longshore transport rates and/or directions along the barrier.

The preservation of these landform features in the morphology of the barrier at several locations provides important insight into the upper extent of the potential erosion widths along the barrier due to either short-term, storm related erosion or longer-term variations associated with longshore transport processes.

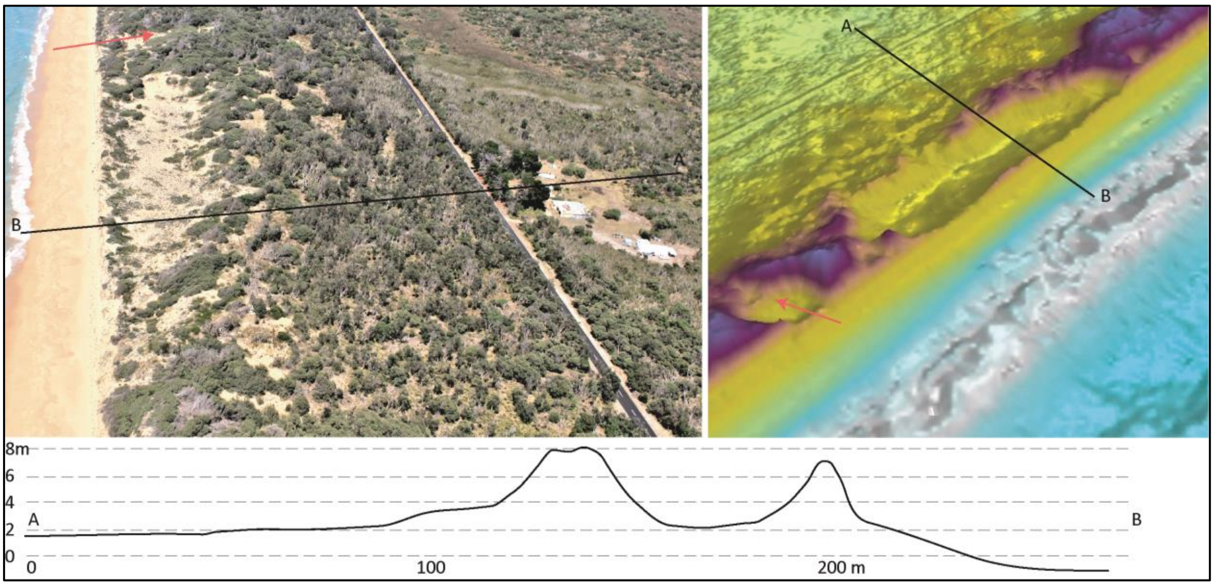


Figure 4-14 Isolated Elongate Shore-Parallel Blowout Complex Northeast of The Honeysuckles

Arrow shows enclosed circular blowout. Profile A-B derived from Lidar contours. (Photograph Neville Rosengren Jan 2013).

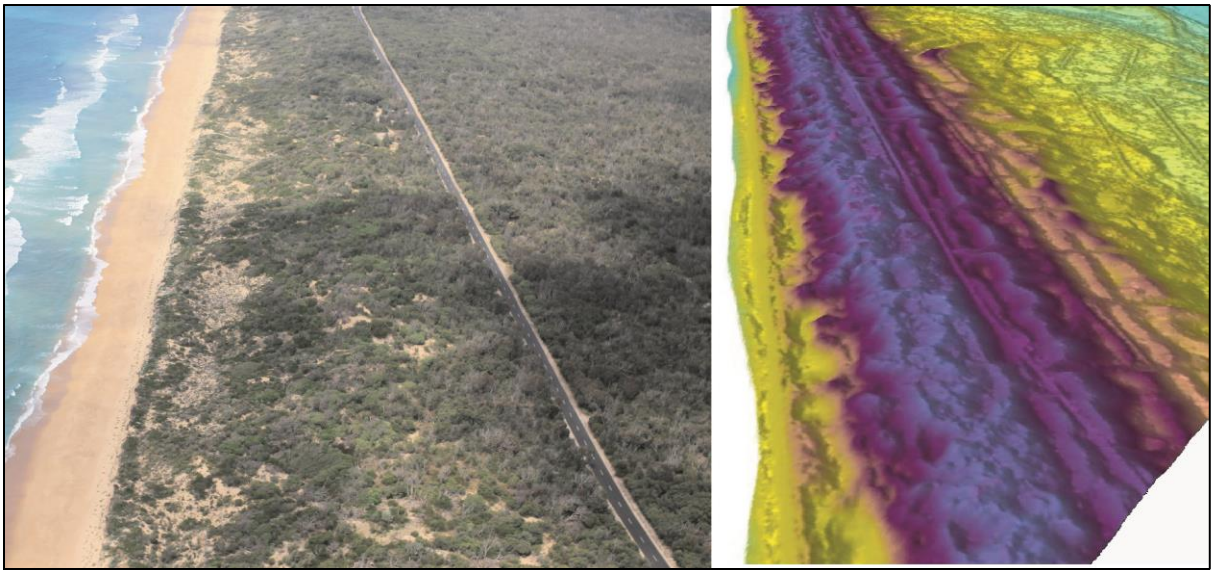


Figure 4-15 Sequence of Shore-parallel Depression Blowouts between Glomar Beach and Flamingo Beach. (Photograph Neville Rosengren Jan 2013).

Table 4-4 Summary of Shore-Parallel Blowout Characteristics and Extents

Position	Morphology	Active/Relict	Distribution	Landward Hazard Extent
Between youngest established foredune and relict foredunes.	Elongate shore-parallel shallow to deep (>4 m) depression with backing scarp and frontal foredune	Partly active	Occur along discrete sectors from The Honeysuckles to Stockyard Hill	30-40 m

4.3 Coastal Overwash

4.3.1 Outer Barrier Washovers

Coastal overwash is the flow of water across a beach and dune system onto lower backbarrier terrain. It generally occurs during higher than normal wave conditions as a result of storm waves and the process is exacerbated if combined with strong onshore winds, storm surge and high tides. Overwash is a concentrated surge of water and sediment movement up a beach face beyond the normal high tide swash limit. *Overwash* is a hydrodynamic process and *washover* is the sediment deposited beyond the beach by the process. Overwash differs from swash in that it extends beyond the high water mark and across higher topography and washover is deposited rather than returned with backwash. Washover can be deposited onto the berm crest or may overtop dunes at the back of the beach and extend as far as the back barrier bay, estuary, or lagoon. Washover deposits vary from linear to lobate splays or fans of sediment and debris or broad sand sheets thinning landward, determined by the type of washover inundation. Washover can be localised e.g. through a narrow gap or may be widespread submergence of a broad length of low coast.

Thom (1984) described the widespread occurrence of washover sediments recorded by extensive onshore drilling into the barrier and backbarrier flats between Seaspray and Lake Bunga. The backbarrier topography and surficial sediment southwest of Seaspray also indicate extensive washover origin. Overwash is a common process and possibly a dominant process during marine transgressions, determined by the slope and elevation of the terrain that is being submerged. Along the Ninety Mile Beach, the rising Holocene sea crossed gently sloping terrain with remnants of earlier formed barriers and the configuration of these determined the occurrence of overwash sites. As the Holocene sea-level stabilised, and fell from a slightly higher level, transgressive barrier formation was succeeded by regressive or prograded barriers and the sandy terrain was built upward by aeolian deposits. The widened barriers masked earlier washover terrain and diminished the opportunity for overwash to occur such that contemporary overwash events presently only occur intermittently and locally along the Outer Barrier within the study area.

The relict and active overwash environments along the Outer Barrier are influenced by the width, elevation and volume of the outer barrier and the elevation and slope of backbarrier terrain, and they are closely related to the 10 geomorphic units identified in this study. Identification of the susceptibility of the Outer Barrier units to overwash is important for assessing the potential response of the barrier to projected sea level rise and the subsequent extent of coastal hazards. The occurrence of overwash can result in dramatic, non-linear changes to the extent and frequency of coastal hazard impacts landward of the barrier. The following sections summarise the extent of the pre-historic and contemporary overwash processes along the Outer Barrier.

4.3.2 Reeves Beach to Seaspray

There is no detailed stratigraphical data of backbarrier sediments southwest of Seaspray but the topography and surficial sediment from a few available boreholes and soil maps (Seargant & Imhof, 2003) indicate extensive washover origin.

Northeast of Woodside Beach the coastal hinterland is dominated by the relict tidal complex of lagoons, channels and sand flats of Jack Smith Lake backed by a 4 to 5 m high bluff, the equivalent of the Gippsland Lakes marginal bluff. This is a compound washover with younger channelled overwash sediment superimposed on broad submergence sheets and fans in front of Jack Smith Lake (Figure 4-16). The lake floor is less than 1 m above mean sea level and the entire complex represents a recently inactive major tidal inlet (Figure 4-17).

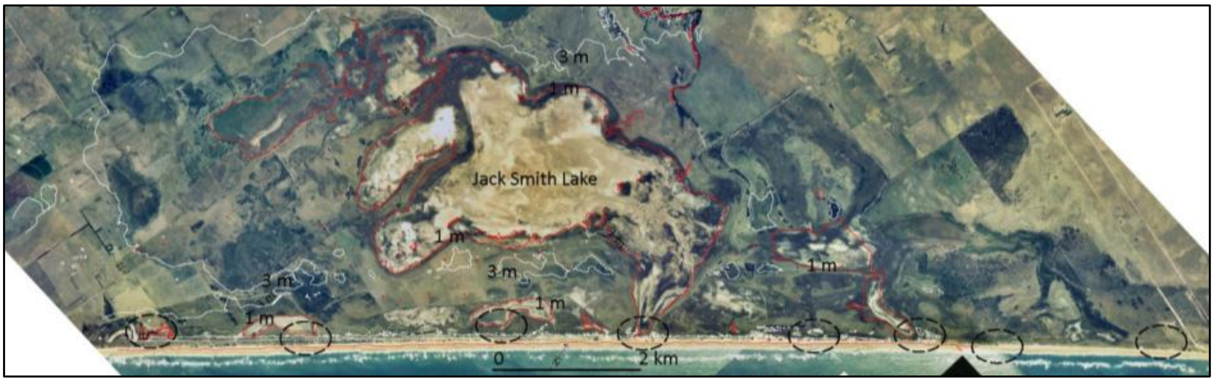


Figure 4-16. Relict Tidal Inlet, Washovers (broken lines), 1 m and 3 m Contours, Jack Smith Lake.

Figure 4-17 Compound Overwash Sites Southwest of Jack Smith Lake

W/O are Older Sites, arrows show younger and active sites. Note the single low, cliffed foredune and narrow steep face of Ninety Mile Beach. (Photograph Neville Rosengren Aug 2009).

A broad submergence washover occurred at McGaurans Beach in September 2001 along several hundred metres of coast that is backed by the lowest foredune along the entire Ninety Mile Beach (Figure 4-18). The washover site subsequently became an active dune and it is likely that a number of broadly lobate backbarrier features here are of similar origin. Adjacent to McGaurans Beach the low foredune has an erosion scarp initiated during the washover event.

Figure 4-18 Washover Sites Developing Transgressive Dunes, McGaurans Beach

Broken line shows dunes activated by washover, inset shows ground photo 2007. (Photographs: Neville Rosengren, July 2007, Aug 2009)

Other recently active washover sites occur northeast of McGaurans Beach at outlets of Lake Denison (Figure 4-19). It is possible that one of these was opened by machinery to relieve flooding. The strong topographical expression of channels, lake floor and bordering bluffs indicates a recent and relatively long history of washover deposition and tidal processes.

Figure 4-19 Washover Sites at Lake Denison (broken line). (Photographs: Neville Rosengren Aug 2009).

A number of documents relating to the initiation and early management of the Prospect Reserve at Seaspray towards the end of the 19th century are available from the Seaspray Reserves Committee of Management. Contained with these documents are references to significant issues encountered by the early managers of this area relating to the exposure of the reserve to storm events and associated overwash of the barrier. The following exerts within these documents relate specifically to these issues:

'To this I received opposition, so therefore when the thistles were cut the sand drifted on until almost the whole of the camping ground was covered, leaving the old site of the hummocks bare and so low that every spring the tide sends the thousands of tons of salt water over the Reserve'

'The next piece of work the manager would have to do would be to plant about half a ton of marram grass where required along the barrier, and after that only as much grass as was needed to maintain the hummocks and the background. Heavy seas had washed away the barrier in some places, and the manager would have to fill up the gaps.'

'The only trouble was that the hummocks had been destroyed, and the heavy spring tides were sweeping over the Reserve. However the people seemed willing to leave it. And after they left he was down looking at the sandy waste as it was then, the sea had just swept over it in places two feet deep.'

While it is likely the grazing by stock and poor access management contributed to the deterioration in the integrity of the barrier during these early stages of the development of Seaspray. The discussions within these documents are, however, considered to reveal a barrier system that was historically prone to experiencing overwash events. The back barrier morphology in the vicinity of Seaspray shows evidence of extensive washover deposits which extend many hundreds of metres landward of the existing shoreline and which are considered to attest to the magnitude and frequency at which these events occurred prehistorically. It is suspected that the introduction of Marram Grass and improved fencing and access management has prevented more contemporary washovers of the barrier in the vicinity of Seaspray.

4.3.3 Ocean Grange

The most apparent overwash terrain and sediments occurs in Unit 6 between Loch Sport Ocean Beach (Stockyard Hill) and Ocean Grange. This is the easternmost expression of a large relict flood-tide delta. The delta migrated from an initial position west of Stockyard Hill and the entrances moved progressively northeast as the ebb jet was deflected by longshore currents (Figure 4-20). This is a large and complex feature with channels and banks and emerged low islands marking the successive position of the entrance(s).

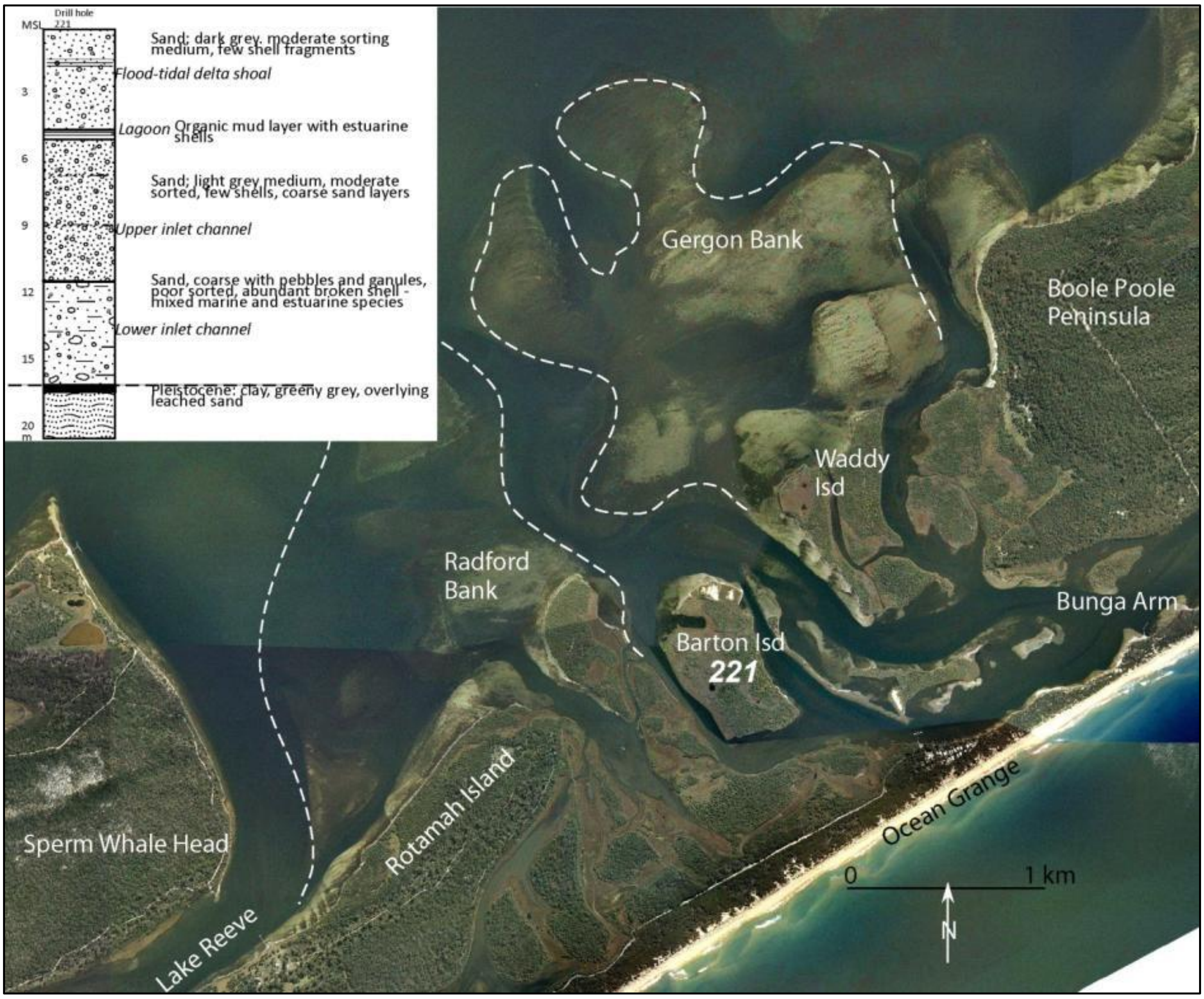


Figure 4-20 Relict Tidal Delta at Ocean Grange (Stratigraphy from Thom (1983))

A deltaic complex of this scale can only have developed where there was a large backbarrier lagoon or estuary to provide space for flood-delta extension and generate sufficient ebb flow to maintain an ocean entrance without closure by spits or barriers. This delta may not have been initiated by channelled overwash but rather by submergence of an incipient low barrier forcing a wide entrance or multiple entrances. The closure of the delta may be the consequence of late Holocene fall in sea-level and spit growth from the east.

4.3.4 Bunga Arm

Sufficient ebb-flows were maintained from the deltaic complex at Ocean Grange to allow the entrance to migrate east of Ocean Grange forming Bunga Arm, preventing the barrier spit from attaching to the earlier Holocene barriers on Boole Poole Peninsula. Remnants of washover events are preserved in the form of lobate to cuspate forelands on the lagoon shore of Outer Barrier along the Bunga Arm (Figure 4-21).

One of the few available records of likely, recent washover events in the Bunga Arm was provided by Eric Bird during the course of this study (Eric Bird pers. comm. 1 October 2012):

'Many years ago (1958?) Joe Southon took me up the Bunga Arm and pointed out a hollow in the outer barrier dunes through which (he said) the sea broke through in a storm in the early 1950s. He told me that the breach lasted only a few days before a sand bank formed across it and then a low dune ridge which at that time was sparsely vegetated. I recall that from the boat we could see over it to the sea. There was a small washover fan inside the breach site. I tried to get confirmation of this event from early 1950s Bairnsdale Advertisers, but was unsuccessful. However, some of the local fishermen backed up Joe's story.'

A somewhat conflicting accountant of this potential washover event is recorded in the Bairnsdale Advertiser which suggests that a man made cut through the barrier was attempted in this area in an unsuccessful effort to alleviate severe flooding during the June 1952 Gippsland Lakes floods. *(Bairnsdale Advertiser, 23/6/52).*

It is possible that the site of the washover observed by Eric Bird in the late 1950's was the location where a channel was cut through the barrier in the unsuccessful attempt to alleviate flooding in the June 1952 flood. Alternatively, the barrier at this location, which would have been disturbed by the artificial excavation, could have been washed over in storms after 1952. However, as identified in the analysis of the storm wave climate of the study area (Section 3.2.1), the early 1950's were a period of significantly increased storminess and it is suspected that washover(s) occurred in this location during this period.

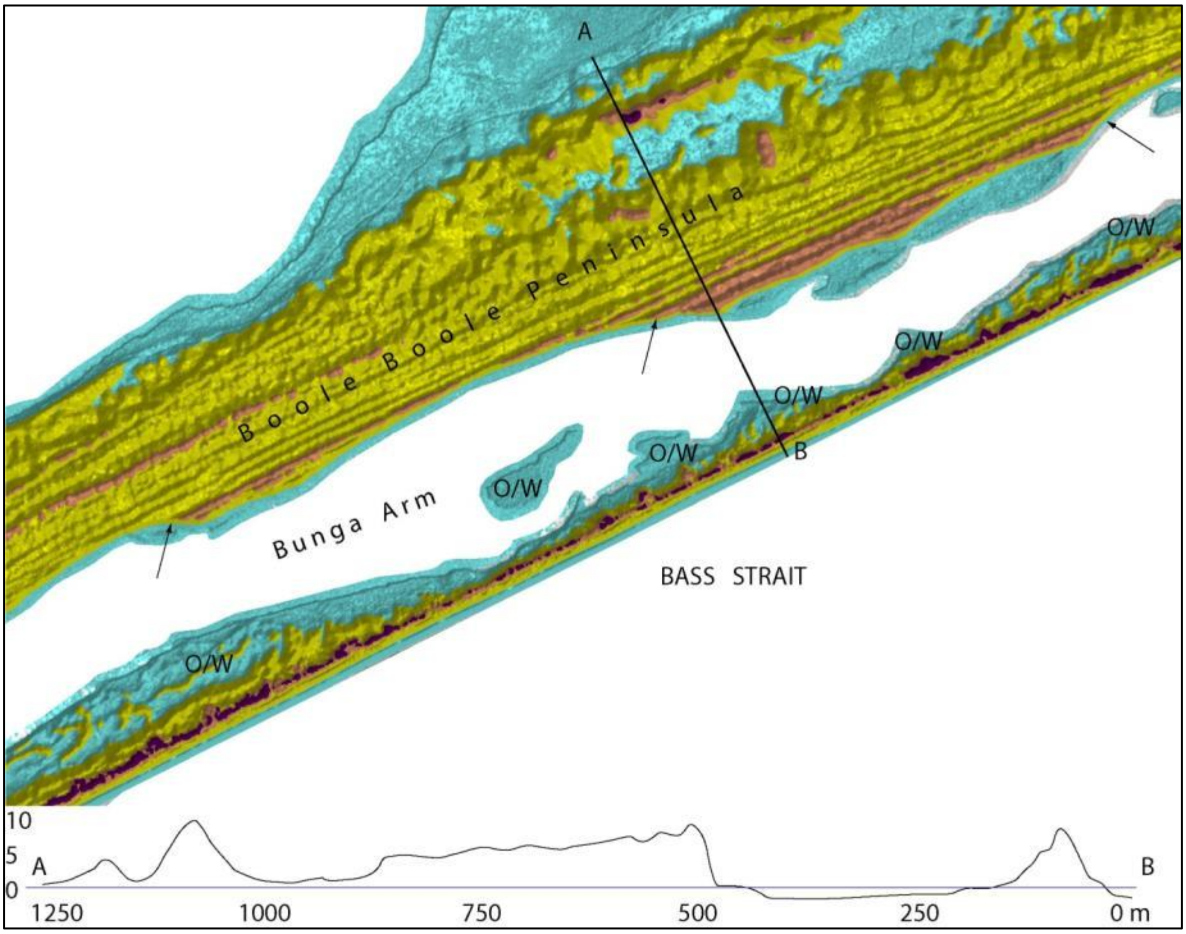


Figure 4-21 Overwash Sites along Bunga Arm (Lidar DSE)

4.3.5 Eastern Beach

A series of dramatic photographs immediately following an overwash of the Outer Barrier, east of Lakes Entrance in 1979 were provided by the Gippsland Coastal Board during the course of this study. The overwash was estimated to be approximately 100 m wide with sand, seaweed, flotsam and considerable volumes of seawater washed into the Golf Course behind the barrier. Anecdotally it is understood excavators were used to rebuild a minor dune in this region following the overwash event (*Eric Sjerp pers comm.*).

Prior to the cutting of the artificial entrance in 1889, the barrier in this region was dissected by the Reeve's River channel that formed an emphemeral entrance to the Gippsland Lakes and the entrance migrated east-west along the barrier in response to longshore drift and streamflow discharges in this area. After the cutting of the artificial entrance in 1889, the eastern part of Reeve's River rapidly filled with overwashed and wind-blown sand. The overwash event observed in the late 70's therefore probably constitutes one of a declining series of overwash events that have now largely filled the prior Reeve's River channel and entrance.

Figure 4-22 Overwash at Eastern Beach, Lakes Entrance in 1979 (Photographer not known)

Figure 4-23 Overwash of the Outer Barrier East of Lakes Entrance in 1979 (Photographer unknown)

4.4 Longshore Transport and Contemporary Shoreline Change

A number of estimates of the annual gross and net longshore transport potentials past the Lakes Entrance Channel have been made, with estimates of gross volumes ranging from 300,000 m^3 to 2,500,000 m^3 and net volumes in the order of 100,000 m^3, with conflicting estimates of direction (Wheeler, 2006); (John Kowarsky & Associates, 2007); (Coastal Engineering Solutions, 2003). Estimates derived from recent dredging of the Lakes Entrance channel and ebb tide delta deposits indicated annual net movement of sediment is generally to the north-east and in the order of

80,000 m^3/year, with gross volumes estimated at 300,000 to 400,000 m^3/year (Damian Snell, Gippsland Ports, pers comm.)

Longshore transport potentials at four representative locations along the Outer Barrier within the study have been modelled as part of this study. The four representative locations were Lakes Entrance, Bunga Arm, Paradise Beach and Seaspray. Details of the longshore transport model development, parameterisation and validation are provided in Appendix A.

The longshore transport potentials have been predicted over the 63 years of available wave hindcast data at the four representative locations. Figure 4-24 displays the variation in predicted gross longshore transport potentials between the four representative locations and over the 63 years of available wave hindcast data. From Figure 4-24 it can be seen that over the last decade, the model is predicting gross longshore transport potentials of approximately 300,000 to 350,000 m^3/year at Lakes Entrance, in good agreement to the volumes estimated from the recent dredging of the entrance channel and cut.

