WATER TECHNOLOGY
WATER, COASTAL & ENVIRONMENTAL CONSULTANTS

Western Port Local Coastal Hazard Assessment
Report 05 (R05) – Erosion Hazards

September 2014

DOCUMENT STATUS

Version	Doc type	Reviewed by	Approved by	Distributed to	Date issued
V01	Draft	CLA	CLA	Melbourne Water & Steering Group	21/06/2013
V02	Draft	TJW	CLA	Melbourne Water & Steering Group	03/07/2013
V03	Draft	Internal	CLA	Project Team	04/07/2013
V04	Draft Final	TJW	CLA	Melbourne Water & Steering Group	20/08/2013
V05	Draft Final	Peer Reviewers	CLA	Melbourne Water & Steering Group	30/05/2014
V06	Final	TWG	CLA	Melbourne Water & Steering Group	14/08/2014
V07	Final	Kristina Sestokas	CLA	Melbourne Water, DEPI, PSG	04/09/2014

PROJECT DETAILS

Project Name	2548-01R05v06
Client	Melbourne Water
Client Project Manager	Kristina Sestokas
Water Technology Project Manager	Christine Lauchlan Arrowsmith
Report Authors	Tim Womersley, Christine Lauchlan Arrowsmith, Josh Mawer, Neville Rosengren, Paul Boon, Jon Hinwood, John Tilleard
Job Number	2548-01
Report Number	R05
Document Name	2548-01R05v06_Erosion

Cover Photo: Rhyll Inlet (Photo: Neville Rosengren, 20 March 2013)

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Certified System Environment ISO 14001 SAI GLOBAL
Certified System Health & Safety AS 4801 SAI GLOBAL

15 Business Park Drive
Notting Hill VIC 3168

Telephone	(03) 8526 0800
Fax	(03) 9558 9365
ACN No.	093 377 283
ABN No.	60 093 377 283

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GLOSSARY

Aeolian	The erosion, transport and deposition of material by wind.
Australian Height Datum(AHD)	A common national plane of level corresponding approximately to mean sea level
AEP	Annual Exceedance Probability: The measure of the likelihood (expressed as a probability) of an event equalling or exceeding a given magnitude in any given year
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
Backshore Proximal (BackProx)	The first distinctive landform type immediately inland of the upper limits of normal high tide wave wash (i.e., may include 'supratidal' landforms). This attribute is intended to capture the way in which coasts are commonly characterised by a distinctively coastal landform developed immediately above the high tide line, e.g., a foredune or a rising sea-cliff. [2]
Backshore Distal (BackDist)	The dominant landform type in the backshore zone extending 500 metres inland of the upper limits of normal high tide wave wash (i.e., may include 'supratidal' landforms). The backshore distal landform type may be a continuation of the proximal type (e.g., a dune-field extending inland behind a foredune) or something quite different (e.g., terrestrial rocky slopes behind a single coastal foredune). [2]
Backshore Profile (BackProf)	The averaged topographic gradient of the backshore zone to 500 metres inland of the HWM, ignoring high foredunes, and categorised into only a few broad classes representing significant differences in backshore landform histories and processes. (e.g., low-lying plains, gently sloping terrain, moderately to steeply sloping terrain, high coastal cliff terrain). [2]
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
Chart Datum (CD)	Common datum for navigation charts. Typically relative to Lowest Astronomical Tide
Chenier	Discrete, elongated, vegetated marine beach ridge, sandy hummock and/or shell bodies stranded on a coastal mudflat or marsh and roughly parallel to a prograding shoreline.
Coastal Hazard	A term to collectively describe physical changes and impacts to the natural environment which are significantly driven by coastal or oceanographic processes.
Colluvium	A term used to describe loose, unconsolidated sediments that have been deposited at the base of a slope or cliff.
Delta	A complex association of geomorphic settings, sediment types and ecological habitats, at a point where a freshwater sources enters an estuarine water body.
Diurnal	A daily variation, as in day and night.
DTM	Digital Terrain Model, a three dimensional representation of the ground surface
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.
Exceedance Probability	The probability of an extreme event occurring at least once during a prescribed period of assessment is given by the exceedance probability. The probability of a 1 in 100 year event (1% AEP) occurring during the first 25 years is 22%, during the first 50 years the probability is 39% and over a 100 year asset life the probability is 63%
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.
Flood Tide	The incoming tidal movement of water resulting in a high tide
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
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
Hydro-isostasy	Deformation (depression/uplift) of the earth's crust in response to loading/unloading of water into oceanic basins
HAT	Highest Astronomical Tide: the highest water level that can occur due to the effects of the astronomical tide in isolation from meteorological effects
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
Intertidal Flats	Intertidal flats are un-vegetated, generally low gradient and low energy environments that are subject to regular tidal inundation and consist of sandy mud and muddy sand.
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.
Littoral Zone	An area of the coastline in which sediment movement by wave, current and wind action is prevalent
Littoral Drift Processes	Wave, current and wind processes that facilitate the transport of water and sediments along a shoreline
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.

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 mean of high water over a long period of time
MHWS	Mean High Water Springs, i.e. the mean of spring tide water levels over a long period of time.
MLWM	Mean Low Water Mark, i.e. the mean of low water over a long period of time
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.
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.
Planform	Planform refers to the form of a channel viewed from above. E.g. Meandering channels are sinuous single channels
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
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
Seral Succession	Seral succession is the notion that vegetation communities change in time according to a process whereby pioneer communities modify the physical environment such that they can no longer grow there, and make way for later stages that are better adapted to the new conditions.
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
Sub-aerial	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
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]
Wind Shear	The stress exerted on the water's surface by wind blowing over the water. Wind shear causes the water to pile up against downwind shores and generates secondary currents

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

[2] Definition taken from the Smartline Introduction http://www.ozcoasts.gov.au/coastal/introduction.jsp

1. INTRODUCTION

1.1 Background

Melbourne Water commissioned Water Technology to undertake the Western Port Local Coastal Hazard Assessment (WPLCHA) project. The project has come about through a partnership between Melbourne Water, the Department of Environment and Primary Industries, South East Councils Climate Change Alliance, Bass Coast Shire Council, Cardinia Shire Council, City of Casey and Mornington Peninsula Shire Council.

The WPLCHA is a component of the Department of Environment and Primary Industries Future Coasts program, and Western Port is one of four priority sites in which local coastal hazard assessments have or are currently being undertaken.

1.2 Scope

As detailed in the project brief, the scope of the WPLCHA is to provide information on the extent of coastal hazards and their physical impacts for the Western Port coastal environment. The WPLCHA is focussed on assessing the physical hazards of erosion and inundation. It does not include any subsequent assessment of impacts of the hazards on built, economic or social infrastructure, assets or values and does not include preparing adaptation responses to the physical hazards.