It can also be seen that gross transport potentials at Lakes Entrance are approximately double those predicted in the south-western end of the study area at Seaspray. There is also some suggestion of an increasing trend in gross transport potentials from the 1990's onwards compared to earlier decades. This trend may be associated with climate variability or potentially climate change, alternatively it is considered possible that some inherent bias exists in the wind speeds that were used to drive the spectral wave model. The assimilation of satellite derived winds in the NCEP reanalysis steadily increased from the 1980's onwards and may contribute to a bias in the subsequent wave and sediment transport modelling results.

Figure 4-25 displays the variation in the predicted net longshore transport potentials between the four representative locations and over the 63 years of available wave hindcast data. From Figure 4-25 it can be seen that net transport potentials are generally north-eastward (negative) across the four locations. Prevailing north-eastward net longshore transport is supported by the geomorphic evidence in the study area with easterly deflection of paleo-entrances through the Outer Barrier at Bunga and Cunninghame Arms. It can however be seen that the net longshore transport potentials can be seen to switch to the south-west during some years. It is suspected that the number and magnitude of the years in which the net longshore transport was south-westerly may be slightly greater than indicated in the analysis presented in Figure 4-25, due to a slight south-westerly bias in the modelled wave hindcast results associated with the NCEP reanalysis wind fields.

Figure 4-26 displays the net cumulative longshore sediment differential between Seaspray and Lakes Entrance over the 63 years of wave hindcast. This analysis is considered to provide an estimate of the gross longshore sediment budget of the Outer Barrier within the study area. From Figure 4-26 it can be seen that a persistent sediment deficit is predicted over this period, with the rate of transport to the east of Lakes Entrance exceeding the potential supply from the south-west at Seaspray. Over the 63 years of wave data, a total deficit of approximately 4,500,000 m^3 is predicted. This corresponds to an approximate annual deficit of 70,000 m^3/year within the study area. The underlying sediment deficit in the study area is consistent with the understanding of the regional coastal process continuum of the East Gippsland coast.

In order to provide an assessment of the extent to which changes in the net longshore sediment transport continuity along the Outer Barrier can be correlated with observed shoreline change, variations in the longshore sediment transport continuity along the Outer Barrier have been compared and contrasted to available historical aerial photography and other shoreline profile data (where available) in the following sections.

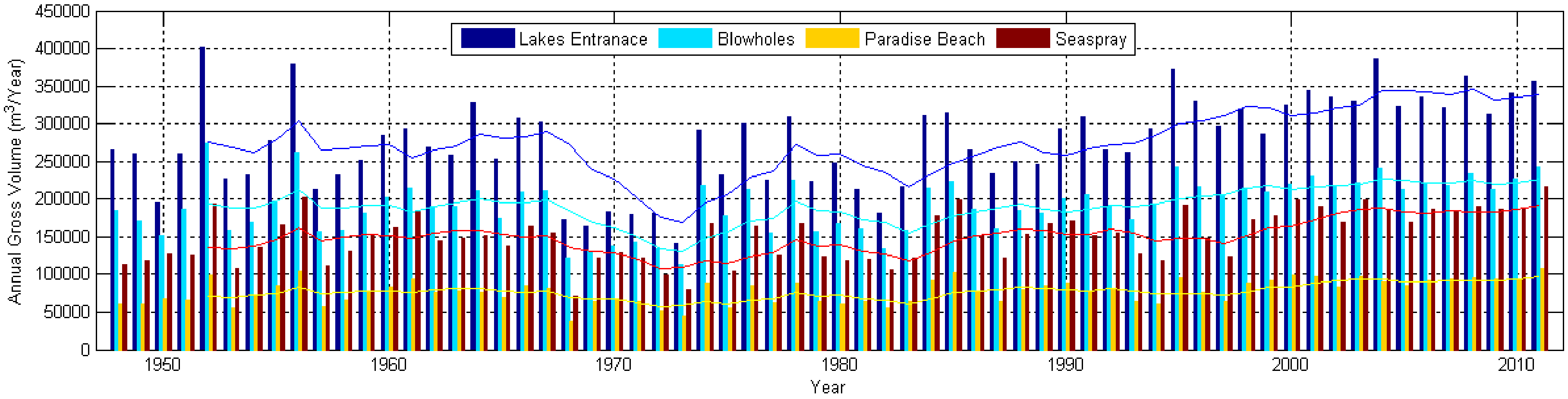


Figure 4-24 Predicted Gross Longshore Transport Potentials along the Outer Barrier (Solid line displays the 5 year moving average)

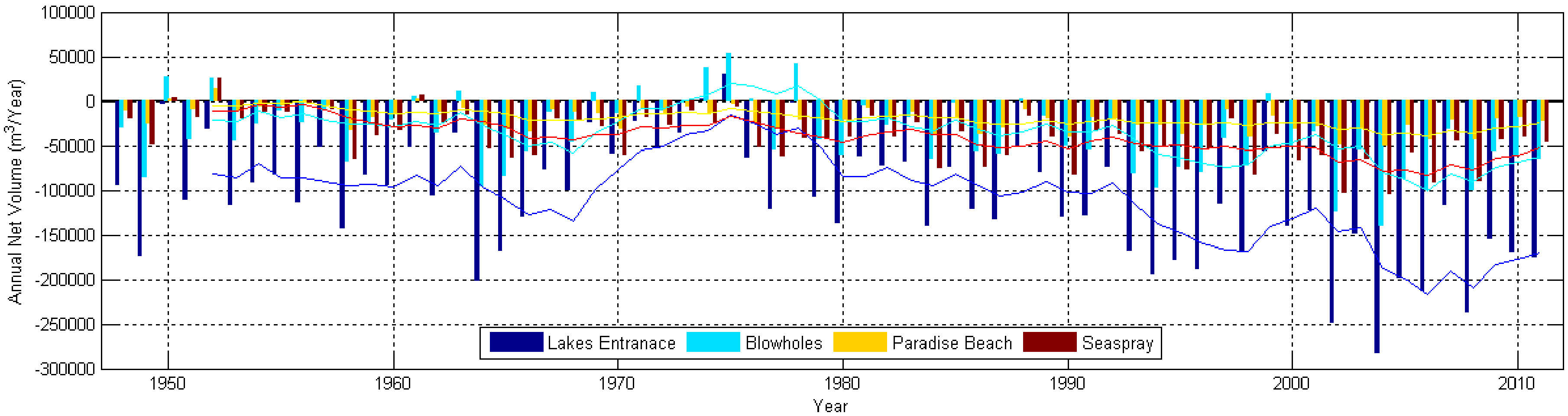


Figure 4-25 Predicted Net Longshore Transport Potential along the Outer Barrier (Solid line displays the 5 year moving average)

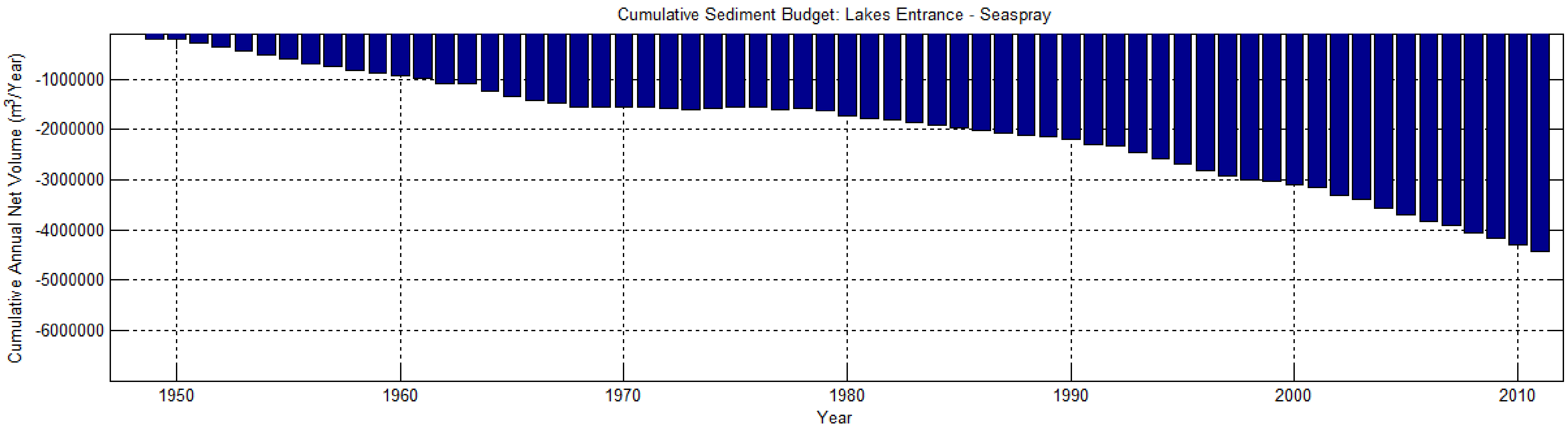


Figure 4-26 Cumulative Net Longshore Sediment Differential between Seaspray and Lakes Entrance

Seaspray

Historical aerial photography of the coastline in the vicinity of Seaspray was provided for the project, with one photo available per decade from 1965 to 2010. The aerial photography was georeferenced in a GIS and the location of the vegetated dune extent was delineated to provide a proxy of shoreline position/variability over this period as shown in Figure 4-27. From Figure 4-27 the following general trends are evident in the shoreline position:

- 1965 – 1984: The vegetated dune extent is generally stable with some regions advancing slightly seaward (prograding) over this period.
- 1992 – 2010: Significant shoreline recession is observed over this period with the vegetated dune extent in 2010 landward of the earliest 1965 photo. Historic shoreline behaviour at Seaspray appears to have changed significantly over the last 20 years compared to the preceding 30 years. Maximum shoreline recession from the 2010 shoreline to the most seaward position of the shoreline from all historical photos is approximately 20 m.

It is possible that some of the recent shoreline recession observed at Seaspray is associated with late 20th century sea level rise. It is also noted from the analysis of the storm wave climate in Section 3.2.1, that the last approximately 5 years (2007-2012) have experienced a clustering of wave storminess which may have contributed to more recent recession. Based on comparisons of shoreline profiles at Seaspray undertaken as part of this study (Report 5 – Shoreline Monitoring) against shoreline profiles extracted from LiDAR survey at the same location in 2007 and displayed in Figure 4-28, the continued recessionary trend at Seaspray can be seen to have continued through to 2012.

Review of the longshore sediment transport budgets at Seaspray has been undertaken to see if the changes in shoreline behaviour identified from the historical photography could be correlated. Figure 4-29 displays the cumulative net longshore sediment transport potentials at Seaspray relative to periods of accretion/stability and recession identified from the historical photography. From Figure 4-26 it can be seen that the modelling analysis indicates that the net north-east longshore transport rates appear to have remained relatively stable, although a slight increase in the rate of net transport is observed from the 1990's onwards compared to earlier decades. It is possible that the shoreline position at Seaspray is very sensitive to small changes in the rates of longshore transport resulting in the recession observed since the 1990's. Alternatively, it is speculated that the underlying sediment budget deficit that exists in the south-western geomorphic units of the Outer Barrier are manifesting in the form of regressive barrier types, small barrier volumes and associated underlying shoreline recession.

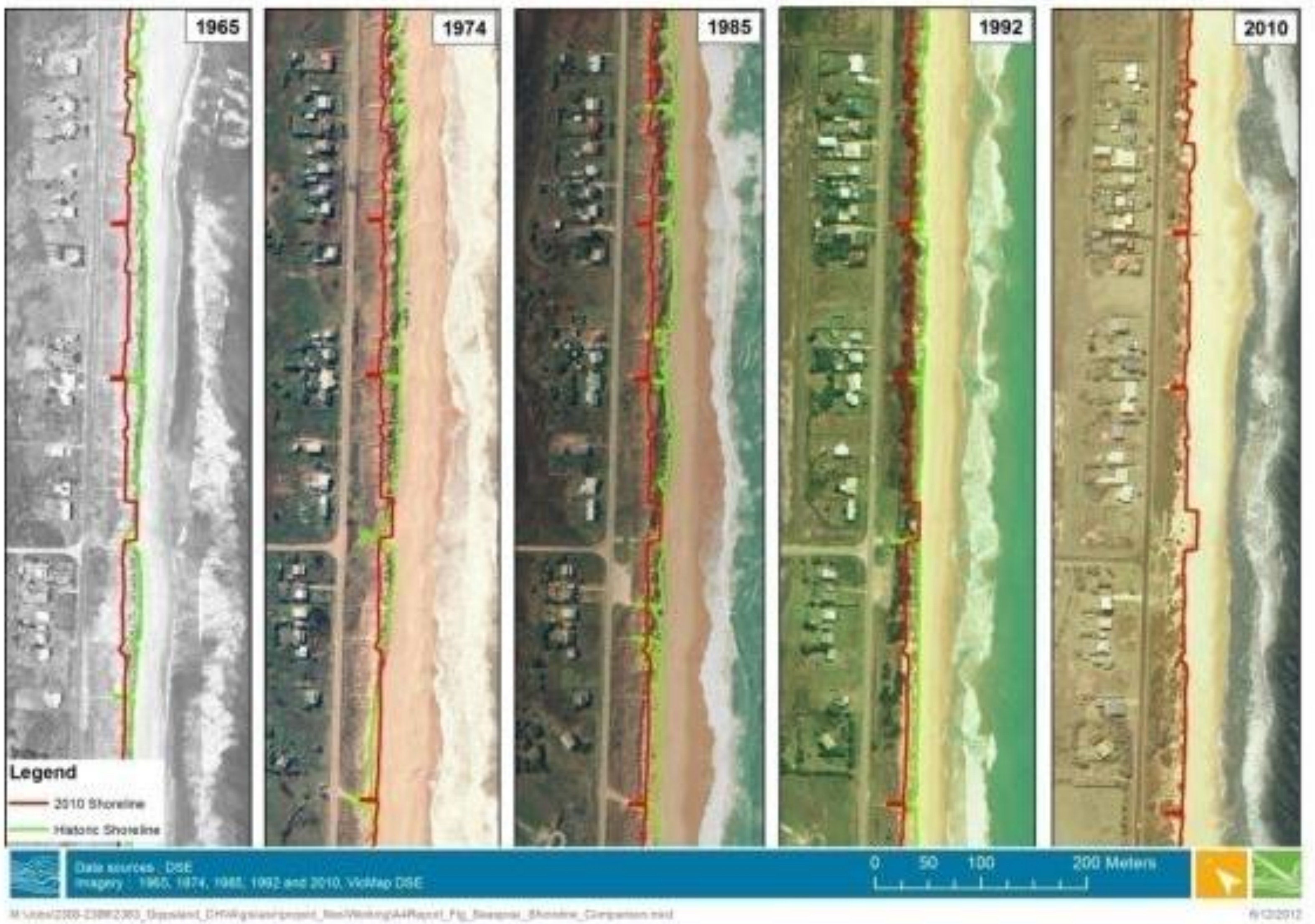


Figure 4-27 Shoreline Variability at Seaspray Delineated from Aerial Photography (1965-2010)

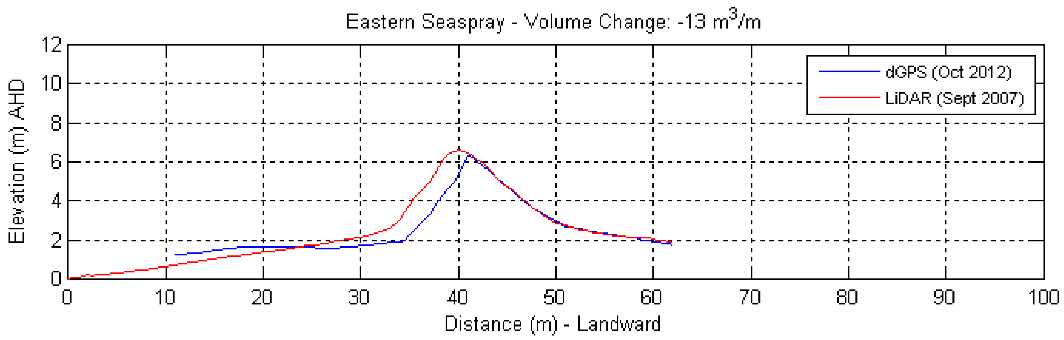


Figure 4-28 **Eastern Seaspray Coastal Profile Survey Comparison (2007-2012)**

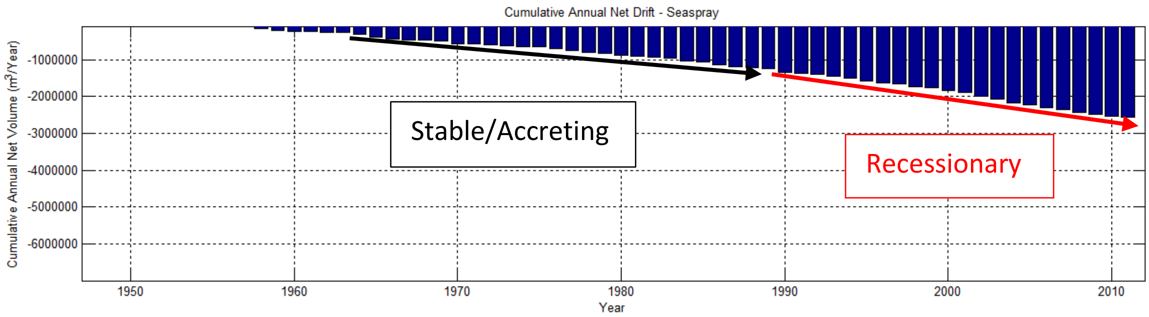


Figure 4-29 **Comparison of Cumulative Net Annual Longshore Drift and Photographic Trends at Seaspray**

East Lakes Entrance

Historical aerial photography of the coastline in the north-east end of the study area towards Red Bluff was provided for the project, with five photos irregularly spaced from 1959 to 2010. The aerial photography was geo-referenced in a GIS and the location of the vegetated dune extent was delineated to provide a proxy of shoreline position/variability over this period as shown in Figure 4-30. From Figure 4-30 the following general trends are evident in the shoreline position:

- 1959 – 1984: A general, slow recessionary trend is evident up to 1984 photo, with vegetated dune extent located landward of the 2010 extent.
- 1984 – 2010: Significant shoreline accretion is observed after 1984. Some continued shoreline progradation is observed between 2006 and 2010. Historic shoreline behaviour at East of Lakes Entrance appears to have switched to a prograding regime over approximately the last 20 years. Maximum shoreline progradation from the 2010 photo to the most landward position of the shoreline from the historical photos is up to 40 m.

Review of the cumulative net annual longshore transport at Lakes Entrance is shown in Figure 4-31. From this, it can be seen that the modelling analysis indicates that during the 1970's in particular, the rate of net north-east transport declined significantly and slightly reversed to the south-west at times. This would correspond to a net transport away from Lakes Entrance towards Bunga Arm to the south-west. During this period, the shoreline east of Lakes Entrance was in a recessionary phase as observed from the aerial photography (in fact the barrier was overwashed in this region in 1979 as discussed later in Section 4.3.5). However, post the mid 1980's, the shoreline east of Lakes Entrance has prograded significantly in this region. From Figure 4-26 it can be seen that net north-east transport at Lakes Entrance increases significantly over this time. A large longshore sediment flux at Lakes Entrance towards Red Bluff, resulting in accretion at Lakes Entrance East and recession at Bunga Arm to the west can potentially be identified from comparisons of changes in shoreline profiles at these two locations undertaken as part of this study (Report 5 – Shoreline Monitoring). Figure 4-32 displays the generally stable to slightly accreting coastal profile East of Lakes Entrance between 2007 and 2012. Figure 4-30 displays the recessionary coastal profile comparisons at the western (1st) blowhole at the Bunga Arm between 2007 and 2012.

Complicating the above assessment is, however, the potential influence of the Lakes Entrance cut and the extent to which the entrance has functioned as a sediment source/sink associated with dredging and spoil disposal over the period encompassing the historical aerial photography in this region.

Figure 4-30 Shoreline Variability East of Lakes Entrance Delineated from Aerial Photography (1959-2010)

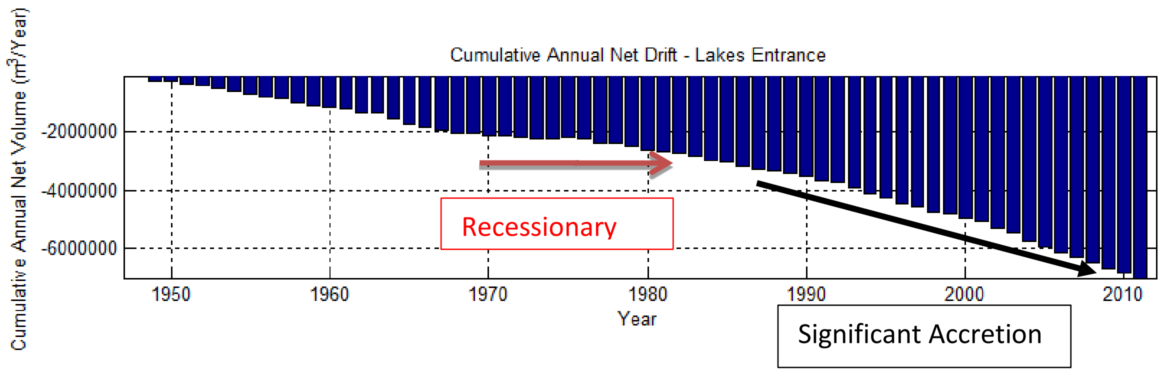


Figure 4-31 Comparison of Cumulative Net Annual Longshore Drift and Photographic Trends at Lakes Entrance

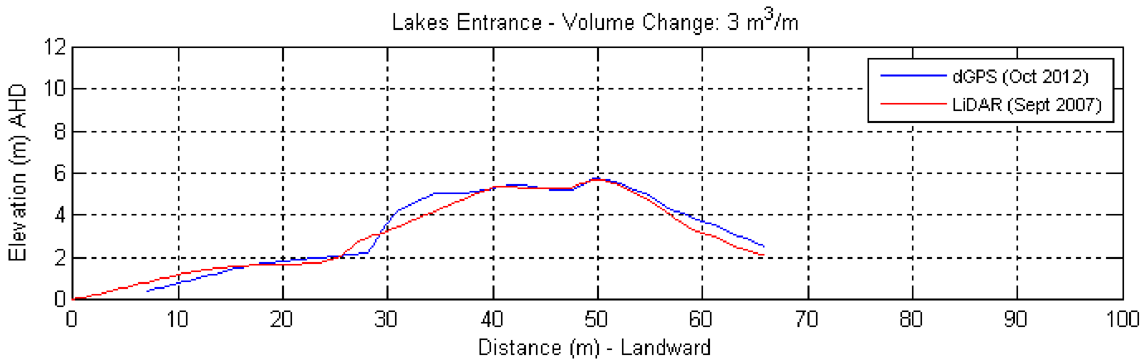


Figure 4-32 East Lakes Entrance Stable/Accreting Coastal Profile

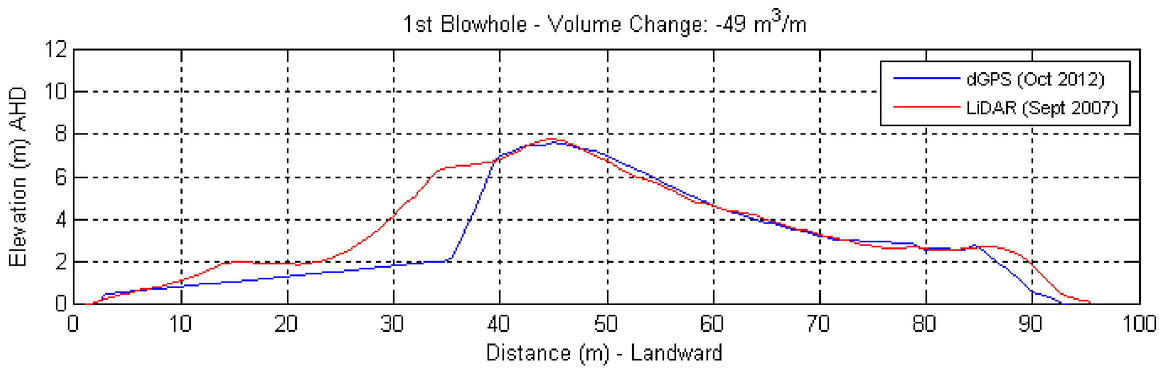


Figure 4-33 Bunga Arm (Western Blowhole) Recessionary Coastal Profile

5. RESPONSE OF COASTAL BARRIERS TO RISING SEA LEVELS

5.1 Overview

Coastal barrier landforms are generally sensitive to sea level rise due to their relatively low elevations, finite volume and the erodibility of the barrier's sediments. As sea level rises and/or sediment supply rates decrease, coastal barriers can respond by one or a combination of three potential mechanisms (Masselink & Hughes, 2003), (Moore, Jevrejeva, & Grinsted, 2010):

- **Barrier Erosion –** The barrier is eroded from the seaward face and sediment is lost offshore until the profile is translated shoreward and upward
- **Barrier Translation –** The entire barrier migrates across the underlying substrate without significant loss of sediment. This is accomplished through erosion of the shoreface and deposition of this sediment behind the barrier by the process of washovers and through aeolian transport.
- **Barrier Overstepping –** Under conditions of rapid sea level rise or disruptions to sediment supply, the barrier may be 'overstepped' leaving a remnant marine sand body offshore.

Of the above three coastal barrier response mechanisms, only barrier erosion and barrier translation responses are considered relevant to the study area given the rates of sea level rise projected this century.

The type or sequence of mechanisms by which a coastal barrier responds to sea level rise is influenced by the morphology of the barrier and hydrodynamic processes it is subject to.

Initially, rising sea levels result in the reworking of sediments on the seaward face of the coastal barrier. The erosive forces of waves will be concentrated on the barrier's shoreface, below the crest level of the barrier. The barrier material is eroded from the seaward face of the barrier and transported offshore resulting in a translation of the shoreline profile of the barrier landward and upward.

With further sea level rise, the erosive forces of wave and storm tides increasingly impact the crest of the coastal barrier and the barrier becomes increasingly susceptible to overwash by storm events. Once the barrier is subject to overwash, the erosion-deposition response of the barrier will typically change. Overwash results in the deposition of eroded material from the seaward face of the barrier to the back barrier. This process is known as barrier rollover (Donnelly, Kraus, & Larson, 2006), and is the mechanism by which barriers transgress i.e. advance landward in response to rising sea level. The impact of washover on coastal evolution is determined by the width, depth and permanence of the washover gaps created, and the volume of sediment emplaced. Additionally, if an estuary or lagoon is reached by the overwash surge, a new tidal connection may be established causing significant secondary landform changes.

Integration of the nearshore geology and stratigraphy of the Outer Barrier discussed in previous sections with the barrier response mechanisms described above enables the development of two conceptual models of the potential responses of the Outer Barrier to sea level rise. Figure 5-1 and Figure 5-2 display the two conceptual models of the potential Outer Barrier response to sea level rise; Barrier Erosion and Barrier Translation.

Barrier Erosion Response

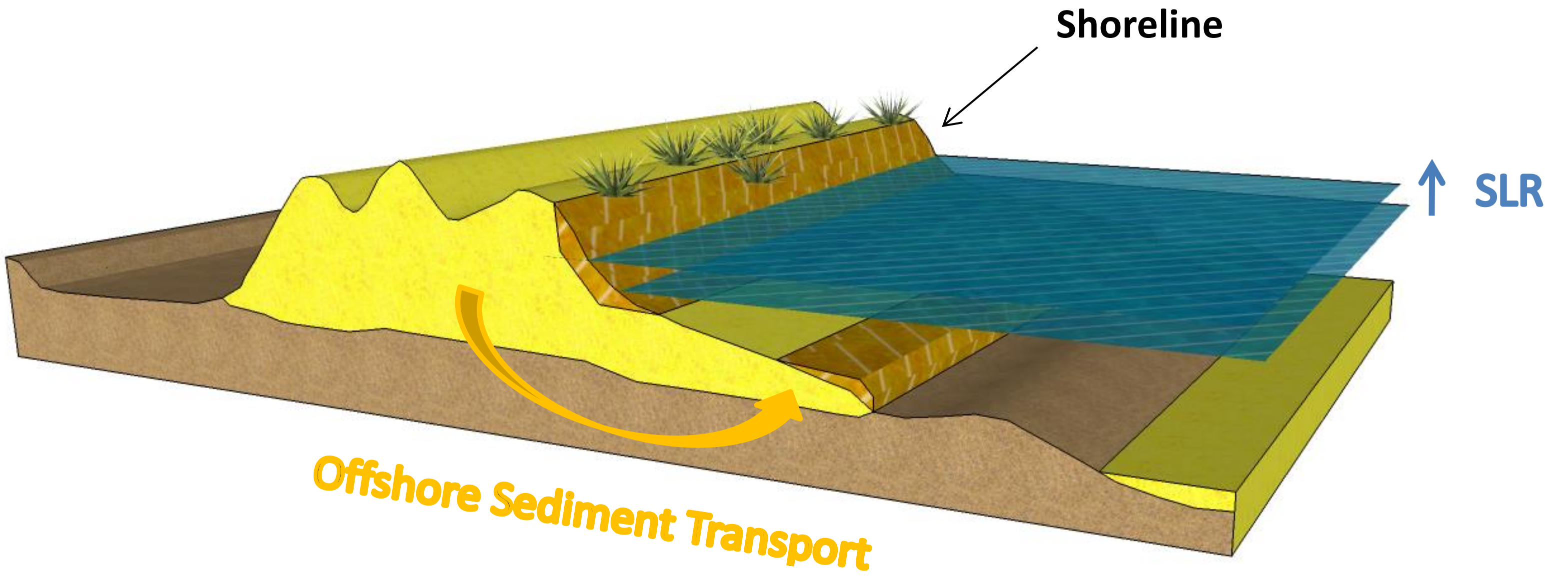


Figure 5-1 Coastal Barrier Conceptual Responses to Sea Level Rise – Barrier Erosion Response

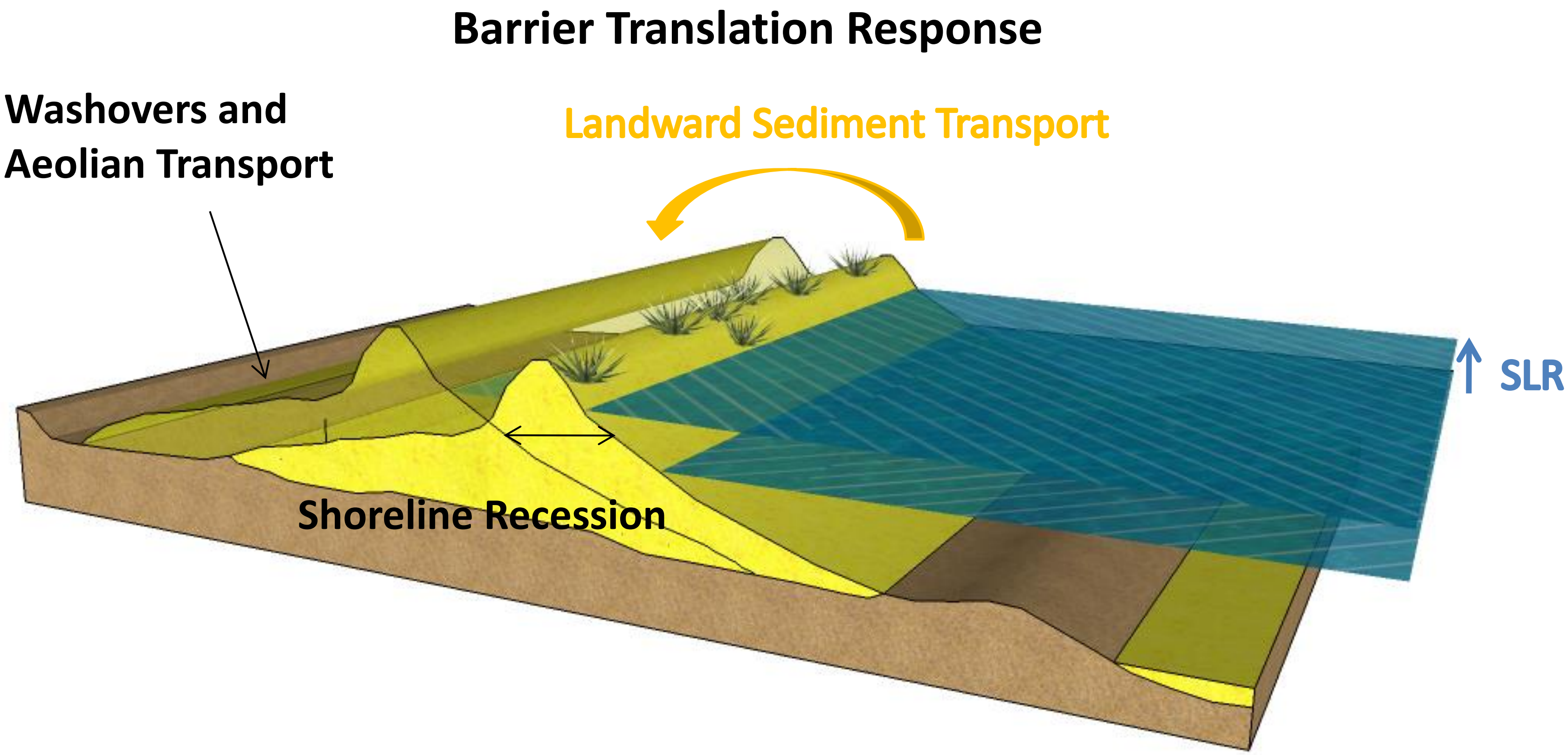


Figure 5-2 Coastal Barrier Conceptual Responses to Sea Level Rise – Barrier Translation Response

The conceptual Outer Barrier response models displayed in Figure 5-1 and Figure 5-2 have been used as a basis to assess the potential response mechanism and variability along the Outer Barrier to projected sea level rise this century. Four locations along the Outer Barrier have been analysed in detail to capture the major variations of the Outer Barrier morphology in terms of the volume, width and height as defined by the geomorphological units identified in Section 2 and summarised in Table 2-1. The four representative locations and associated geomorphic units are summarized below:

- Woodside Beach to Glomar Beach (Seaspray) (Unit 3)
- Paradise Beach (Units 4, 5, 6)
- Bunga Arm (Unit 7)
- Eastern Beach (Units 8,9,10)

For each one of the above representative locations, equilibrium profile models have been applied to identify the following:

- For a given sea level rise scenario, identify the likely mechanism of potential barrier response, i.e. barrier erosion or barrier translation and the potential extent of shoreline recession/change.
- Identify the likely sea level rise thresholds in which the likelihood of the barrier response to the sea level rise evolving to one of barrier translation significantly increases, with corresponding implications on the potential extent of coastal hazards.

5.2 Barrier Erosion

The Bruun (1962) model is one of the most widely used conceptual models for predicting beach profile response to rising sea levels due to its ease of application, and lack of accepted alternatives for long-term beach profile response. The Bruun model is based on the consideration of a shoreline profile at or close to equilibrium with a particular sea level, and that is neither gaining nor losing significant volumes of sediment. A rise in relative sea level will then lead to erosion as wave action erodes the beach face, transporting sediment offshore. Over time this process translates the previous shoreline profile shoreward and upward in response to the higher sea level. This process results in a redistribution of sediment across the profile but does not lead to net gain or loss of sediment. The equilibrium profile model only provides an estimate of the shoreline profile response to sea level rise and assumes the near shore sediment budget is in or close to equilibrium. As these conditions rarely exist in reality, the recession distances calculated by equilibrium profile models must be incorporated into a broader assessment including other variables/factors controlling shoreline position.

The amount of recession (R) predicted by the Bruun model is given as:

$$R = \frac{L*}{(B + h*)} S$$

Where h_* is the offshore depth at which sediment exchange is negligible, often termed the depth of closure, L_* is the horizontal distance from the shoreline to h_*, B is the height of the berm or dune crest and S is the amount of sea level rise for which the profile recession is being considered (Mariani, et al., 2012).

Application of the Bruun rule requires that the following three main assumptions are met: (1) Longshore sediment transport does not play a significant role in shoreline morphology, (2) the current shoreline is in, or near equilibrium and (3) the outer barrier is comprised of unconsolidated, fine grained sand. In a general sense, it is believed these assumptions are reasonably met along the

Ninety Mile Beach coastline as net longshore sediment transport rates are small, the outer barrier is comprised of fine grained sand, and it has been assumed the profile is in a current state of, or near equilibrium.

The application of equilibrium shoreline profile theory to provide an estimate of the longer term shoreline recession due to sea level rise along the outer barrier has included considerable analysis to ensure the development of the parameters defining the equilibrium profiles are determined from site specific analysis of the shoreline morphology. The sensitivity of such parameters have been assessed in order to provide a likely range of shoreline recessions based on uncertainties in the definition of parameters in the Bruun model.

5.2.1 Depth of Closure

One of the largest uncertainties in applying the Bruun model is the definition of the closure depth (h_* and h_c) as it cannot be easily physically measured or determined, and thus must be estimated. Various methods exist for defining closure depths, the most common of which is Hallermeier limits (1978) (1981) (1983), which are based on the site specific wave climate. The Hallermeier inner limit is given by:

$$h_c = 2.28He - 68.5\,(\frac{He^2}{gTe^2})$$

Where H_e and T_e is the nearshore wave height and associated wave period that is exceeded only 12 hours per year. The corresponding Hallermeier outer limit can be approximated as $h_{c\ outer} \approx 1.5 \times h_c$ (Mariani, et al., 2012).

Another common definition of closure depth is that of Berkemeier (1985), who noted that $h_c = 1.57H_e$ potentially provided a satisfactory estimate of closure depth, based on a series of measured transects and a 6 cm limit of change criterion.

H_e has been determined for each of the four representative sites based on 63 years of wave hindcast data. The estimates of H_e from the long term wave hindcast using the Hallermeier and Berkemeier relationships produced what were considered unrealistically small depths of closure. They were not able to be validated based on the interpretation of the depth of closure for the study area from review of near shore bathymetric profiles and geology. It is noted that the wave hindcast analysis tends to over-predict extreme wave conditions compared to the Lakes Entrance wave rider buoy record, which should result in conservative estimates of depth of closure using these relationships. This perhaps suggests that the Hallermeier and Berkemeier methods for estimating the depth of closure in the study area are not valid.

For these reasons, a third alternative depth of closure was subsequently developed for the four representative sites. This was based on the depth of closure inferred from the available nearshore geology and sediment data discussed in Section 4.1.1. From Section 4.1.1, it was identified that the maximum depth at which the Outer Barrier sediments extended was approximately 15 m. Beyond this depth, the characteristics of the surface sediments suggest that depths are too great for wave action to mobilise sediment onshore and this is considered to provide a conservative outer estimate of the maximum depth of closure for the Outer Barrier.

5.2.2 Dune and Berm Height

The parameter *B* is given in the Bruun model as the height of the foredune or berm in the eroded nearshore zone and thus both the height of the foredune and height of the berm for each site were used as input values of *B* into the Bruun model in order to assess recession sensitivity. The terms B, L_* and h_c combine together in the Bruun model to give an average slope of the beach face and nearshore zone, of which according to the Bruun model, controls the amount of profile recession due to sea level rise.

5.2.3 Application of the Bruun Model at Representative Locations

The following presents the results of the application of the Bruun model to shoreline profiles at the four key representative locations along the Outer Barrier for 0.2, 0.4 and 0.8 m SLR scenarios.

The sensitivities of the shoreline recession estimates provided by the Bruun Model to uncertainty in the definition of parameters in the model are provided for the following:

- *(A) is the profile adjusted using the Hallermeier h_c outer;*
- *(B) is the profile adjusted using the Berkinmeier h_c, and*
- *(C) is the profile adjusted using the hc inferred from site specific geologic/sediment data.*

The relevant MSL and 10% AEP storm tide elevation are plotted for each sea level rise scenario to provide an indication of the relative susceptibility of the Outer Barrier to overwash.

The estimates of shoreline recession using the Bruun model are particularly sensitive to the definition of the parameters that are used in the model, particularly h_c. Estimates of shoreline recession therefore vary by a factor of approximately 2, depending upon particular definition of the parameters used in the Bruun model.

Seaspray

Table 5-2 summarises the key Bruun Model parameters adopted for the representative shoreline profile at Seaspray. Figure 5-3 displays the results of the equilibrium profile adjustment at Seaspray predicted from the application of the Bruun model parameters displayed in Table 5-2.

Seaspray has the lowest nearshore slope and consequently the greatest amount of predicted recession of all four representative locations. From Figure 5-3 it can be seen that for SLR beyond approximately 0.4 m and regardless of the Bruun model parameters adopted, much of the barrier volume would potentially be consumed by profile adjustment and the elevation and volume of the barrier above key water level planes would be minimal. Under this scenario, the likelihood of overwash increases significantly and the barrier responses could be expected to evolve to one of translation for sea level rise scenarios greater than approximately 0.4 m.

Table 5-1 Bruun Model Parameter Estimates for Seaspray

Closure Depth, H_c (m)		Length, L (m)	Dune Height, B (m)	Recession Factor
Hallermeier h_c	8	490	7	33
Berkemeier h_c	4	302	7	27
Geologic h_c	15	1012	7	46

Note: the recession or barrier erosion distance is calculated as the recession factor times SLR scenario height.

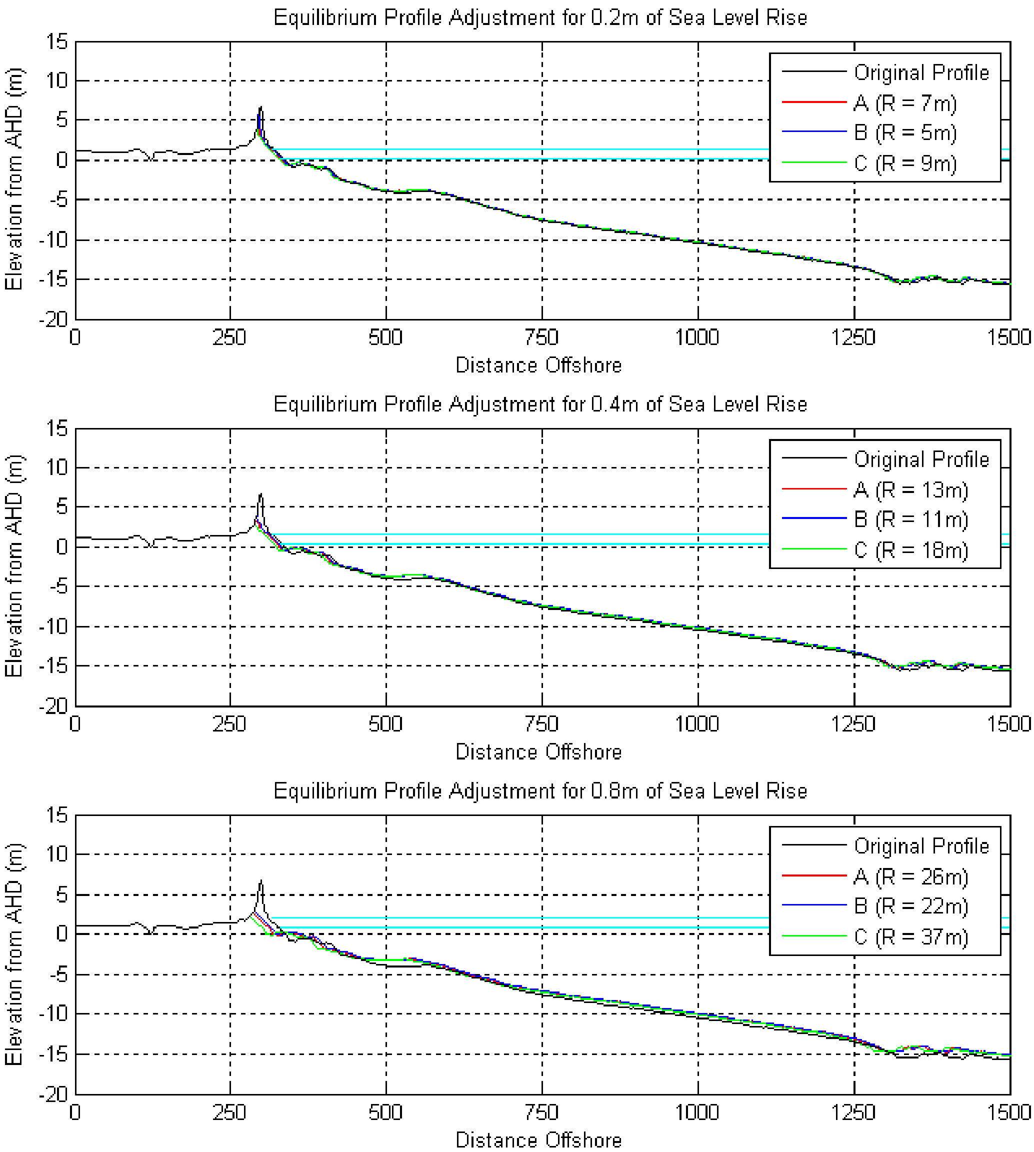


Figure 5-3 Application of the Bruun Model to the Seaspray Profile for 0.2, 0.4 and 0.8 m SLR

Paradise Beach

Table 5-2 summarises the key Bruun Model parameters adopted for the representative shoreline profile at Paradise Beach. Figure 5-4 displays the results of the equilibrium profile adjustment at Paradise Beach predicted from the application of the Bruun model parameters displayed in Table 5-2.

From Figure 5-4 it can be seen that due to the height and volume of the barrier at this location, a relatively linear erosion response of the barrier is predicted for all sea level rise scenarios up to 0.8 m. The amount of profile adjustment predicted at this location is however very sensitive to the assumptions regarding the depth of closure.

Table 5-2 Bruun Model Parameter Estimates for Paradise Beach

Closure Depth, H_c (m)		Length, L (m)	Dune Height, B (m)	Recession Factor
Hallermeier h_c	8	454	13	22
Berkemeier h_c	4	292	13	17
Geologic h_c	15	938	13	34

Note: the recession or barrier erosion distance is calculated as the recession factor times SLR scenario height.

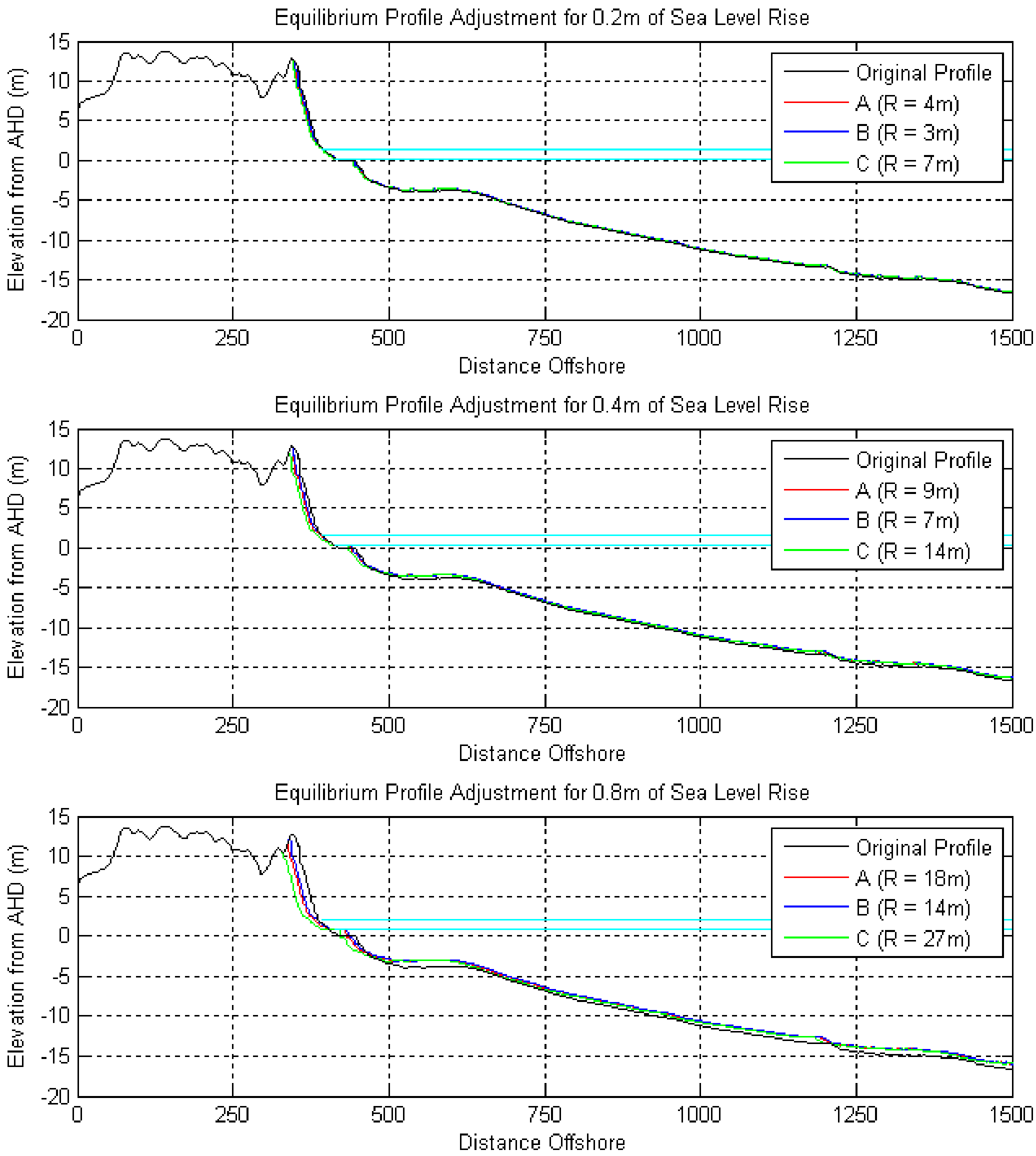


Figure 5-4 Application of the Bruun Model to the Paradise Beach Profile for 0.2, 0.4 and 0.8 m SLR

Bunga Arm

Table 5-3 summarises the key Bruun Model parameters adopted for the representative shoreline profile at Bunga Arm. Figure 5-5 displays the results of the equilibrium profile adjustment at Bunga Arm predicted from the application of the Bruun model parameters displayed in Table 5-3.

From Figure 5-5 it can be seen that for SLR beyond approximately 0.4 m and regardless of the Bruun model parameters adopted, much of the barrier volume would potentially be consumed by profile adjustment and the elevation and volume of the barrier above key water level planes would be minimal. Under this scenario, the likelihood of overwash increases significantly and the barrier responses would be expected to evolve to one of translation.

Table 5-3 Bruun Model Parameter Estimates for Bunga Arm

Closure Depth, H_c (m)		Length, L (m)	Dune Height, B (m)	Recession Factor
Hallermeier h_c	8	354	9	21
Berkemeier h_c	4	254	9	20
Geologic h_c	15	648	9	27

Note: the recession or barrier erosion distance is calculated as the recession factor times SLR scenario height.

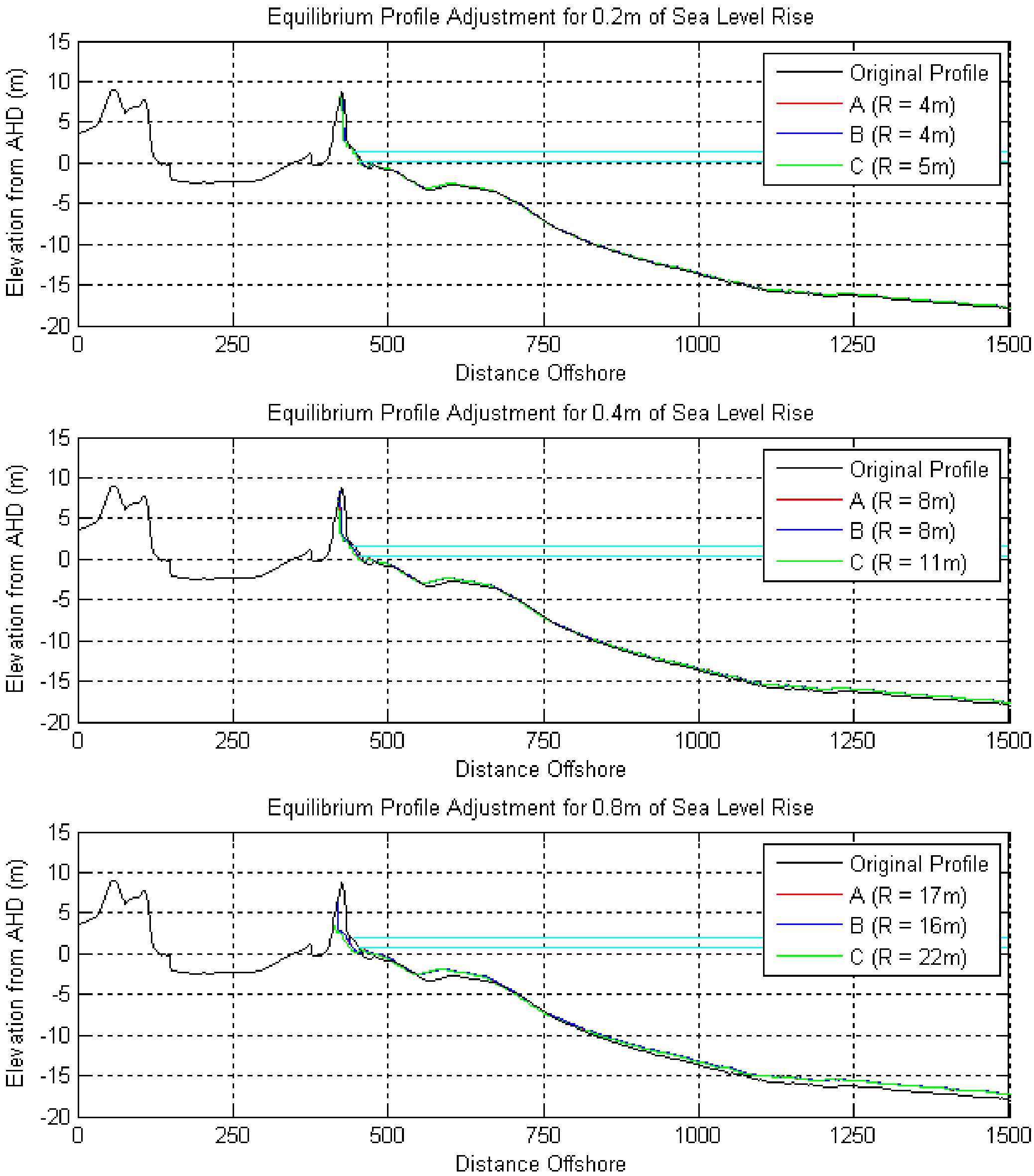


Figure 5-5 Application of the Bruun Model to the Bunga Arm Profile for 0.2, 0.4 and 0.8 m

East Lakes Entrance

Table 5-4 summarises the key Bruun Model parameters adopted for the representative shoreline profile at East Lakes Entrance. Figure 5-6 displays the results of the equilibrium profile adjustment at East Lakes Entrance predicted from the application of the Bruun model parameters displayed inTable 5-4.

From Figure 5-6 it can be seen that for SLR beyond approximately 0.8 m, much of the barrier volume would potentially be consumed by profile adjustment and the elevation and volume of the barrier above key water level planes would be minimal. Under this scenario, the likelihood of overwash increases significantly and the barrier responses would be expected to evolve to one of translation.

Table 5-4 Bruun Model Parameter Estimates for East Lakes Entrance

Closure Depth, H_c (m)		Length, L (m)	Dune Height, B (m)	Recession Factor
Hallermeier h_c	8	368	7	25
Berkemeier h_c	4	286	7	26
Geologic h_c	15	784	7	36

Note: the recession or barrier erosion distance is calculated as the recession factor times SLR scenario height.

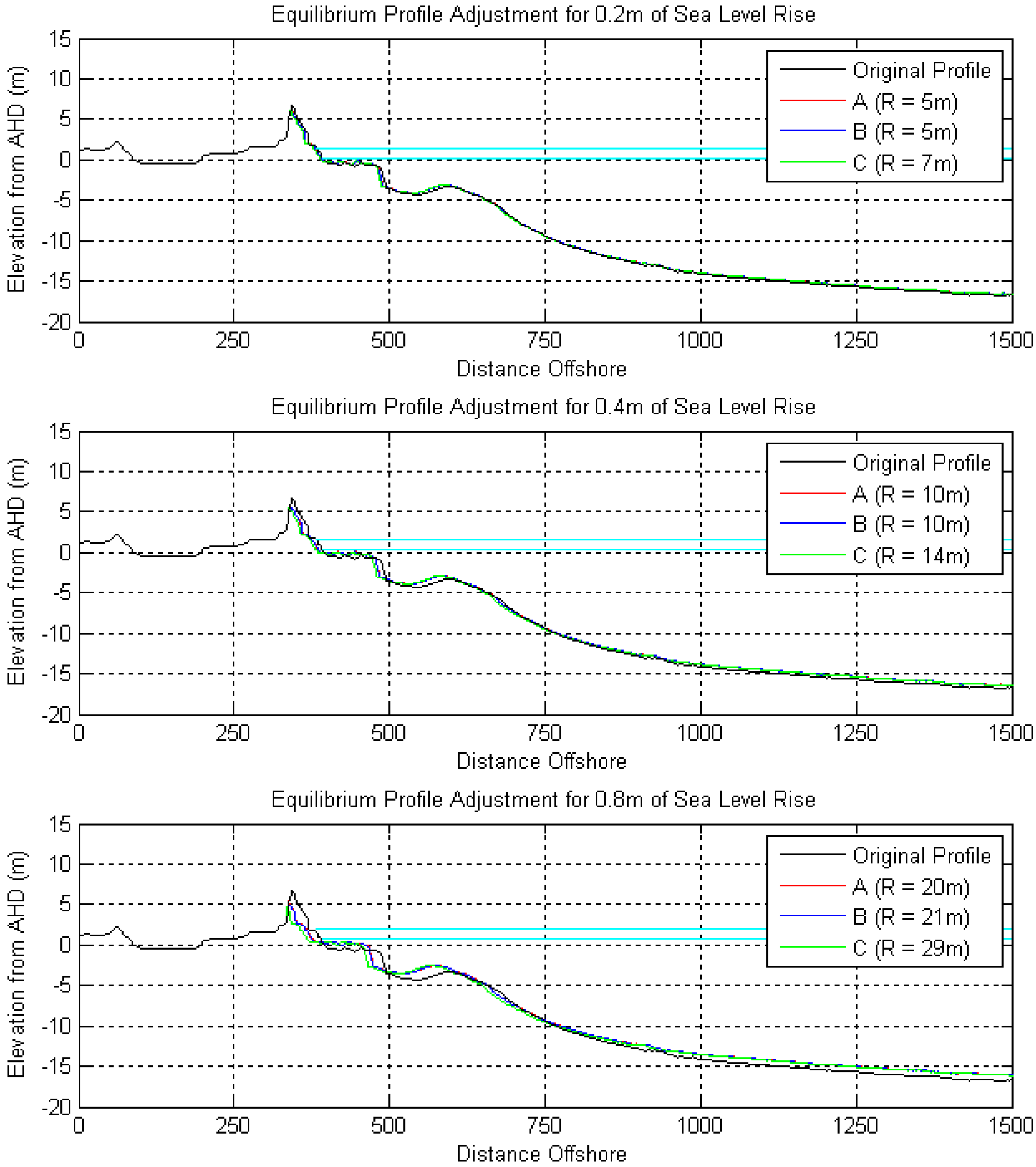


Figure 5-6 Application of the Bruun Model to the Eastern Beach Profile for 0.2, 0.4 and 0.8 m SLR

5.3 Barrier Translation

The application of the barrier erosion model in the previous section has identified that for some representative locations along the Outer Barrier, landward and upward profile adjustment to sea level rise would potentially exceed the height and width of the existing barrier under various sea level rise scenarios. Under these conditions, the potential for overwash processes to begin to transport sediment landward of the barrier increases and the sea level rise response of the barrier could be expected to evolve to the translation mechanism.

To estimate the potential extent of profile adjustment possible due to barrier translation, a modified version of Bruun Model from Dean and Maurmeyer (1983) for barrier island equilibrium translation response has been applied as displayed in Figure 5-7.

This model of barrier island equilibrium response predicts significantly greater recession than the original Bruun Model as the sediment eroded on the ocean side is used to balance the sea level rise on both the ocean and barrier side, and thus requires increased volumes of sediment to be transported landward to reach an equilibrium profile form (Wolinsky & Murray, 2009) (Dean & Dalrymple, 2002).

Dean and Maurmeyer's (1983) modified version of the Bruun Model is given as:

$$R = S\,\frac{(L_o + W + L_L)}{h_{*o} - h_{*L}}$$

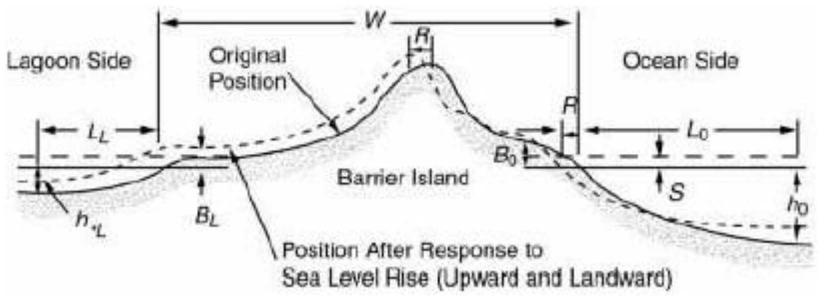


Figure 5-7 Barrier Island Equilibrium Response (Dean & Maurmeyer, 1983)

It is important to recognise that, as with all equilibrium profile models, the adjusted shoreline profiles calculated using the barrier island equilibrium model represent an estimate of the final (equilibrium) shoreline profile adjustment. This is assumed to follow a static increase in mean sea level and after all cross-shore sediment transport and aeolian-vegetation transport processes have returned to equilibrium. In reality, the response of the shoreline profiles is dynamic and the equilibrium adjustment may never be fully achieved under a scenario of rising sea levels. However, application of the barrier island equilibrium model does provide useful information for understanding the potential magnitude and extent of coastal hazard impacts that could result from the landward translation of the barrier due to sea level rise.

5.3.1 Application of the Barrier Island Equilibrium Model at Representative Locations

The sensitivities of the profile adjustment estimate provided by the Barrier Island Equilibrium Model to uncertainty in the definition of parameters in the model are provided for the following:

- *(A) is the profile adjusted using the Hallermeier hc outer;*
- *(B) is the profile adjusted using the Berkinmeier hc; and*
- *(C) is the profile adjusted using the hc inferred from site specific geologic/sediment data.*

The relevant MSL and 10% AEP storm tide elevation are plotted for each sea level rise scenario to provide an indication of the relative susceptibility of the barrier to overwash.

Barrier translation results in coastal hazard impacts extending across the barrier and into backbarrier areas due to overwash and washover processes. The total extent of coastal hazards includes both the shoreward recession estimate (Recession - R) as well as an additional estimate of the total extent of profile translation into back barrier areas (Translation – T). Note that T is not a value derived directly from the Dean & Maurmeyer Model, it has been estimated from the maximum extent of predicted backshore profile translation.

Seaspray

Table 5-5 summarises the key Barrier Island Equilibrium Model parameters adopted for the representative shoreline profile at Seaspray. Figure 5-8 and Figure 5-9 display the results of the equilibrium profile adjustment at Seaspray predicted from the application of the Barrier Island Equilibrium Model parameters displayed in Table 5-5 for the 0.4 m and 0.8 m SLR scenarios respectively.

From these figures it can be seen that the extent of shoreline recession/translation is significantly greater than that predicted under the barrier erosion (Bruun) model. It should also be noted that profile adjustment is predicted over distances exceeding 250 m landward existing shoreline for sea level rise scenarios of 0.8m. The extent of this profile adjustment landward of the existing barrier is associated with overwash and aeolian transport processes.

Table 5-5 Barrier Island Equilibrium Model Parameter Estimates for Seaspray

Closure Depth, H_c (m)		Length, L (m)	Width, W (m)	Recession Factor
Hallermeier h_c	8	490	60	69
Berkemeier h_c	4	302	60	91
Geologic h_c	15	1012	60	71

Note: the recession or barrier translation distance is calculated as the recession factor times SLR scenario height.

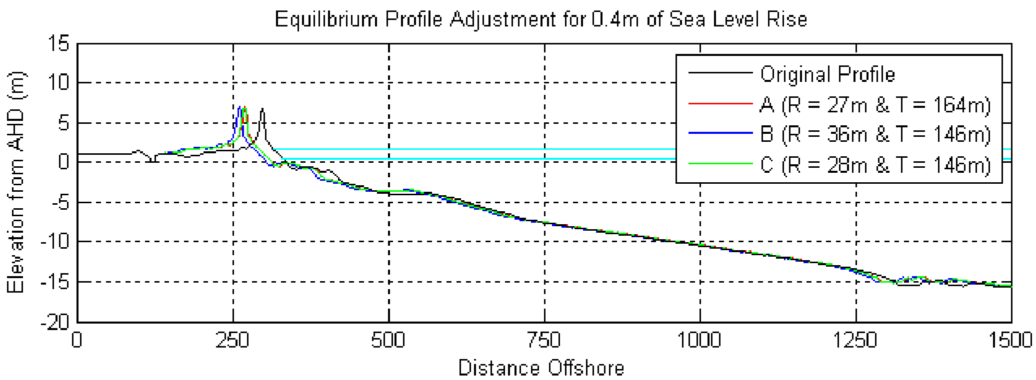


Figure 5-8 Application of the Barrier Island Equilibrium Model on the Seaspray Profile for 0.4 m SLR

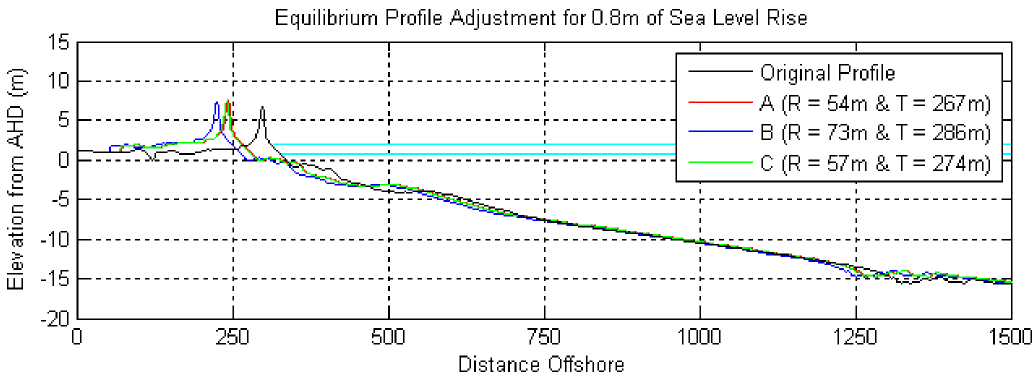


Figure 5-9 **Application of the Barrier Island Equilibrium Model on the Seaspray Profile for 0.8 m SLR**

Bunga Arm

Table 5-6 summarises the key Barrier Island Equilibrium Model parameters adopted for the representative shoreline profile at Bunga Arm. Figure 5-10 and Figure 5-11 display the results of the equilibrium profile adjustment at Bunga Arm predicted from the application of the Barrier Island Equilibrium Model parameters displayed in Table 5-6 for the 0.4 m and 0.8 m SLR scenarios respectively.

Profile adjustment is predicted over distances exceeding 300 m landward of the existing shoreline for sea level rise scenarios of 0.8m. The extent of this profile adjustment landward of the existing barrier is associated with overwash and aeolian transport processes into the Bunga Arm lagoon.

Table 5-6 **Barrier Island Equilibrium Model Parameter Estimates for Bunga Arm**

Closure Depth, H_c (m)		Length, L (m)	Width, W (m)	Recession Factor
Hallermeier h_c	8	354	108	58
Berkemeier h_c	4	254	108	91
Geologic h_c	15	648	108	50

Note: the recession or barrier translation distance is calculated as the recession factor times SLR scenario height.

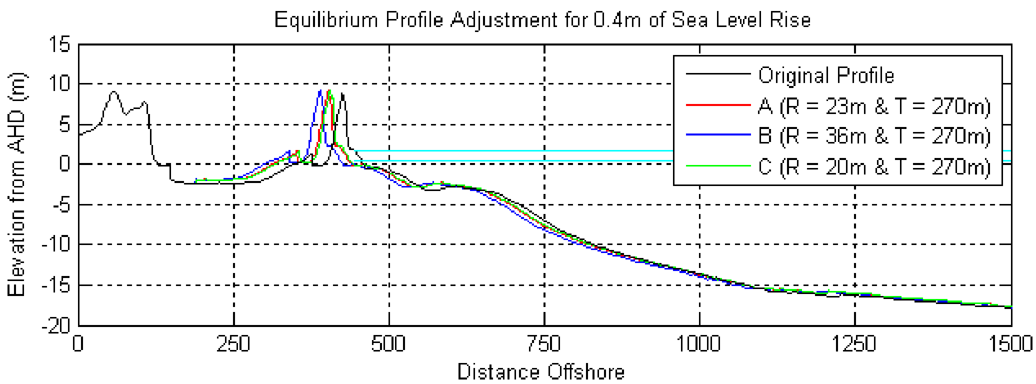


Figure 5-10 **Application of the Barrier Island Equilibrium Model on the Bunga Arm Profile for 0.4 m SLR**

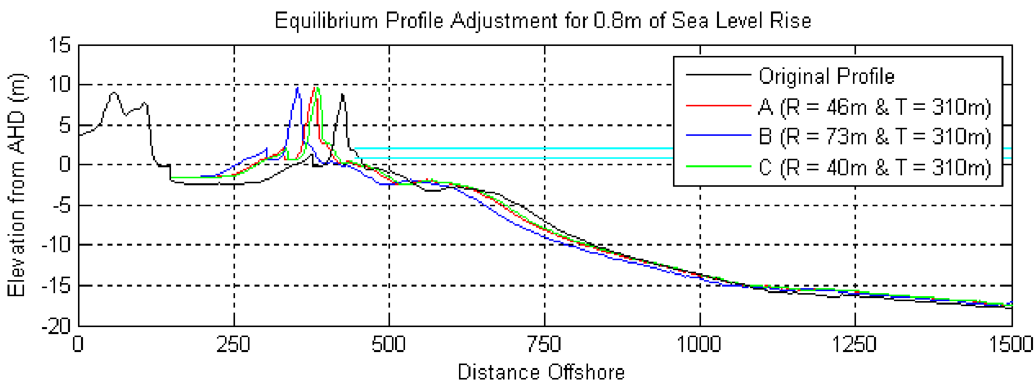


Figure 5-11 Application of the Barrier Island Equilibrium Model on the Bunga Arm Profile for 0.8 m SLR

Eastern Beach

Table 5-7 summarises the key Barrier Island Equilibrium Model parameters adopted for the representative shoreline profile at Bunga Arm. Figure 5-12 and Figure 5-13 display the results of the equilibrium profile adjustment at Bunga Arm predicted from the application of the Barrier Island Equilibrium Model parameters displayed in Table 5-7 for the 0.4 m and 0.8 m SLR scenarios respectively.

Profile adjustment is predicted over distances exceeding 250 m landward of the existing shoreline for sea level rise scenarios of 0.8m. The extent of this profile adjustment landward of the existing barrier is associated with overwash and aeolian transport processes into the former Reeve's River tidal entrance channel.

Table 5-7 Barrier Island Equilibrium Model Parameter Estimates for Eastern Beach

Closure Depth, H_c (m)		Length, L (m)	Width, W (m)	Recession Factor
Hallermeier h_c	8	368	196	71
Berkemeier h_c	4	286	196	120
Geologic h_c	15	784	196	65

Note: the recession or barrier translation distance is calculated as the recession factor times SLR scenario height.

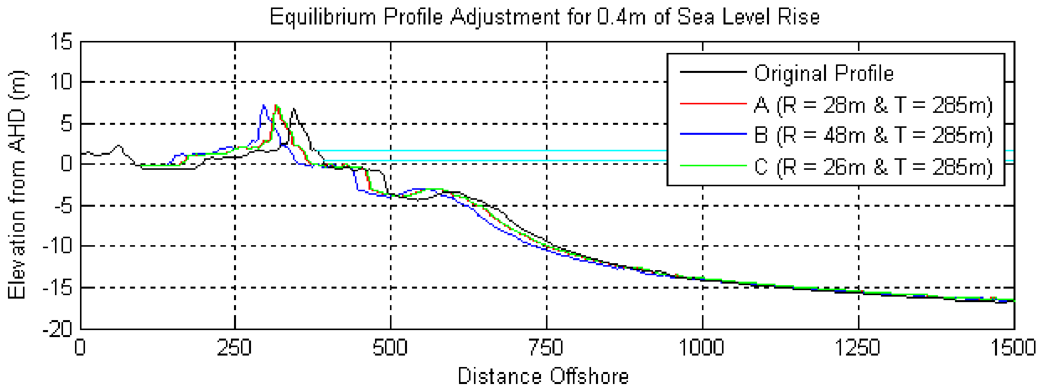


Figure 5-12 Application of the Barrier Island Equilibrium Model on the Eastern Beach Profile for 0.4 m SLR

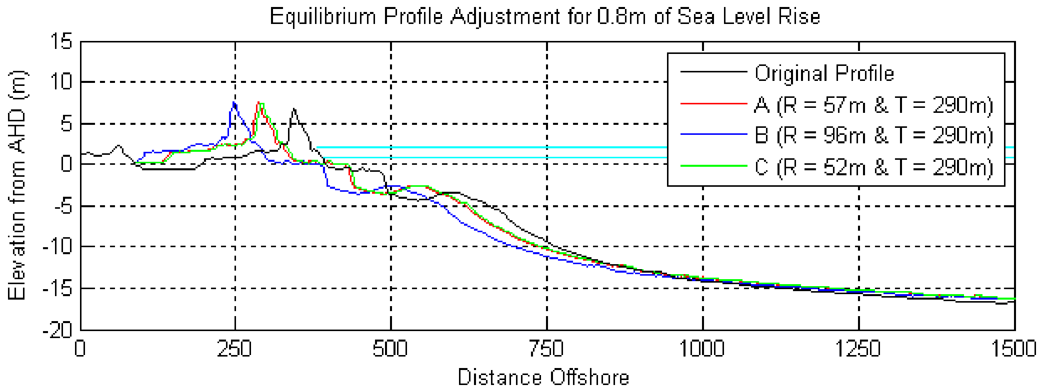


Figure 5-13 Application of the Barrier Island Equilibrium Model on the Eastern Beach Profile for 0.8 m SLR

6. SHORT-TERM STORM RELATED EROSION

There is very limited data available on the impact of short term, storm related erosion along the Outer Barrier. However, a series of photographs taken at the Seaspray SLSC immediately following the June 2007 East Coast Low event do provide some useful information for estimating the magnitude of the cross-shore transport volume and erosion widths from this storm.

The photos are considered particularly useful as the remains of the access ramps following the storm event provide a reasonably reliable measure of scale to enable the profile lowering and setback from this storm to be estimated with some reliability at this location.

Figure 6-1 shows an example of the relative position of the beach and dune to the western beach access ramp as captured in 2004. Figure 6-2 shows the relative position of the beach and dune to the western beach access ramp immediately following the June 2007 storm. From the comparison of these two photos and the relative scale provided by the access ramp, an estimate of approximately 2.5-3.0 m of profile lowering occurred at the back of the beach with the dune scarp receding by a similar order of magnitude. Similar estimates were derived from the same pre and post storm photo comparisons of the eastern beach access ramp.

Taking these estimates of the change to the geometry of the profile following the June 2007 storm and integrating along the width of the profile, including some assumptions as to the width and gradient of the profile seaward of the photo extent, an estimate of the total cross-shore sediment transport volume (storm bite) of approximately 50-70 m^3/m has been derived at Seaspray for this storm. It is considered significant that this estimate of storm bite volume represents approximately one quarter to one fifth of the total barrier volume above MHHW at some locations in the vicinity of Seaspray.

Figure 6-1 Seaspray SLSC Western Beach Access Ramp (Pre Storm, 2004)

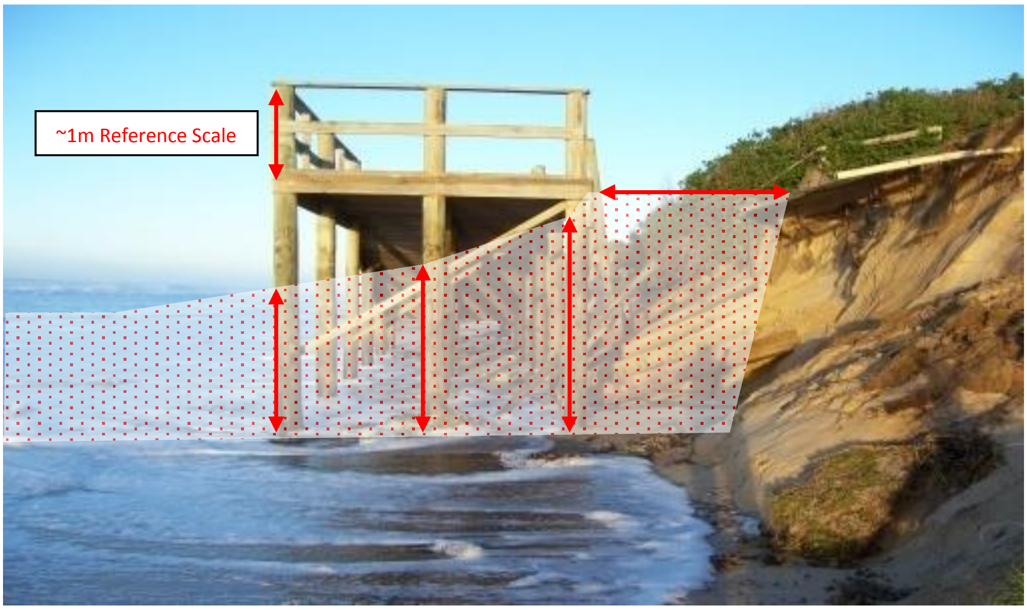


Figure 6-2 Seaspray SLSC Western Beach Access Ramp (Post Storm, 2007)

6.1 Assessment of Short Term, Storm Related Erosion

In order to provide additional information on the potential magnitude of the short-term, storm related erosion impacts along the Outer Barrier, cross-shore sediment transport modelling has been undertaken at the representative shoreline profile locations.

As described in Section 3.2, the historical hindcast storm wave climate along the Outer Barrier exhibits a strong clustering of the large storm wave events. This strong clustering of storm wave events leaves little time for beach profile recovery (accretion), which occurs over time scales of multiple years, due to onshore sediment transport during calm wave conditions. Assessing the probability and magnitude of various possible sequences of storm events for short-term erosion potential was beyond the scope of this study, and therefore, a sequence of five large storm events from the 1970s, which was identified as the period of clustering with the largest cumulative wave energy, was used in the cross-shore sediment transport model. Characteristics of the five storms used are described below in Table 6-1 and Figure 6-3.

Table 6-1 General Characteristics of the Five Storm Events used to Assess Short Term Storm Erosion (Storm Bite) in the Cross-shore Sediment Transport Model

	Event 1	Event 2	Event 3	Event 4	Event 5
Date	June 1974	June 1975	March 1976	October 1976	June 1978
Max Hs (m)	3.6	5.2	4.3	3.7	4.6
Mean Tp (s)	11.1	13.2	12.3	10.7	12.4
Duration (hr)	104	116.25	104.5	85.5	98.25
POT >3 m Cumulative Wave Energy (MJh/m^2)	0.3456	0.719	0.4399	0.2573	0.4375
Est. ARI (years)	10	110	30	6	30

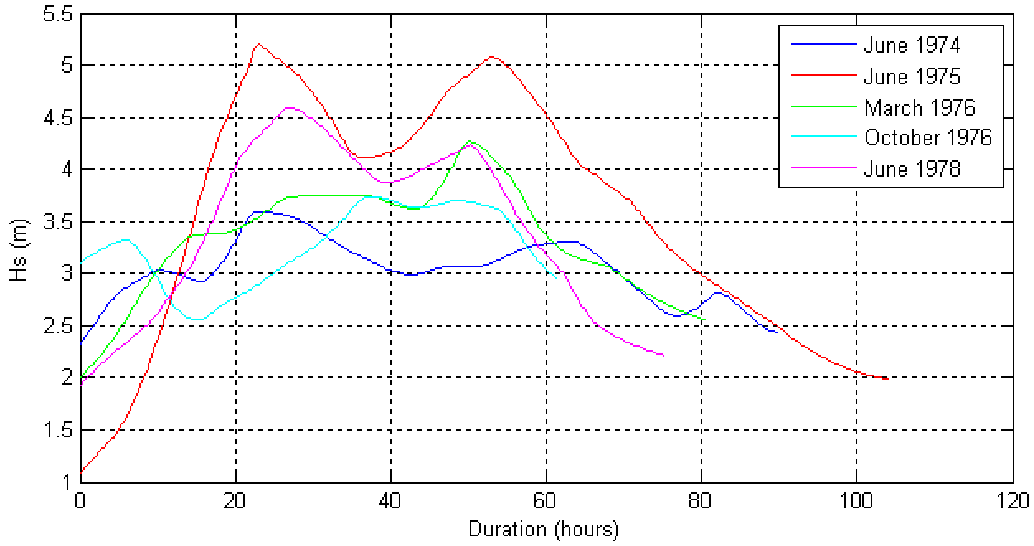


Figure 6-3 Significant Wave Heights of the Five Storm Events Described Above for Eastern Lakes Entrance

The LITPROF model (DHI, 2012) requires wave heights in the form of root mean square wave heights (H_{rms}). The significant wave heights from the hindcast wave data were converted to H_{rms} based on the theoretical prediction relationship H_{rms}/H_s = 0.71 of Longuet-Higgins (1952). The model also required wave periods in the form of zero up-crossing periods (T_z), which were available directly as an output of the wave hindcast model.

The sequence of storms were run back to back in the chronological order at which they originally occurred (Event 1 to 5), resulting in a 402 hour long time-series of wave conditions. The assumption was made that, as a worst case scenario, there was no time for beach profile recovery between events. Thus the events were run directly one after another, without any periods of calm wave conditions between events.

The water level variation was run over a typical spring tidal cycle and constant water level residual of 0.2 m was linearly added to the tidal levels, based on the analysis of the water level residuals for ECL type storm events as described in Section 3.3.2. The tidal + residual water level used as an input into the cross-shore sediment transport modelling is shown below in Figure 6-4.

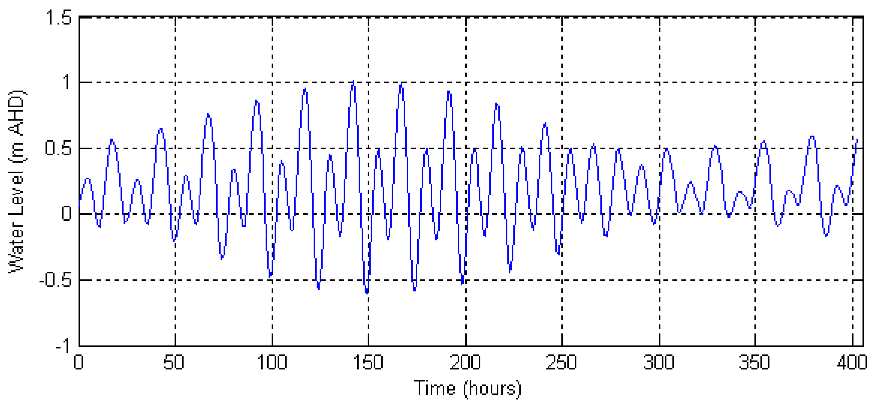
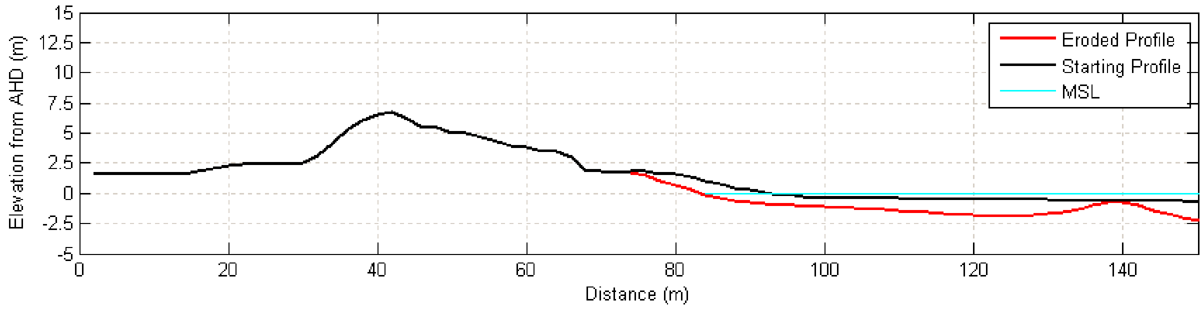
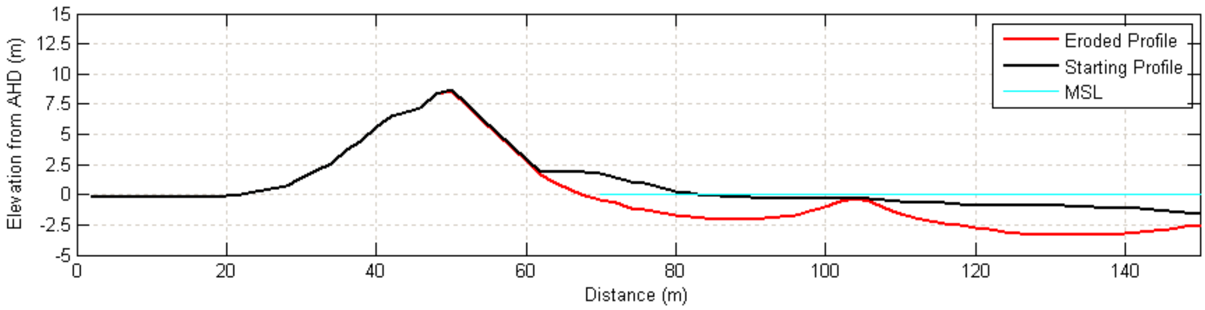


Figure 6-4 Water Level Time Series used as an Input in to the Cross-shore Sediment Transport Model – LITPROF

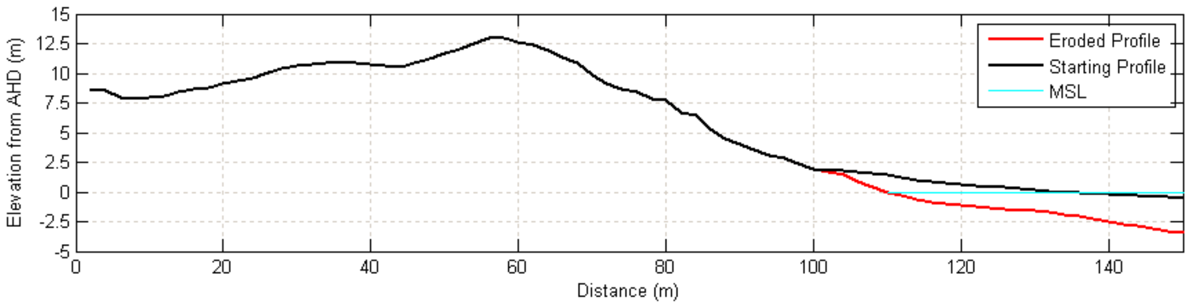
Eastern Beach



Bunga Arm



Paradise Beach



Seaspray

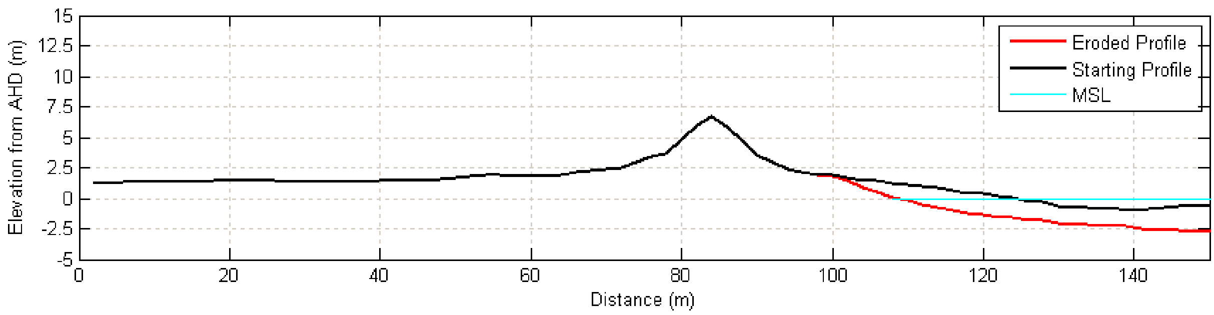


Figure 6-5 Original and Final Profile from the Cross-shore Sediment Transport Model, after being Subjected to the Above Sequence of Five Storm Events

The cross-shore sediment transport model results, shown in , are consistent with the observations of (Wright, Nielsen, Short, Coffey, & Green, 1982) who observed the offshore bar exhibited the largest change in morphology, with smaller changes in beach face morphology in comparison. This was attributed to the bar and trough configuration having a “filtering effect” causing a relatively constant shore break height.

In addition to storm wave characteristics, the antecedent beach profile has a large influence on the magnitude of storm bite associated with a given storm or sequence of storms. Beach profiles already in an erosive state typically have a large offshore bar, which in turn acts to help dissipate storm wave energy offshore. Conversely beach profiles in an equilibrium state tend to have flatter, more uniform offshore profile. This causes waves to break closer to the shoreline, resulting in comparatively larger amounts of energy reaching the nearshore zone and beach face, until a significant offshore bar is formed, leading to initially higher volumes of erosion.

The bathymetric LiDAR data, from which the profiles for the cross-shore sediment transport modelling were extracted, was flown immediately post the June 2007 East Coast Low, that caused eroded profiles along the study area. However, the bathymetric LiDAR data was the only available high resolution data covering the study area. Therefore, the modelled storm bite volumes and erosion widths may potentially underestimate the maximum storm bite that could occur due to the above sequence of storms.

Substantial uncertainty is therefore considered to exist in the significance of short term, storm related erosion hazards in the study area. The limited observational information from the June 2007 East Coast Low at Seaspray suggests that the erosion widths from this storm were relatively small, in the order of 2-3 m. The storm bite modelling, considering a clustering of five major storms produced similarly small erosion widths due to the rapid offshore bar development.

Alternatively, the review of the dune morphology of the Outer Barrier undertaken in Section 4.2 identified multiple shore-parallel depression complexes that are likely to have their origin as significant, localised regions of short term erosion associated with rip cell embayments. The erosion widths associated with these features are in the order of 30 – 40 m.

It is therefore concluded that until further data is available and additional analysis can be undertaken of this hazard along the Outer Barrier, a provisional allowance of 5 m for short term erosion should be adopted. Additionally, the consequence of development of significant, localised short term erosion hazards of 30-40 m, associated with rip cell embayments, should also be considered.

7. EVALUATION OF SOURCES OF UNCERTAINTY

The analysis and modelling assessment of the potential extent of coastal hazards along the Outer Barrier has a number of significant potential sources of uncertainty. These sources of uncertainty require evaluation to understand the sensitivity that these sources of uncertainty may have on the definition of the coastal and inundation hazards in the study area.

From the analysis of the Outer Barrier coastal and the Gippsland Lakes inundation hazards assessments, the following significant sources of uncertainty were identified:

- The consequences of overwash of the Outer Barrier on the extent of erosion and inundation hazards in the Gippsland Lakes or back barrier areas
- Land subsidence associated with aquifer deflation

The following sections evaluate the sensitivity of these major sources of uncertainty on the coastal hazard assessment in the study area.

7.1.1 Barrier Translation and Overwash Processes

The potential for translation of the Outer Barrier due to sea level rise and associated overwash and washover processes has been identified as likely for sea level rise scenarios greater than approximately 0.4 m for a number of geomorphic units along the Outer Barrier.

The potential extents of coastal hazards along the Outer Barrier are very sensitive to the potential occurrence of overwash events as they result in rapid, large and non-linear increases in erosion extents. In addition, at Bunga Arm, the occurrence of overwash would likely result in an ephemeral connection to the Gippsland Lakes which may be significant to inundation hazards.

While it is not possible to precisely predict the location and timing of potential overwash events along the Outer Barrier, it is possible to assess the potential consequences of an overwash event which provides important understanding for evaluating the coastal hazards within the study area.

For these reasons additional analysis has been undertaken to further develop an understanding of the dynamics and consequences of overwash events at Seaspray, Bunga Arm and Lakes Entrance.

Bunga Arm

Geomorphic and anecdotal evidence of historical and contemporary overwash events in Bunga Arm have been discussed in Section 4.3.4. Through the assessment of coastal barrier response to rising sea levels in Section 5, Bunga Arm was identified as a location at which overwash events will continue, and likely increase in frequency in the future with higher mean sea levels. Through the process of barrier translation it is expected that the Bunga Arm lagoon will begin to infill with sediment as the outer barrier is translated landward in response to higher mean sea levels.

As a result of Bunga Arm being identified as a location vulnerable to overwash and barrier breaching, the impact of a breach at Bunga Arm on catchment generated flood levels and inundation extents has been assessed in detail in Section 6.1.1 of the accompanying technical report, Report 2: Inundation Hazards.

Seaspray

The impact of an overwash of the outer barrier at Seaspray was assessed through the development of a coupled hydrodynamic and sediment transport model of the region from Merriman Creek to the eastern extent of The Honeysuckles. The model extended from approximately 15 m water depth offshore to the marginal bluff on the landward side of the barrier, and included the settlements of Seaspray and The Honeysuckles.

To create a condition that would initiate overwash of the Outer Barrier, the model topography was edited initially to include a lowered section of barrier to the east of Seaspray. The section was approximately 85 m wide, with a maximum dune crest that was 0.5 m below the peak water elevation of a 1% AEP storm tide sequence incorporating 0.8 m of mean sea level rise.

The model was simulated with the 1% AEP storm tide water level sequence, initiating an overwash event through the barrier. From Figure 7-1, the landward transport of sediment can be seen, with washover deposits radiating out approximately 150 m landward of the overwash site and over a width of 250 m. The landward extent of sediment transport in this scenario corresponds well with the extents of landward barrier translation predicted from the application of the Barrier Island Equilibrium Model applied at this location in Section 5.3. Additionally, it is noted that the spatial extent and general morphology of the washover deposit predicted from this modelling scenario are similar to the contemporary washover deposits identified within this geomorphic unit at McGaurans Beach and other locations to the south-west.

The hydrodynamic model also predicts significant backbarrier inundation from the overwash scenario. The extent of the inundation hazards resulting from an overwash event at this location are considered in more detail in Section 6.1.1 of the accompanying technical report, Report 2: Inundation Hazards.

The modelling assessment of an overwash scenario in the vicinity of Seaspray has highlighted the consequence of overwash and the barrier translation process on the extent of coastal hazards along this geomorphic unit of the Outer Barrier.

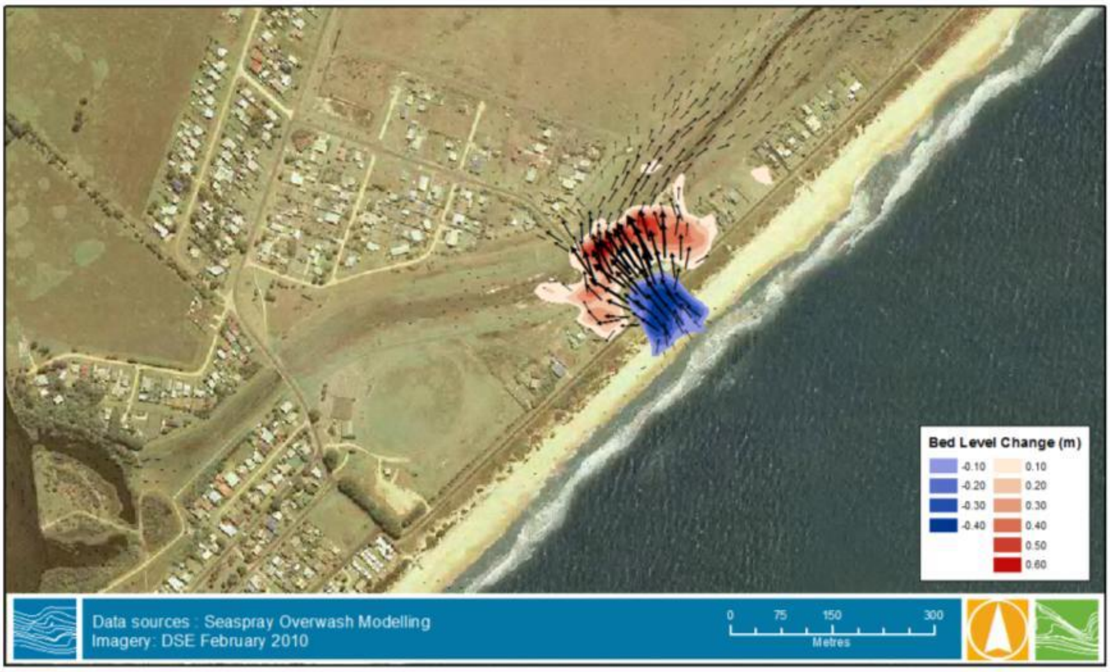


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Figure 7-1 Predicted Extent of Washover Deposits due to an Overwash Scenario at Seaspray

Lakes Entrance

The impact of an overwash of the outer barrier at Lakes Entrance was assessed through a coupled hydrodynamic and sediment transport model. In order to create a condition that would initiate overwash at Lakes Entrance, the model topography was edited initially to include a lowered section of barrier at Eastern Beach, at a similar location to the 1979 overwash event. The section was approximately 80 m wide, with a maximum dune crest that was 0.6 m below the peak water elevation from a 1% AEP storm tide sequence incorporating 0.8 m of mean sea level rise.

Figure 7-2 shows the predicted extent of sediment deposition resulting from the washover event. The predicted width of the washover sediment fan corresponds well with the estimated width of washover sediment from the 1979 overwash event based on available photographs.

The other potential hazard associated with an overwash event is inundation of the backbarrier. Overwash modelling showed that there was little change in inundation extent around Lakes Entrance during an overwash from a 1% storm tide incorporating 0.8 m of sea level rise in comparison to the same storm tide, with no overwash at Eastern Beach, although there was a 1-3 cm increase in peak water level.

Figure 7-2 Predicted Extent of Washover Deposits at Eastern Beach, Lakes Entrance

7.1.2 Land Subsidence

Extraction of oil and gas, dewatering of open pit coal mines and groundwater extraction for irrigation has been identified as lowering pressures within the Latrobe Aquifer (Freij-Ayoub, et al., 2007). Reduction of pore water pressure within the aquifer has the potential to result in consolidation/compression of the aquifer sediments causing a lowering of the land surface above the aquifer. On the coastline and within the Gippsland Lakes, the relative fall in the land surface would cause isostatic sea level rise.

A modelling analysis of the potential extent and rate of subsidence of the Latrobe Aquifer was conducted by (Freij-Ayoub, et al., 2007). The modelling analysis considered a realistic and a pessimistic subsidence scenario for the period up to 2056. Figure 7-3 displays the predicted pessimistic subsidence contours up to 2056 for the study area. As can be seen from Figure 7-3, subsidence of up to 1.0 m is predicted towards the south-west of the study area, near Paradise Beach. The magnitude of the potential isostatic sea level rise in the south-west of the study area is therefore similar to that associated with projected eustatic sea level rise and a combination of the two would result in a very rapid sea level rise scenario for the south-west of the study area.

It is noted that the modelled subsidence predictions are based on a number of assumptions, uncertainties and limitations and thus there is a large uncertainty surrounding the likely rate of subsidence and associated shoreline recession into the future.

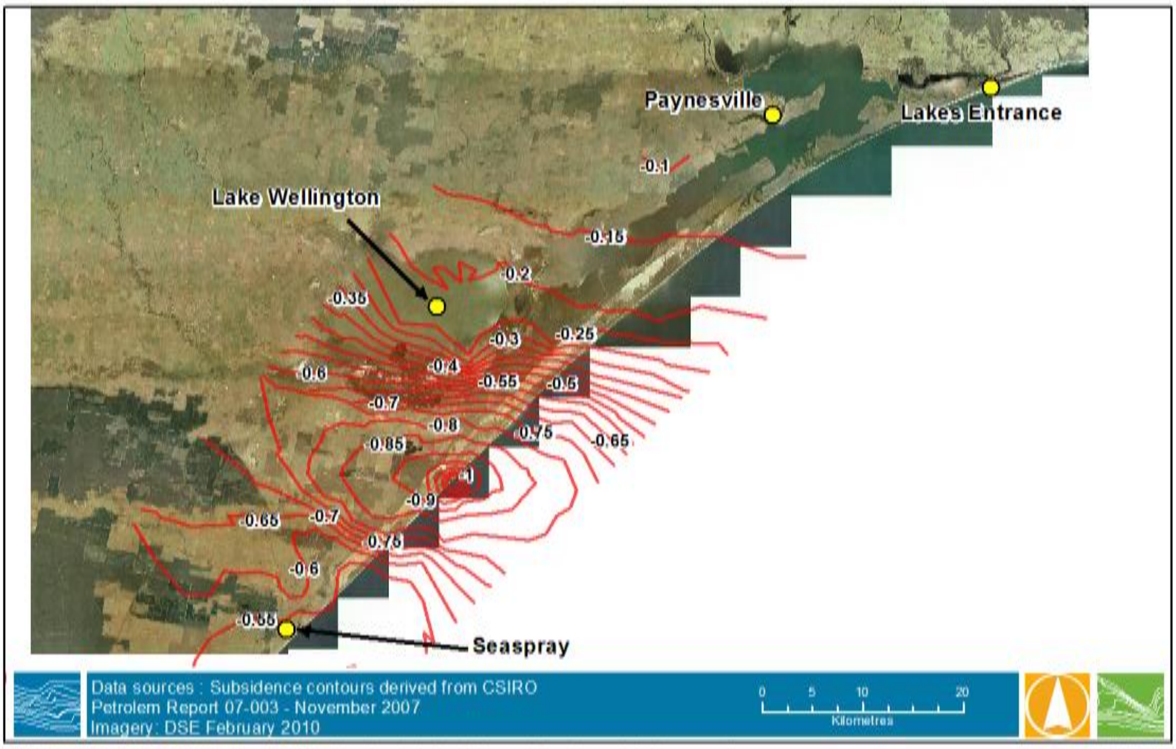

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Figure 7-3 Predicted Subsidence Contours for the Year 2056 Pessimistic Subsidence Scenario

If the projected subsidence is to occur it will result in the long-term shoreline recession associated with sea level rise occurring at variable rates along the coastline within the study area, and at larger magnitudes than predicted in the assessment which was based solely on projected eustatic sea level rise. It is likely that with the addition of land subsidence, the largest increase in recession rate and magnitude would occur around Paradise Beach, with decreasing impacts to the south-west and north-east, with little impact east of Loch Sport.

Figure 7-4 and Figure 7-5 below show the equilibrium profile adjustment for 0.8 m eustatic sea level and with an additional relative sea level rise due to land subsidence, for Paradise Beach and Seaspray respectively. Despite the largest amount of land subsidence being predicted to occur near Paradise Beach, the predicted increase in the shoreline recession due to equilibrium profile readjustment is significantly less at Paradise Beach in comparison to Seaspray. When the Paradise Beach equilibrium profile is readjusted for the predicted sea level rise and land subsidence, there is a relatively small change in the predicted shoreline recession, due to the large barrier volume and high elevation, limiting the barrier response to erosion.

Conversely, at Seaspray, where land subsidence is predicted to be approximately 30% less than at Paradise Beach, the barrier response is predicted to significantly increase. When the shoreline profile at Seaspray is adjusted for land subsidence in addition to eustatic sea level rise, using the Barrier Island Equilbrium Model, the extent of landward translation of the barrier exceeds 300 m.

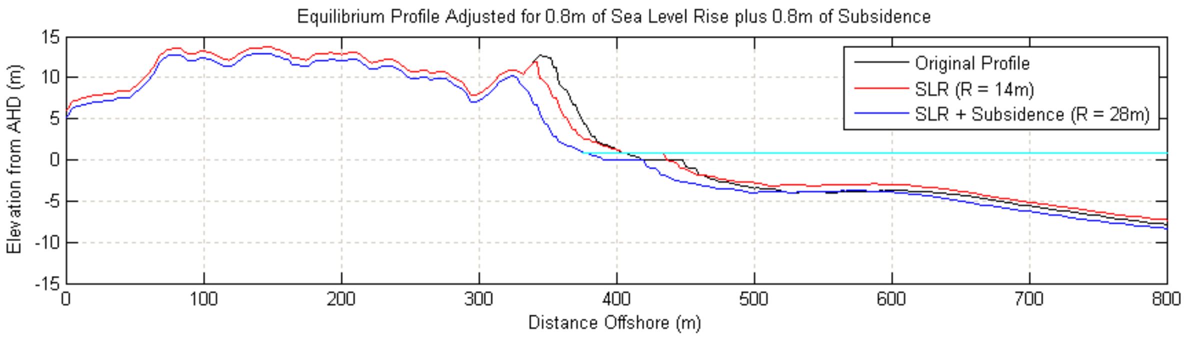

Figure 7-4 **Paradise Beach Equilibrium Profile Adjustment for 0.8 m Sea Level Rise and 0.8 m SLR with 0.8 m of Land Subsidence**

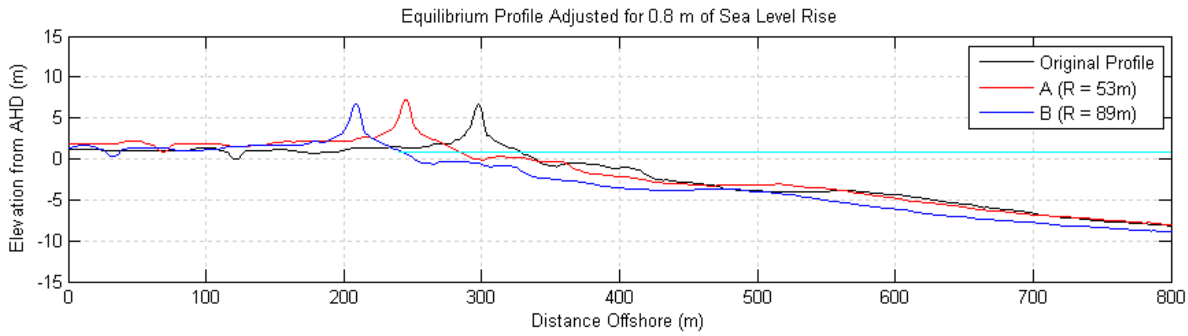

Figure 7-5 **Seaspray Barrier Translation Profile Adjustment for 0.8 m Sea Level Rise and 0.55 m of Land Subsidence**

8. COASTAL BARRIER HAZARD DEFINITION

8.1 Method

Precise, geomorphic predictions over mesoscale (10-100 year) timeframes are extremely difficult due to the stochastic and non-linear nature of the physical processes that influence coastal systems such as the Outer Barrier. Nevertheless, based on the analysis undertaken as part of this study, it is considered possible to provide an informed, precautionary assessment of potential coastal hazard extents and variability under various sea level rise scenarios for each of the different geomorphic units of the Outer Barrier identified in this study.

A range of physical processes have been identified in this analysis that may potentially contribute too and/or influence the total extent and or relative timing and frequency of coastal hazard impacts due to sea level rise along the Outer Barrier.

These processes are summarised as follows:

- Short-term storm related erosion;
- Longshore sediment transport continuity/budgets;
- Aeolian-biological sediment transport processes; and
- Equilibrium profile recession/translation to sea level rise

The way in which the above contributing hazard processes combine to yield a precise prediction of the ultimate extent of coastal hazard impacts for a particular sea level rise increment or future point in time along the Outer Barrier is, however, well beyond any existing predictive tools or techniques. Therefore, a precautionary, risk-based approach has been adopted to provide appropriate guidance relating to the potential extent of the coastal hazard impacts that could be expected along the Outer Barrier due to sea level rise.

The type, variability, extent and timing of the coastal hazard impacts that could be expected within the various geomorphic units of the Outer Barrier is considered to be integrally related to the mechanism of barrier response that is experienced for a given increment of sea level rise(i.e. barrier erosion or barrier translation).

Consideration of the relative likelihood of either response mechanism occurring and/or the sea level rise thresholds which could be expected to result in a transition from barrier erosion to translation therefore provides the basis for the provision of guidance as to the potential type and extent of the coastal hazard impacts due to sea level rise along the Outer Barrier.

The additional significant processes contributing to coastal hazards including longshore sediment transport continuity, short-term storm related erosion and aeolian-biological sediment transport processes, both potentially contribute to the combined extent of the coastal hazards and/or increase the likelihood of transition between barrier response mechanism for a given sea level rise/timeframe increment.

Figure 8-1 and Figure 8-2 illustrate schematically how the above coastal hazard processes and components have been combined to define total coastal hazard extents for the barrier erosion and barrier translation response mechanisms respectively.

The individual coastal hazard processes have been summarised in the following sections at the four locations which are considered representative of the geomorphic units of the Outer Barrier within the study area.

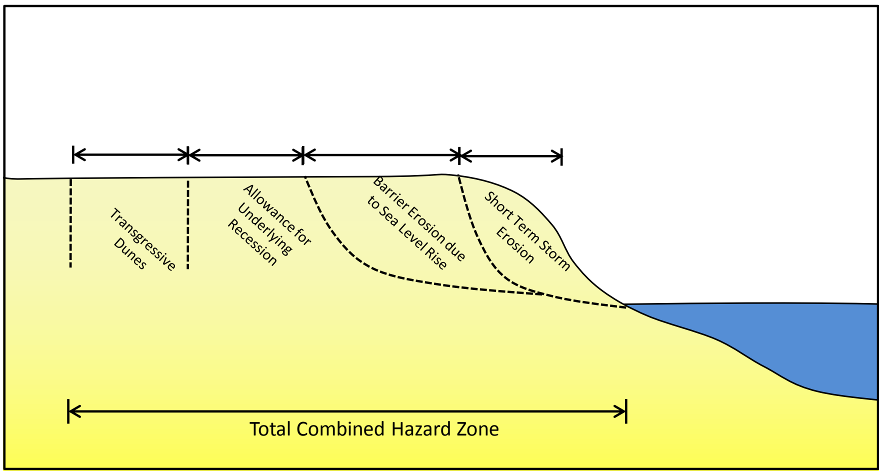

Figure 8-1 **Schematic of Coastal Hazard Components used to Determine Overall Coastal Hazard Extent for Locations/Sea Level Rise Scenarios According to the Barrier Erosion Mechanism**

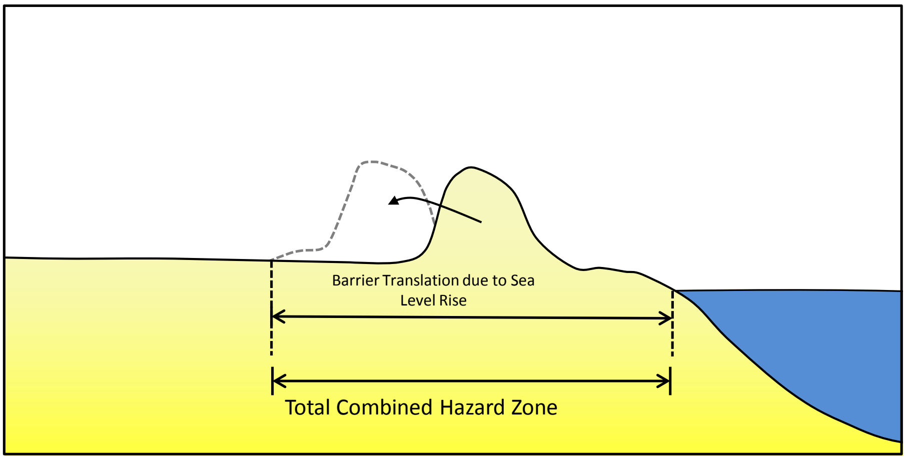

Figure 8-2 **Schematic of Coastal Hazard Components used to Determine Overall Coastal Hazard Extent for Locations/Sea Level Rise Scenarios According to the Barrier Translation Mechanism**

8.2 Woodside Beach to Glomar Beach (Seaspray) (Unit 3)

The following summarises the key underlying geomorphic susceptibility of Unit 3 - Woodside to Beach to Glomar Beach (Seaspray) and the extent to which the individual coastal hazard processes that have been identified for this unit could be expected to contribute to an overall coastal hazard zone for different sea level rise/timeframe scenarios. Table 8-1 provides a summary of the anticipated coastal barrier response, coastal hazard component setbacks and the adopted total combined coastal hazard extent for each sea level rise and timeframe scenario. Figure 8-3 displays the total coastal hazard zone conceptually for each sea level rise/timeframe scenario for this unit. The upper estimate of the combined coastal hazard extents for each sea level rise and timeframe scenario has been mapped in a GIS for Seaspray (Unit 3) and is displayed in Figure 9-2.

Geomorphology

The morphology Unit 3 of the Outer Barrier, including Seaspray and The Honeysuckles exhibits transgressive and/or receding characteristics. The barrier comprises a single, narrow ridge with a volume of only 250 m^3/m in places. The back barrier morphology shows limited development of dune ridges compared to the wide washover and lagoon deposits which are rich in estuarine and even marine species indicating a long period of back barrier lagoon development and frequent marine incursions as recently as the last 3,000 years. Underlying lagoon facies are exposed on the shoreward face of the barrier following storm events, indicating Late Holocene barrier translation.

Longshore Sediment Budgets

The limited historical aerial photography or other survey datasets to validate modelled transport rates and shoreline response make it difficult to draw definitive and precise quantitative conclusions as to the extent to which variations in the longshore transport continuity are contributing to overall shoreline position and/or whether underlying long term trends in shoreline position exist in this unit.

Longshore transport modelling suggests there is an underlying sediment deficit of the order 70,000 m^3/year on average, due to the gradual north-east longshore drift of sediment and differentials in the potential rates of transport within the study area. The analysis of the geomorphology, historical photography and longshore sediment transport continuity do however suggest the underlying sediment deficit is most pronounced in the south-western geomorphic units of the study area, including this unit, and may be contributing to contemporary shoreline recession. Rates of shoreline recession at Seaspray have approached 1 m/year on average over the last 20 years but shoreline position was relatively stable over the preceding 30 years. Approximately 5% of the total barrier volume has been lost from sections of the barrier between Seaspray and The Honeysuckles based on coastal profile comparisons from 2007 to 2012.

Based on the historical information, future rates of shoreline recession due to underlying sediment deficits may be of the order of 1.0 m/year for this unit. This provisional rate has been adopted until further data and understanding of the barrier response to the underlying sediment deficit and longshore transport budgets can be established.

Short Term Storm Related Erosion

As discussed in Section 6, the limited information from historical storms and the results of the cross-shore sediment transport modelling have resulted in the provisional adoption of a maximum short-term storm related erosion width of 5 m for the Outer Barrier.

It is however noted that the morphology of the Outer Barrier north of The Honeysuckles in this unit shows evidence of significant localised increase in erosion widths in the form of shore parallel depression complexes which are interpreted as being associated with rip cell embayments. Localised increases in short term erosion widths into the foredunes are therefore potentially as large as 30-40 m in this unit.

Aeolian-Biological Sediment Transport

Introduction of Marram Grass has significantly influenced the position and form of the Seaspray - Honeysuckles foredune, allowing the ridge to build vertically much higher than would occur with native species and has been apparently successful in reducing sand drift and storm overwash based on available historical accounts.

However, active transgressive dunes in the form of backscarp sand aprons are currently transporting sand distances of approximately 40 m landward of the foredune scarp in some locations along this unit.

Continued erosion and destabilisation of the foredune scarp due to either long-term sediment continuity related recession and/or sea level rise could be expected to increase the number and lateral extent of backscarp transgressive dunes in the future. In addition, the potential for elongate shore normal or parallel blowouts to rapidly develop across the barrier due to sustained erosion and destabilisation of the foredune scarp may locally increase rates of effective shoreline recession and/or form low points which become vulnerable to overwash.

Coastal Barrier Response

Continued barrier recession is expected under existing sea level rise conditions due to underlying longshore sediment budget deficit in this region. Extrapolation of the recent historical rates of shoreline recession of approximately 1 m/year into the next 20-30 years observed in this unit would potentially result in the recession compromising the integrity of the barrier at some isolated locations along the length of the barrier within this unit, even without the impact of further sea level rise.

For incremental sea level rise less than approximately 0.2 m and timeframes of 20-30 years, the barrier response is anticipated to remain essentially erosional, with continued decline in the barrier volume, width and height. Coastal hazard impacts are expected to remain largely limited to the shoreward face of the barrier, except for relatively isolated active transgressive dune impacts. However, potential future scenarios including ongoing, high rates of underlying sediment budget related shoreline recession, land subsidence or a localised increase in short-term erosion impacts associated with rip cell embayment's, could result in localised over wash of the barrier and an increased landward coastal hazard impact zone locally.

For incremental sea level rise of approximately 0.4 m or greater and timeframes of 50-60 years, the likelihood of coastal hazard impacts extending into back barrier areas increases significantly. The combination of long-term sediment budget recession or sea level rise profile adjustment could be expected to reduce the integrity of the barrier to the extent that overwash events may be initiated at multiple, though discrete, locations along the length of the barrier in this unit. Coastal hazard impacts associated with these events could extend over 150 m landward of the foredune. Transgressive dunes could also be expected to increase in number and extent due to sustained scarping and destabilisation of the foredune. Potential land subsidence could be expected to dramatically increase the frequency and extent of washovers in this unit and time frame.

Under sea level rise increments of approximately 0.8 m or greater and timeframes of 80-100 years, major barrier translation could be expected with multiple and frequent overwash events experienced along the length of the barrier, impacting large areas both laterally and landward of the foredune in this unit. Intermittent connection with back barrier lagoons may be initiated across the barrier in this unit. Washover deposits associated with the overwash events may evolve into broad transgressive dunes.

Table 8-1 Summary of Outer Barrier Hazard Zone Distances for Seaspray (Unit 3)

Sea Level Rise & Timeframe Scenario	Barrier Response	Coastal Hazard Component/Process (m)				Adopted Total Combined Coastal Hazard Zone (m)
		Short Term Storm Erosion	Longshore Sediment Budget Recession	Aeolian Sediment Transport Processes	Recession/ Translation due to Sea Level Rise	
Existing	Erosional	5-35	-	40	-	75
0.2 m (2030)	Erosional	5-35	0-17	40	5-9	50-101
0.4 m (2070)	Erosional (Isolated Translation)	5-35	0-57	40	11-18 (146)	56-150 (146)
0.8 m (2100)	(Erosional) Translation	(5-35) -	(0-87) -	(40) -	(22-37) 286	(67-199) 286

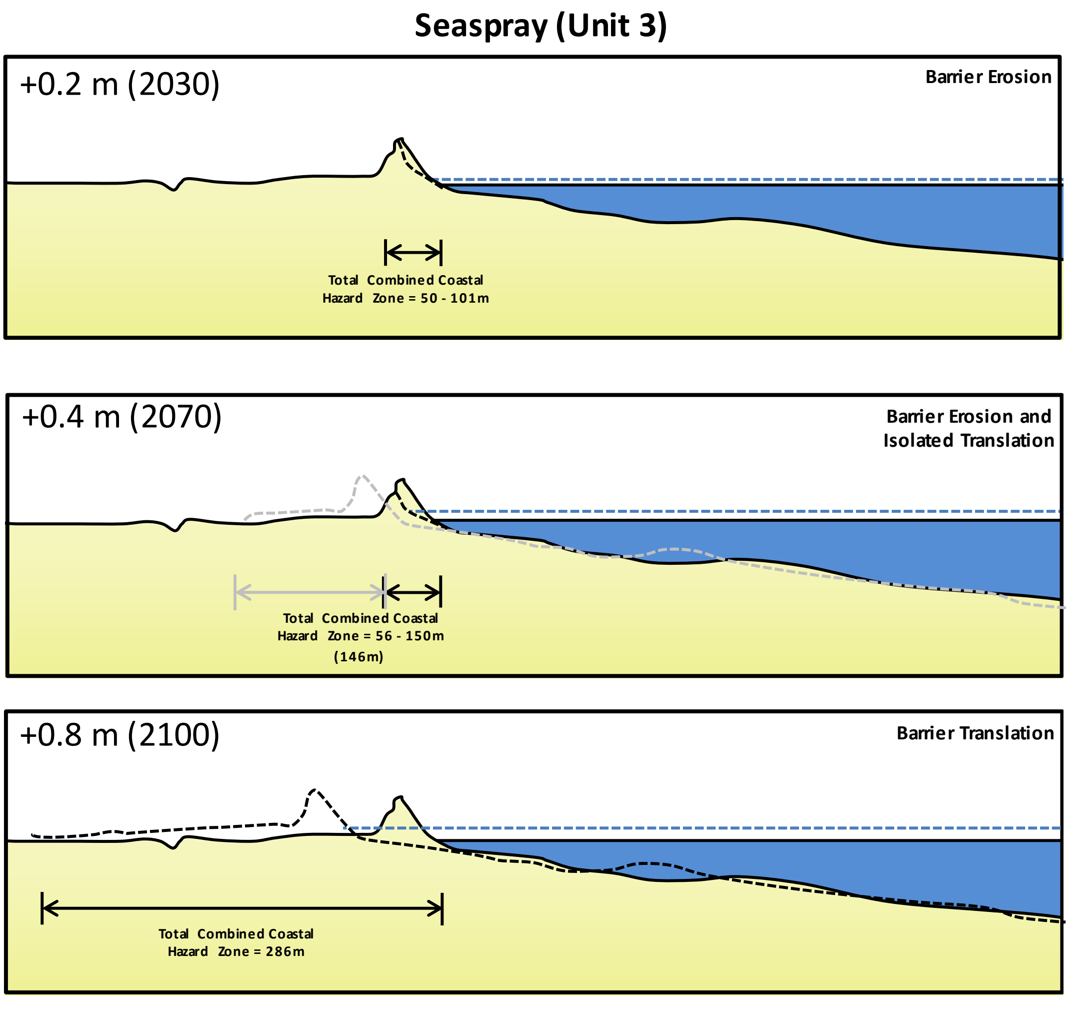

Figure 8-3 Outer Barrier Hazard Zone Distances for Seaspray (Unit 3)

8.3 Paradise Beach (Unit 4, 5, 6)

The following summarises the key underlying geomorphic susceptibility of Units 4, 5 and 6 (Paradise Beach) and the extent to which the individual coastal hazard processes that have been identified for this unit could be expected to contribute to an overall coastal hazard zone for different sea level rise/timeframe scenarios. Table 8-2 provides a summary of the anticipated coastal barrier response, coastal hazard component setbacks and the adopted total combined coastal hazard extent for each sea level rise and timeframe scenario. Figure 8-4 displays the total coastal hazard zone conceptually for each sea level rise/timeframe scenario for these units.

The upper estimate of the combined coastal hazard extents for each sea level rise and timeframe scenario has been mapped in a GIS for Unit 4, 5 and 6 and is displayed in Figure 9-2.

Geomorphology

The morphology of barrier Units 4, 5 and 6 are characterised by a wide barrier, up to 500 m in places, with multiple ridges between 10 to 15 m high. The volume of the barrier increases to several thousand cubic metres per linear metre of shoreline.

The stratigraphy of the barrier shows characteristics of a stationary barrier that has experienced a long (3,000+yrs) period of accretion and upward growth by wind and vegetation establishment.

The sensitivity of the assessment of the potential extents and relative timing of coastal hazards along these units is therefore not considered particularly high. The large barrier volume and heights in this unit are expected to limit the potential for major, non-linear changes in coastal hazard impacts with sea level rise.

Longshore Sediment Continuity

An absence of historical aerial photography or other survey datasets to validate modelled transport rates and shoreline response within these units make it difficult to draw any conclusions as to the extent to which variations in the longshore transport continuity are contributing to overall shoreline position and/or whether underlying long-term trends in shoreline position exist within these geomorphic units.

The morphology of the Outer Barrier in this unit has long sequences of shore parallel depression complexes that are interpreted as evidence of previous periods of shoreline recession in this unit. The extent of this shoreline recession, as interpreted from these depression complexes, is in the range of 30-40 m.

Short Term Storm Related Erosion

As discussed in Section 6, the limited information from historical storms and the results of the cross-shore sediment transport modelling have resulted in the provisional adoption of a maximum short-term storm related erosion width of 5 m for the Outer Barrier.

It is noted that the morphology of the Outer Barrier in these units show evidence of significant localised increase in erosion widths in the form of isolated shore parallel depression complexes which are interpreted as being associated with rip cell embayments. Localised increases in erosion widths into the foredunes are potentially as large as 30-40 m in these units.

Aeolian-Biological Sediment Transport

Narrow, generally trough-shaped transgressive dunes cutting shore normal or at oblique angles are widespread on the multiple dune sequence crests from Paradise Beach to Ocean Grange. At Ocean Grange, active blowout troughs cut across all established foredune crests and into back barrier areas.

These are large scale transgressive dune features that can extend up to 60 m landward from the foredune scarp.

Continued erosion and destabilisation of the foredune scarp due to either long-term sediment budget related recession and/or sea level rise could be expected to increase the number and lateral extents of these features in the future.

Coastal Barrier Response

The volume, width and height of the barrier in these units are expected to limit the response of the barrier to erosion of the shoreward face of the barrier including sea level rise scenarios up to 0.8 m. Profile adjustment to increases in sea level could therefore be expected to result in a relatively linear recession of the shoreward face of the barrier.

Major scarping and slumping of the foredune could be expected to destabilise dune vegetation and result in the development of more extensive trangressive dunes which could extend further across existing dune ridges.

Table 8-2 Summary of Outer Barrier Hazard Zone Distances for Paradise Beach (Unit 4, 5 & 6)

Sea Level Rise & Timeframe Scenario	Barrier Response	Coastal Hazard Component/Process (m)				Adopted Total Combined Coastal Hazard Zone (m)
		Short Term Storm Erosion	Longshore Sediment Budget Recession	Aeolian Sediment Transport Processes	Recession/ Translation due to Sea Level Rise	
Existing	Erosional	5–35	-	60	-	95
0.2 m (2030)	Erosional	5–35	0-35	60	3-7	68-137
0.4 m (2070)	Erosional	5–35	0-35	60	7-14	72-144
0.8 m (2100)	Erosional	5-35	0-35	60	14-27	79-157

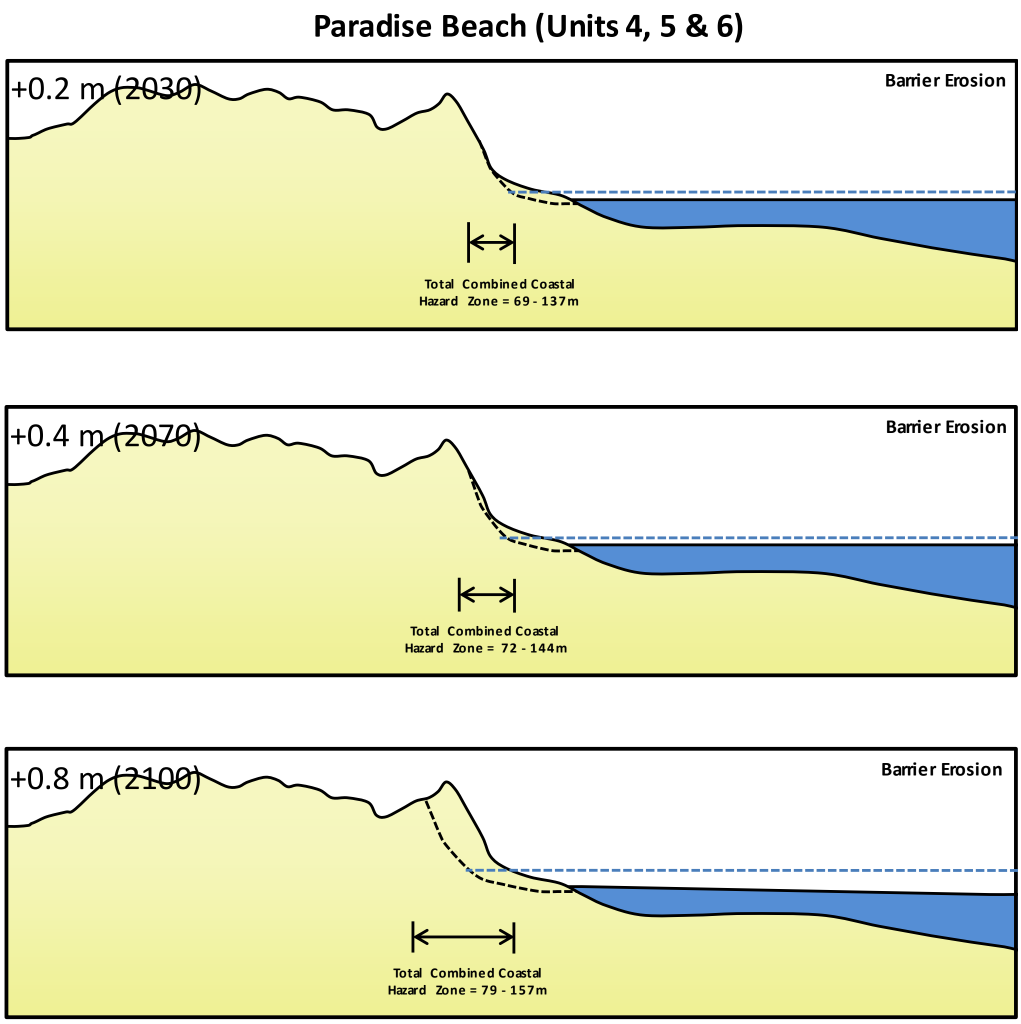

Figure 8-4 Coastal Outer Barrier Hazard Zone Distances for Paradise Beach (Unit 4, 5 and 6)

8.4 Bunga Arm (Unit 7)

The following summarises the key underlying geomorphic susceptibility of Unit 7 (Bunga Arm) and the extent to which the individual coastal hazard processes that have been identified for this unit could be expected to contribute to an overall coastal hazard zone for different sea level rise/timeframe scenarios. Table 8-3 provides a summary of the anticipated coastal barrier response, coastal hazard component setbacks and the adopted total combined coastal hazard extent for each sea level rise and timeframe scenario. Figure 8-5 displays the total coastal hazard zone conceptually for each sea level rise/timeframe scenario for this unit.

The upper estimate of the combined coastal hazard extents for each sea level rise and timeframe scenario has been mapped in a GIS for Unit 7 and is displayed in Figure 9-2.

Geomorphology

East of Ocean Grange the geomorphology of the outer barrier changes as the alignment trends more easterly parallel to Bunga Arm. The barrier narrows, its volume declines to approximately 300 m^3/m in places, the number of ridges decreases and there are active blowouts. The established foredune is narrow and discontinuous and the surface is a complex of hummocks, ridges and troughs with blowouts and former washover sites extending into Bunga Arm.

Bunga Arm comprises the relicts of an easterly deflected tidal channel associated with a major, long-lived tidal entrance and associated flood tide delta that existed in this region up until approximately 4,000 years ago.

Anecodotal historical accounts suggest minor overwash events into Bunga Arm have likely occurred in this unit over the last century.

Longshore Sediment Budgets

An absence of historical aerial photography or other survey datasets to validate modelled transport rates and shoreline response within this unit make it difficult to draw any conclusions as to the extent to which variations in the longshore transport continuity are contributing to overall shoreline position and/or whether underlying long-term trends in shoreline position exist within this geomorphic unit.

Comparisons of coastal profiles from 2007 and 2012 in this unit show that significant shoreline recession has occurred over this period, with the foredune scarp receding by approximately 10-12 m at locations surveyed. At locations with particularly low barrier volumes, the percentage decline in total barrier volume due to this recession approaches 15%. It is however not possible to determine whether these changes are related to longshore sediment budget related recession or short term, cross-shore sediment transport processes.

The assessment of the extent and relative timing of the potential coastal hazards in this unit are particularly sensitive to future shoreline changes driven by longshore sediment budgets due to the small barrier volumes and heights.

Short Term Storm Related Erosion

Information from historical storms and cross-shore sediment transport modelling indicate that maximum short-term storm related erosion widths are likely to be of the order of 5 m generally. The extent of the short-term storm related erosion is limited as the synoptic weather systems that generate the largest waves do not generate significant storm surges. In addition, wave heights are generally limited by rapid response of the offshore bar systems during storm events.

It is however noted that the potential for localised increases in erosion widths into the foredunes associated the development of rip cell embayments could extend 30-40 m in this unit.

Aeolian-Biological Sediment Transport

Active transgressive dunes in the form of blowout troughs and backscarp sand aprons exist with moderate frequency in this unit. At one isolated location, a large blowout trough cuts across the entire barrier and spills into Bunga Arm.

Comparisons of coastal profiles from 2007 and 2012 at a location of an active foredune face blowout and backscarp dune apron show rapid landward translation of the barrier and deflation of the foredune crest.

Continued erosion and destabilisation of the foredune scarp due to either long-term sediment budget related recession and/or sea level rise could be expected to increase the number and lateral extent of transgressive dunes in the future. The potential for trough or foredune face blowouts to rapidly develop across the barrier due to sustained erosion and destabilisation of the foredune scarp are considered likely to locally increase rates of effective shoreline recession and/or form low points which become vulnerable to overwash into Bunga Arm in the future.

Coastal Barrier Response

For incremental sea level rise of less than approximately 0.2 m and timeframes of 20-30 years, the barrier response is anticipated to remain essentially erosional, with continued decline in the barrier volume, width and height. Coastal hazard impacts are expected to remain largely limited to the shoreward face of the barrier, however isolated, active transgressive dunes could develop low points in the barrier which would become vulnerable to minor overwash events.

For increments of sea level rise of approximately 0.4 m or greater and timeframes of 50-60 years, the likelihood of coastal hazard impacts extending into back barrier areas increases significantly. The combination of long-term sediment budget recession or sea level rise profile adjustment could be expected to reduce the integrity of the barrier to the extent that relatively infrequent and minor overwash events may be initiated at a small number of locations in this unit. Coastal hazard impacts associated with these events would extend locally into Bunga Arm lagoon. Transgressive dunes could also be expected to increase in number and extent due to sustained scarping and destabilisation of the foredune.

At sea level rise increments of approximately 0.8 m or greater and timeframes of 80-100 years, the potential for major barrier translation exists and could result in multiple and frequent overwash events experienced along the length of the barrier in this unit, with significant quantities of washover deposits emplaced in Bunga Arm lagoon.

Ephemeral tidal connection between Bunga Arm lagoon and the ocean may be initiated, however these are not expected to be self-sustaining and their influence on water levels in the greater Gippsland Lakes are considered to be minor.

Table 8-3 Summary of Outer Barrier Hazard Zone Distances for Bunga Arm (Unit 7)

Sea Level Rise & Timeframe Scenario	Barrier Response	Coastal Hazard Component/Process (m)				Adopted Total Combined Coastal Hazard Zone (m)
		Short Term Storm Erosion	Longshore Sediment Budget Recession	Aeolian Sediment Transport Processes	Recession/ Translation due to Sea Level Rise	
Existing	Erosional	5-35	-	60	-	65-95
0.2 m (2030)	Erosional	5-35	0-35	60	4-5	69-135
0.4 m (2070)	Erosional (Isolated Translation)	5-35	0-35	60	8-11 (270)	73-141 (270)
0.8 m (2100)	(Erosional) Translation	(5-35) -	(0-35) -	(60) -	(17-22) 310	(82-152) 310

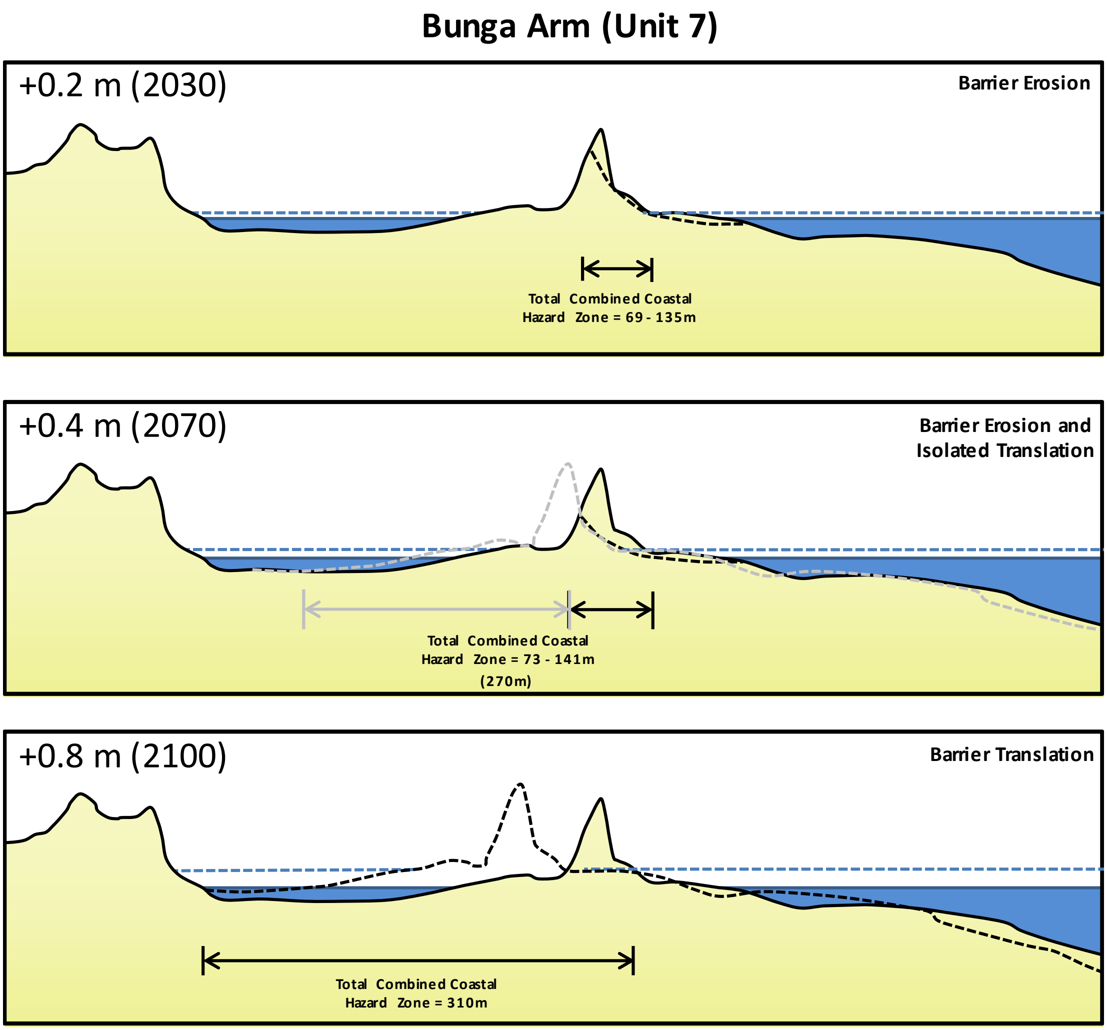

Figure 8-5 Coastal Outer Barrier Hazard Zone Distances for Bunga Arm (Unit 7)

8.5 Eastern Beach (Unit 8, 9, 10)

The following summarises the key underlying geomorphic susceptibility of Units 8, 9 and 10 (Eastern Beach) and the extent to which the individual coastal hazard processes that have been identified for these units could be expected to contribute to an overall coastal hazard zone for different sea level rise/timeframe scenarios. Table 8-4 provides a summary of the anticipated coastal barrier response, coastal hazard component setbacks and the adopted total combined coastal hazard extent for each sea level rise and timeframe scenario. Figure 8-6 displays the total coastal hazard zone conceptually for each sea level rise/timeframe scenario for these units.

The upper estimate of the combined coastal hazard extents for each sea level rise and timeframe scenario has been mapped in a GIS for Unit 8, 9 and 10 and is displayed in Figure 9-2.

Geomorphology

The geomorphology of these units show variation in origin and contemporary processes however the physical dimensions of the barrier are relatively similar such that the coastal hazards are considered to be reasonably similar across these units.

The Barrier Landing unit is notable for the localised narrowing of the barrier width and volume associated with the southerly projection of a tidal channel associated with the entrance.

The barrier in the Lakes Entrance unit displays the only sustained foredune and barrier ridge accretion of the Outer Barrier in the study area. The accretion is a consequence of training wall extensions that have captured longshore drifting sand along both western and eastern walls. The barrier width, volume and height increase locally some 2 km west and east of the entrance.

The Eastern Beach unit (unit 9) is particularly narrow and low. The foredune ridge in this unit is the youngest section of barrier within the study area having only developed following the cutting of the artificial entrance to the west which subsequently closed the natural Reeve's River entrance that migrated along this unit. The eastern extent of the Reeve's River channel has since largely been infilled by overwash and wind-blown sand. The most recent overwash recorded in this unit was in 1979.

Longshore Sediment Budgets

Analysis of limited historical aerial photography and modelled transport rates suggest that shoreline position in the Eastern Beach and Lake Bunga to Red Bluff units can be seen to potentially vary in response to changes in direction of the net longshore sediment transport.

In the mid to late 1970's a period of intense east to south-east storm activity resulted in net longshore transport directions switching to the west, away from Red Bluff and the shoreline position was observed to be receding. The available evidence suggests that this recession narrowed the foredune ridge to such an extent that an overwash occurred in the Eastern Beach unit in 1979.

However since approximately the mid 1980's, the net longshore transport rates have been strongly easterly and the shoreline has prograded some 40 m in places through to 2010. The likelihood of an overwash with the existing width and height of the foredune ridge along Eastern Beach is considered very low in the short term.

The analysis and consideration of the influence of longshore sediment budgets on shoreline position is likely to be influenced and therefore complicated by the dredging and spoil disposal activities at Lakes Entrance.

Based on the available information and analysis, a longshore sediment budget related setback of between 0-40 m has been adopted, based on the historical amount of shoreline change that can be attributed to this process and until further data and understanding of this process can be established at this location.

Short Term Storm Related Erosion

Information from historical storms and cross-shore sediment transport modelling indicates that maximum short-term storm related erosion widths are likely to be of the order of 5 m generally. The extent of the short-term storm related erosion is limited as the synoptic weather systems that generate the largest waves do not generate significant storm surge. In addition, wave heights are generally limited by rapid response of the offshore bar systems during storm events.

It is however noted that the potential for localised increases in erosion widths into the foredunes associated the development of rip cell embayments could extend 30-40 m in these units.

Aeolian-Biological Sediment Transport

Relatively limited active transgressive dune activity is evident in these units, except for some disturbances on the eastern side of Lakes Entrance associated with localised human activity. Limited transgressive dune activity is considered a function of sustained shoreline progradation and incipient foredune development that is observed in these units.

Erosion and destabilisation of the foredune scarp due to either long-term sediment budget related recession and/or sea level rise could, however, be expected to initiate the development of transgressive dunes which may increase rates of effective shoreline recession and/or form low points, which may become vulnerable to overwash in the future. A provisional setback of 40 m for potential future transgressive dune activity due to sustained scarping and recession of the foredune has been adopted.

Coastal Barrier Response

For incremental sea level rise of less than approximately 0.2 m and timeframes of 20-30 years, the barrier response is anticipated to remain essentially stable or slightly erosional, depending on the influence of longshore sediment budget processes.

For incremental sea level rise of approximately 0.4 m or greater and timeframes of 50-60 years, the combination of long-term sediment budget recession or sea level rise profile adjustment could potentially reduce the integrity of the barrier to the extent that isolated, infrequent and relatively minor overwash events may be initiated in these units.

At sea level rise increments of approximately 0.8 m or greater and timeframes of 80-100 years, major barrier translation could be expected with multiple and frequent overwash events experienced along the length of the barrier in these units. Ephemeral tidal connection across the barrier at Barrier Landing and the ocean may be initiated, however these are not expected to form self-sustaining tidal connections to the Gippsland Lakes.

Table 8-4 Summary of Outer Barrier Hazard Zone Distances for Eastern Beach (Unit 8, 9 & 10)

Sea Level Rise & Timeframe Scenario	Barrier Response	Coastal Hazard Component/Process (m)				Adopted Total Combined Coastal Hazard Zone (m)
		Short Term Storm Erosion	Longshore Sediment Budget Recession	Aeolian Sediment Transport Processes	Recession/ Translation due to Sea Level Rise	
Existing	Erosional	5-35	-	40	-	45-75
0.2 m (2030)	Erosional	5-35	0-40	40	5-7	49-122
0.4 m (2070)	Erosional (Isolated Translation)	5-35	0-40	40	10-14 (285)	55-129 (285)
0.8 m (2100)	(Erosional) Translation	(5-35) -	(0-40) -	(40) -	(20-29) 290	(65-144) 290

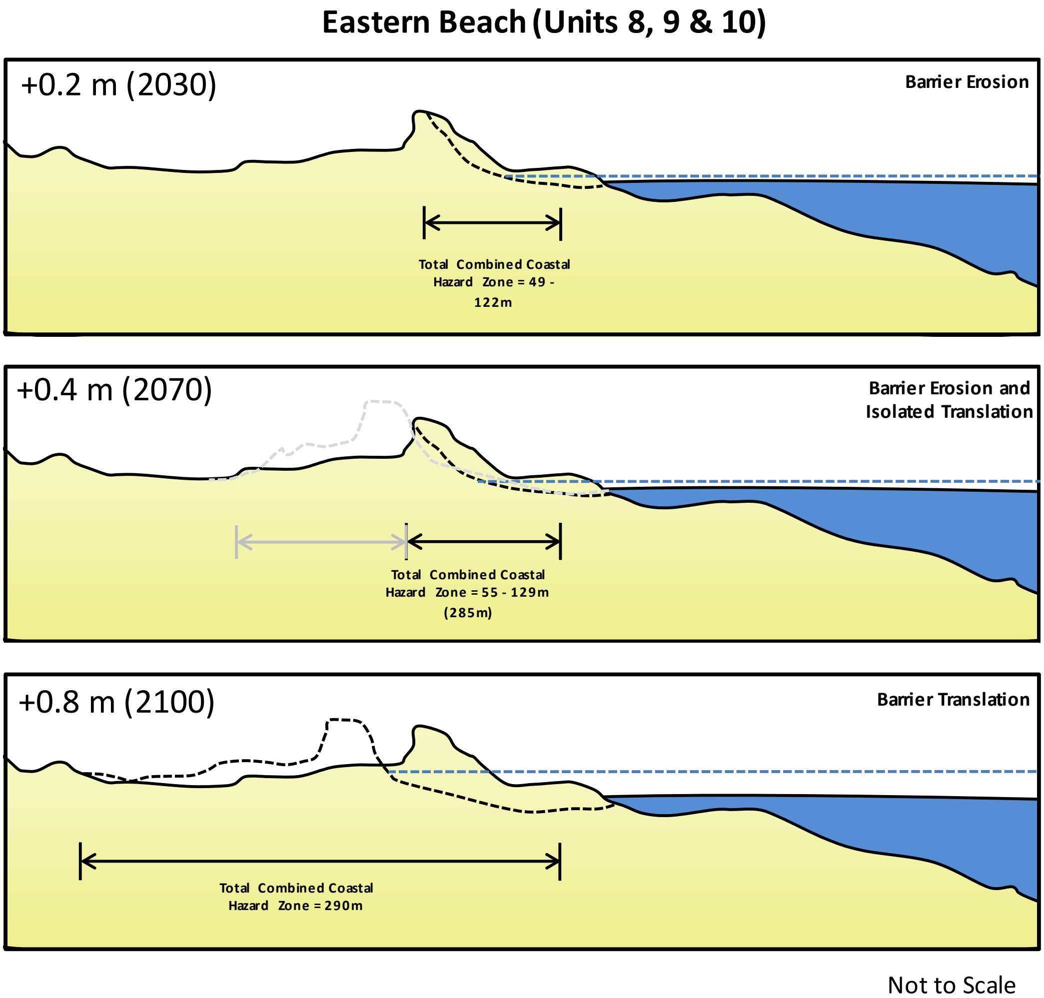

Figure 8-6 Coastal Outer Barrier Hazard Zone Distances for Eastern Beach (Unit 8, 9, 10)

9. SUMMARY

The extent of the potential coastal hazard impacts along the Outer Barrier due to sea level rise has been assessed as integrally related to the existing volume, height and width of the Outer Barrier landform and the subsequent potential for the barrier response mechanism to switch from an erosion response to a translation response. Translation of the barrier through overwash processes results in a relatively rapid, non-linear change in the landward extent of the coastal hazard impacts to back barrier areas.

A range of physical processes have been assessed that contribute to coastal hazard impacts along the Outer Barrier and/or could be expected to influence the type and timing of the barrier response to sea level rise. In many instances, the limited amount of available data and the extreme complexity in integrating stochastic and non-linear processes into the future, results in large uncertainty as to the precise timing and extent of the coastal hazard impacts that could be expected for various sea level rise/timeframe scenarios along the Outer Barrier.

Nevertheless, based on the analysis undertaken as part of this study, it is considered that an informed, precautionary assessment of potential coastal hazard extents and variability under various sea level rise scenarios and timeframes can be provided for the different geomorphic units of the Outer Barrier identified in this study.

Figure 9-1 displays a qualitative indication of the variation in susceptibility of the Outer Barrier to coastal hazard impacts. Higher susceptibility indicates greater likelihood and extent of barrier translation and associated overwash processes occurring due to sea level rise scenarios up to 0.8 m. Figure 9-2 displays an overview of the total combined coastal hazard zones for the Outer Barrier for each sea level rise/timeframe scenario determined for each geomorphic unit in Section 8. Comparison of these two figures shows that in areas where there is high susceptibility in Figure 9-1, such as Ocean Grange, there is also a larger defined hazard zone as shown in Figure 9-2. Similarly the lower susceptibility rating at Paradise Beach corresponds to a narrower hazard zone.

A number of significant limitations and uncertainties exist that should be acknowledged when interpreting and the considering the findings of this assessment and the coastal hazard zones displayed in Figure 9-2.

- There is a paucity of historical aerial photography or other survey datasets in the study area to validate modelled longshore sediment transport rates and shoreline response. This makes it difficult to draw definitive and precise quantitative conclusions as to the extent to which variations in longshore transport continuity are contributing to overall shoreline position and/or whether underlying trends in shoreline position exist.
- Coastal hazard impacts associated with overwash of the Outer Barrier are identified as contributing a large proportion of the identified total coastal hazard zone. However, predicting the absolute timing, location and landward extent of such impacts is not possible with any level of precision. A precautionary approach should be adopted within any geomorphic unit that has been identified as susceptible to overwash in this assessment.

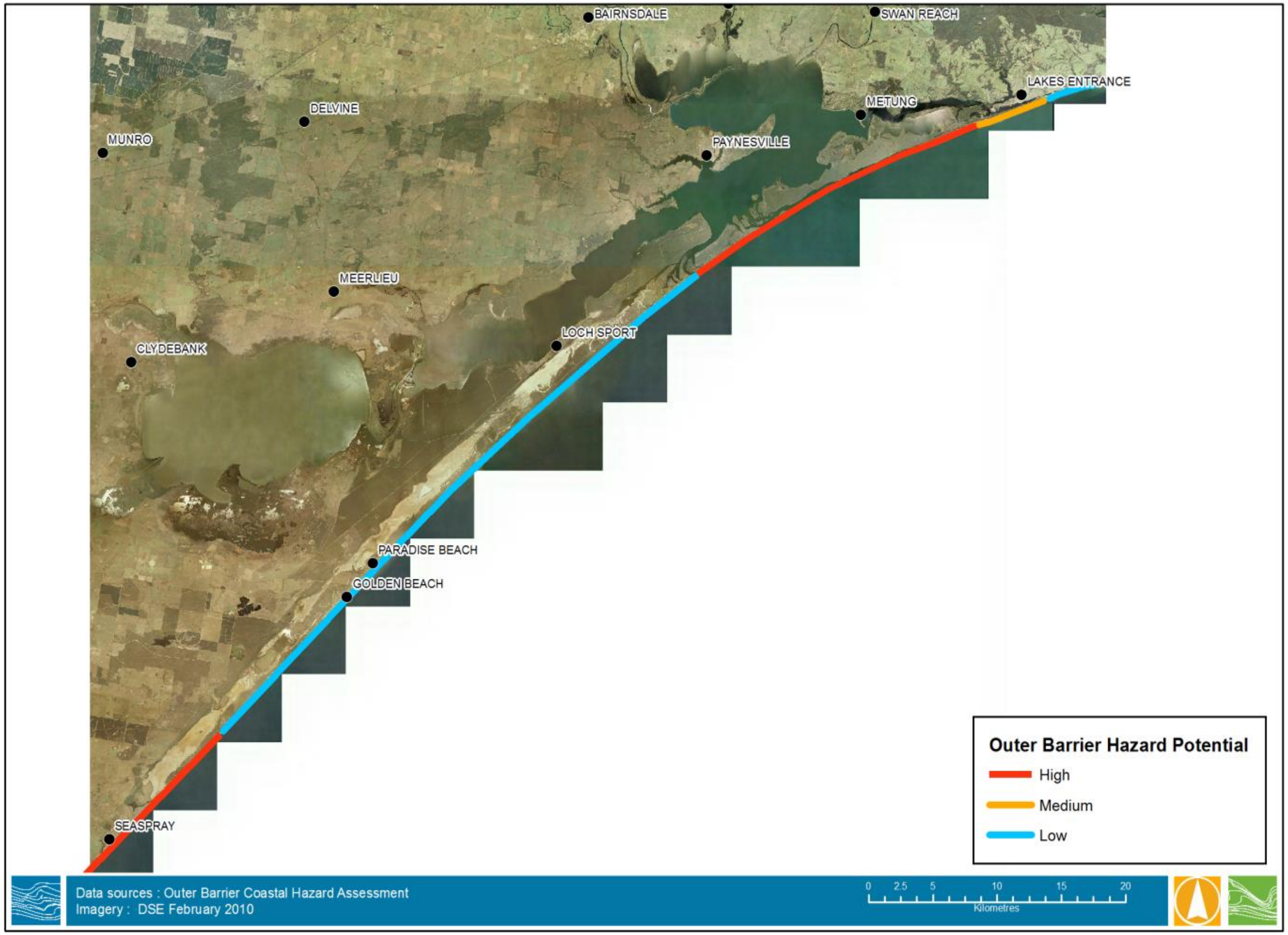

Figure 9-1 Outer Barrier Coastal Hazard Impact Susceptibility

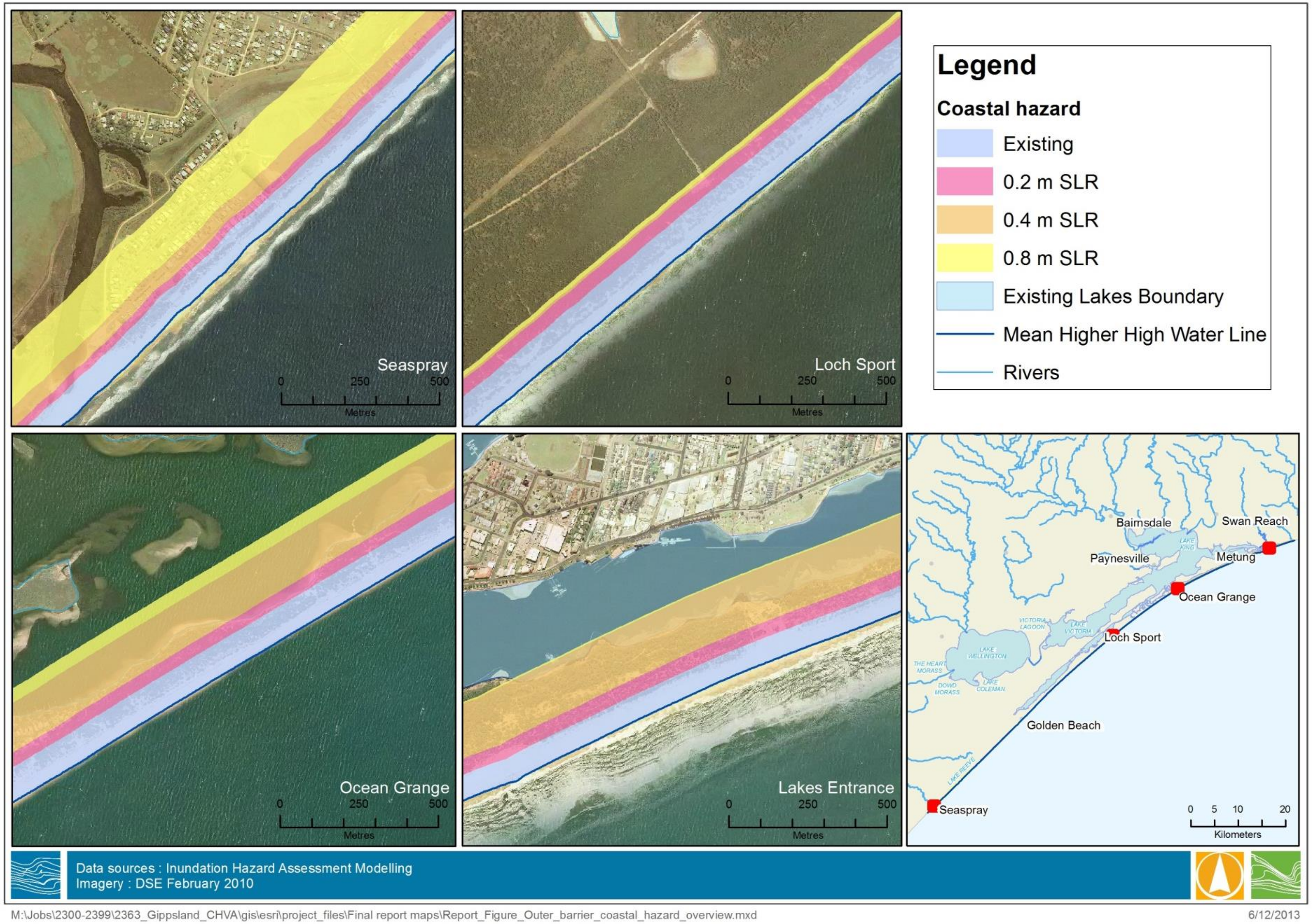

Figure 9-2 Combined Coastal Hazard Zones for the Outer Barrier

9.1 Recommendations

Significant knowledge and data gaps are considered to exist that require further research and analysis to improve the certainty and precision of the predicted coastal hazard zones due to sea level rise along the Outer Barrier. The following recommendations are suggested to improve the assessment of the coastal hazard zones along the Outer Barrier:

- Only approximately 5% of the Outer Barrier was covered by historical aerial photography and made available for the study. The collation and analysis of additional historical aerial photography would assist in understanding the underlying shoreline variability and trends along the Outer Barrier.
- A small number of coastal profile survey transects were undertaken for the study. Comparison of these profiles to earlier LiDAR survey revealed significant change and dynamics in the morphology of the barrier. Ongoing survey of the Outer Barrier through either repeat transect surveys or other airborne remote sensing techniques should be undertaken to develop a longer and higher resolution time-series of elevations and geomorphological change along the Outer Barrier.
- Very limited dating of the sediments of the Outer Barrier currently exists. Additional, precise dating of the Outer Barrier sediments would improve the understanding of the evolution of this landform and assist in interpreting likely future rates of change.

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APPENDIX A – DESCRIPTION OF NUMERICAL MODELS

Numerical Models

Overview

In order to conduct a thorough analysis of the physical processes operating in, and around the Gippsland Lakes, and the effects climate change on these processes a range of numerical coastal modelling tools were developed. The numerical models were extensively calibrated and validated to a range of existing ambient and extreme conditions in order to ensure a full range of natural conditions could be predicted to sufficient detail.

The following coastal numerical models were developed as part of this study:

- Finite Volume Hydrodynamic model of the Gippsland Lakes
- Finite Volume Spectral Wave Model of the Gippsland Lakes
- Finite Volume Spectral Wave Model of Bass Strait and part of the Southern Ocean and Tasman Sea
- LITPACK Cross-shore and Long-shore Sediment Transport Model

Detailed descriptions of the extensive calibration and their ability to reproduce past events are given in the following sections for each of the models developed.

Open Coast Spectral Wave Model

The Danish Hydraulic Institutes (DHI), MIKE 21 Spectral Wave (SW) model was employed for this study. MIKE 21 SW is a 3rd generation spectral wind-wave model capable of simulating wave growth by action of wind, non-linear wave-wave interaction, dissipation by white-capping, wave breaking and bottom friction, refraction due to depth variations, and wave-current interaction. The spectral wave action balance equation is solved in either Cartesian or spherical co-ordinates. The discretisation of the governing equations is performed using a cell-centred finite volume method with an unstructured mesh in the geographical domain. An explicit method was applied for the time integration.

The flexible mesh bathymetry for the MIKE 21 SW model was developed from the Australian Geoscience 2007 bathymetry grid. The model domain and bathymetry is shown in Figure A1. A coarse mesh resolution was applied offshore, with an increasing resolution surrounding the study area.

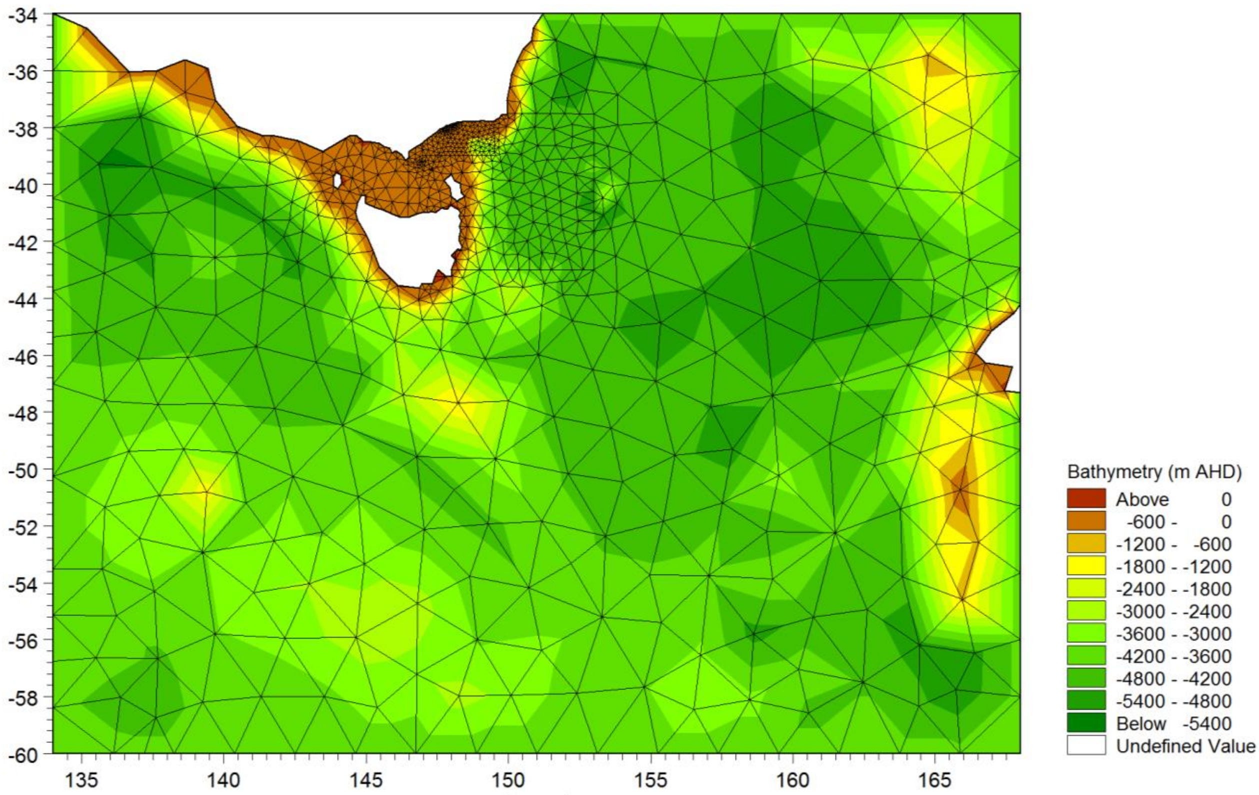

Figure A1 Spectral Wave Model Domain Schematisation

Boundary Conditions

Boundary conditions for the calibration of the spectral wave model were derived from the global NCEP/NCAR Reanalysis model. Results from the NCEP/NCAR Reanalysis model are available from the 1/1/1948 to present. The model results are provided on a rectangular grid, 2.5^0 N by 2.5^0 E.

The surface u and v vector wind velocity outputs from the NCEP/NCAR Reanalysis model were extracted at a 4 hourly temporal resolution, over a 2.5^0 by 2.5^0 spatially varying grid encompassing 30^0 to 60^0 North and 130^0 to 170^0 East, for the full duration of the available NCEP/NCAR Reanalysis outputs. The spatially and temporally varying u and v wind velocity grids were then applied as forcing conditions over the spectral wave computation domain displayed in Figure A1.

Model Calibration

The spectral wave model for the study was calibrated to measured wave data offshore of Lakes Entrance. A directional wave rider buoy was installed by Gippsland Ports in mid-2007, offshore of Lakes Entrance in approximately 20 m water depth. The buoy is located at $37^0$54.62"S, 147^0 58.82"E. Wave conditions in the Bass Strait, with particular consideration given to just offshore of Lakes Entrance in the vicinity of the wave rider buoy, were hindcast covering the time period between 14/4/2008 and 17/9/2010.

Modelled significant wave heights, peak periods, and mean directions were then extracted from the model at the location of the wave rider buoy over the 29 month period and directly compared against the measured wave rider buoy data. Where large differences existed between the predicted and observed wave conditions, reasons for the differences were investigated and changes to the spectral wave model specifications were made and the model was re-simulated to determine the impact of the changes. A number of changes were made to the model specification in order to improve the level of agreement between observed and modelled wave conditions.

Figure A2 displays a comparison of the observed and modelled spectral wave parameters at Lakes Entrance over the 29 month period and Figure A3 displays a comparison of observed and modelled significant wave height exceedance probabilities. In general the model slightly over predicted wave heights (as illustrated in Figure A3, by up to approximately 1 m), and slightly under predicted wave periods. These small discrepancies were attributed to the NCEP/NCAR Reanalysis wind field data used to force the model. However, the use of the NCEP/NCAR Reanalysis data was required to achieve the 64 years of wave hindcast.

Given the above, the level of agreement achieved in these comparisons are considered appropriate to enable the spectral wave model to be used to hindcast historical storm events and to develop design storm wave condition estimates for the coastline within the study area.

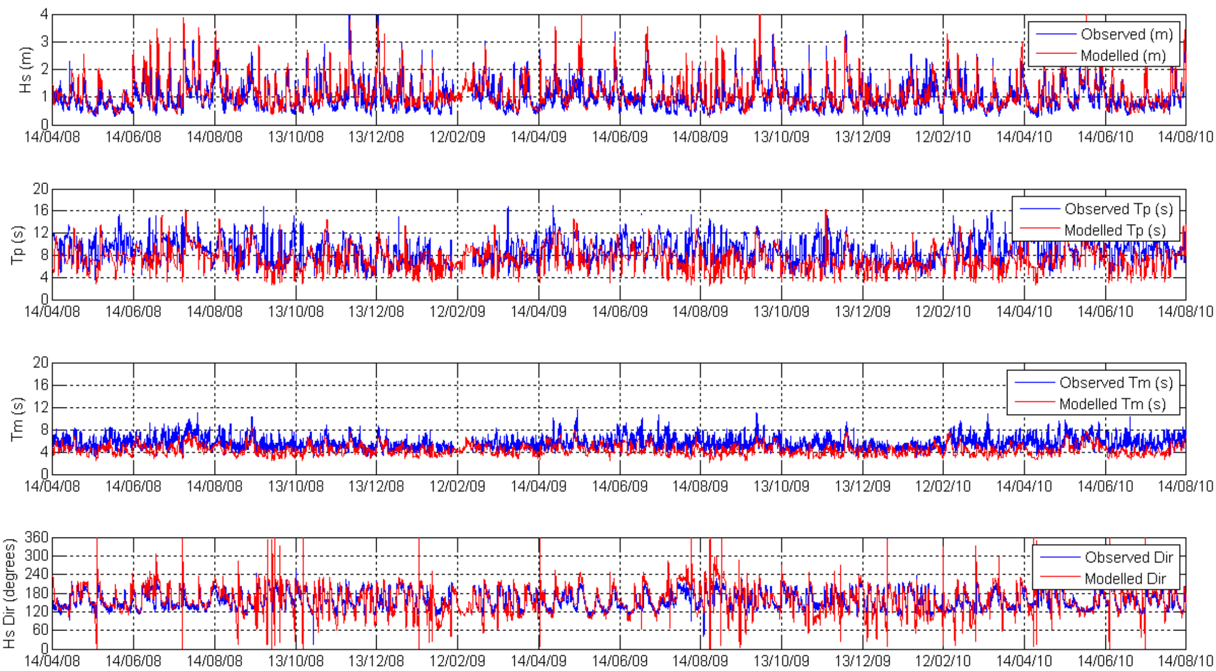

Figure A2 **Comparison of Observed and Modelled Wave Parameters at Lakes Entrance Wave Rider Buoy, where Hs = Significant Wave Height, Tp = Peak Wave Period, Tm = Mean Wave Period and Dir = direction.**

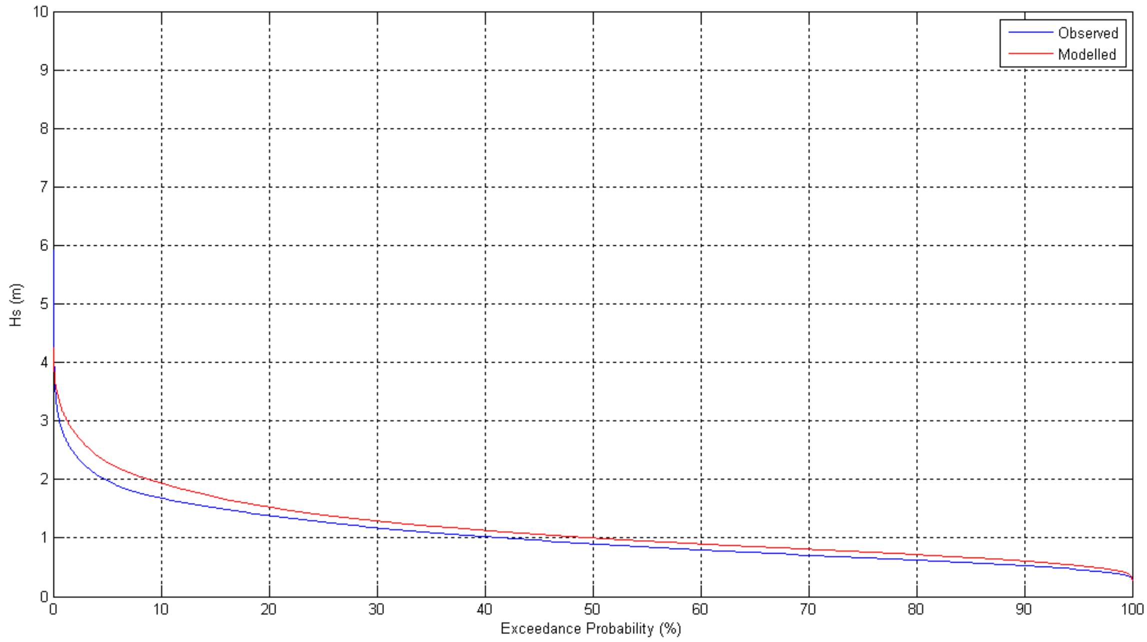

Figure A3 Comparison of Observed and Modelled Significant Wave height Exceedance Probabilities (April 2008 – September 2010).

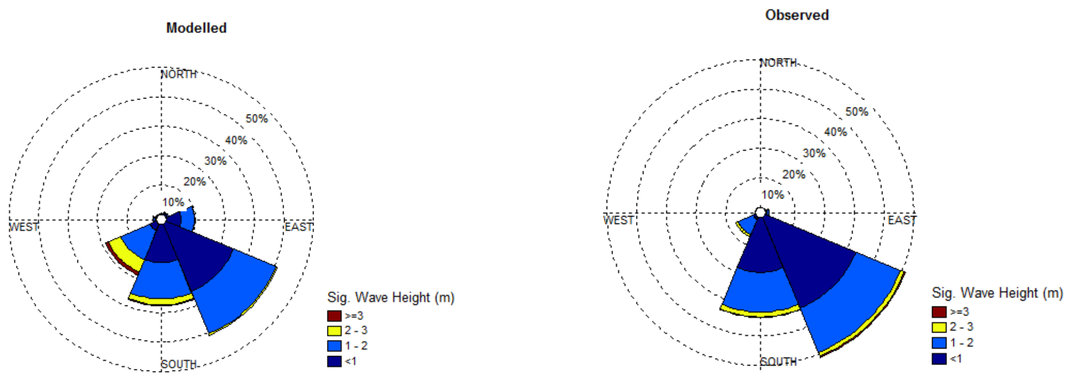

Figure A4 Rose Plots of Modelled and Observed Significant Wave Heights from the Calibration Period

Longshore Sediment Transport Model

DHI's LITPACK - LITDRIFT deterministic longshore sediment transport model was used to assess the longshore sediment transport along Ninety Mile Beach for this project. The LITDRIFT model consists of a hydrodynamic model which describes the propagation, shoaling, breaking of waves and the resulting radiation stresses and momentum balance which give rise to longshore sediment transport (DHI, 2011). The resulting hydrodynamics are used to force the intra-wave period non-cohesive sediment transport model, which calculates the instantaneous and time averaged sediment transport in two horizontal directions.

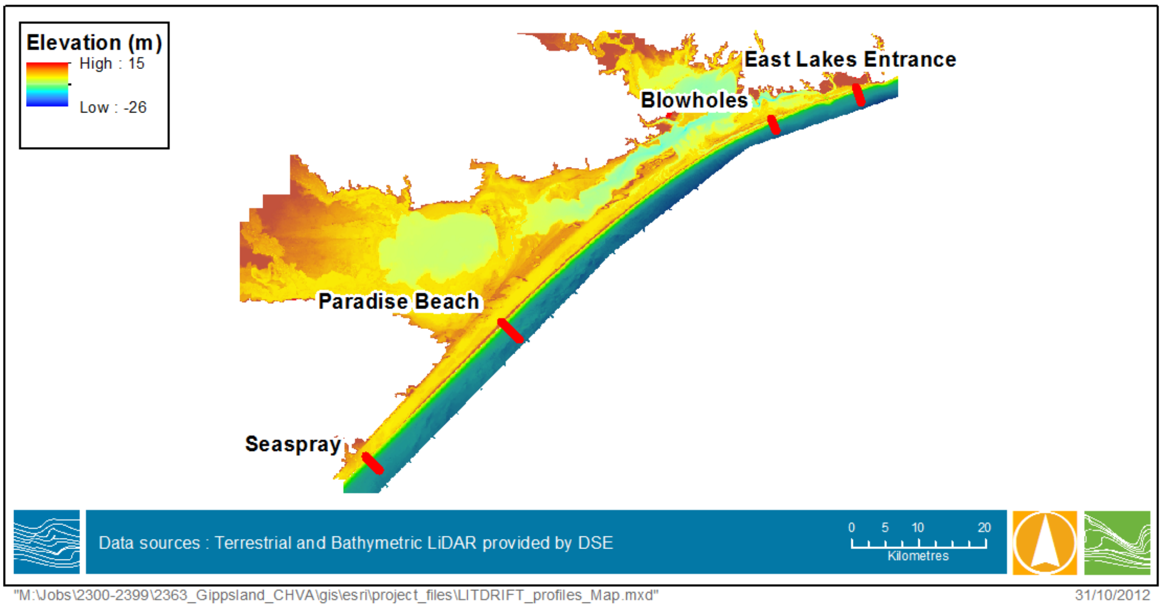

Figure A5 Location of the Four Cross-shore Beach Profiles used in the LITDRIFT Model

The longshore sediment transport was assessed at four locations: Seaspray, Paradise Beach, the Blowholes and East of Lakes Entrance (Figure A5).

Model Inputs

Cross-shore profiles were extracted from terrestrial and bathymetric LiDAR (as described in Section 4.1.2, Report 2 Inundation Hazards), starting from behind the dune-line out to approximately 20 m water depth, with a 2 m spatial resolution in the horizontal direction for each location.

Sediment characteristics were described in the model as a constant d_{50} grainsize of 0.3 mm. 63 years of wave conditions were extracted offshore from each of the four locations from the Open Coast Spectral Wave Model hindcast (Section 1.2), and used to force the LITDRIFT Model.

Cross-shore Storm Bite Beach Profile Model

DHI's LITPACK – LITPROF cross-shore profile change model was used to assess the cross-shore sediment transport, also known as "storm bite", associated with large storm wave events. The same four beach profiles as used for the Longshore Sediment Transport Model were used in the storm bite model.

As described in Section 3.2, the historical hindcast storm wave climate along Ninety Mile Beach exhibits a strong clustering of the large storm wave events. This strong clustering of storm wave events leaves little time for beach profile recovery (accretion), which occurs over time scales multiple years, due onshore sediment transport during calm wave conditions. Assessing the probability and magnitude of various possible sequences of storm events for short-term erosion potential was beyond the scope of this study, and therefore, a sequence of five large storm events from the 1970s, which was identified as the period of clustering with the largest cumulative wave energy, was used in the cross-shore sediment transport model. Characteristics of the five storms used are described below in Table A1, and time series of the storm wave heights are shown in Figure A6.

Table A1 **General Characteristics of the Five Storm Events used to Assess Short Term Storm Erosion (Storm Bite) in the Cross-shore Sediment Transport Model**

	Event 1	Event 2	Event 3	Event 4	Event 5
Date	June 1974	June 1975	March 1976	October 1976	June 1978
Max Hs (m)	3.6	5.2	4.3	3.7	4.6
Mean Tp (s)	11.1	13.2	12.3	10.7	12.4
Duration (hr)	104	116.25	104.5	85.5	98.25
POT >3m Cumulative Wave Energy (MJh/m^2)	0.3456	0.719	0.4399	0.2573	0.4375
Estimated ARI (years)	10	110	30	6	30

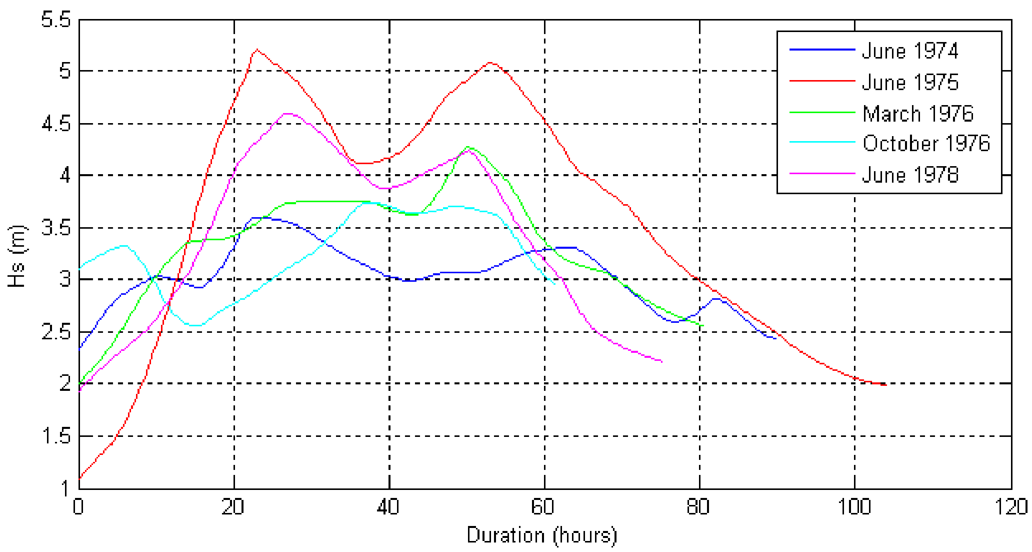

Figure A6 **Significant Wave Heights of the Five Storm Events Described Above for Eastern Lakes Entrance**

The LITPROF model required wave heights in the form of root mean square wave heights (Hrms). The significant wave heights from the hindcast wave data were converted to Hrms based on the theoretical prediction relationship Hrms/Hs = 0.71 of Longuet-Higgins (1952). The model also required wave periods in the form of zero up-crossing periods (Tz), which were available directly as an output of the wave hindcast model.

It was assumed there was no beach recovery (accretion) between the five storm events described above, and therefore a single time series was created to force the cross-shore sediment transport model by combining the storm events back to back, so they occurred directly one after the other.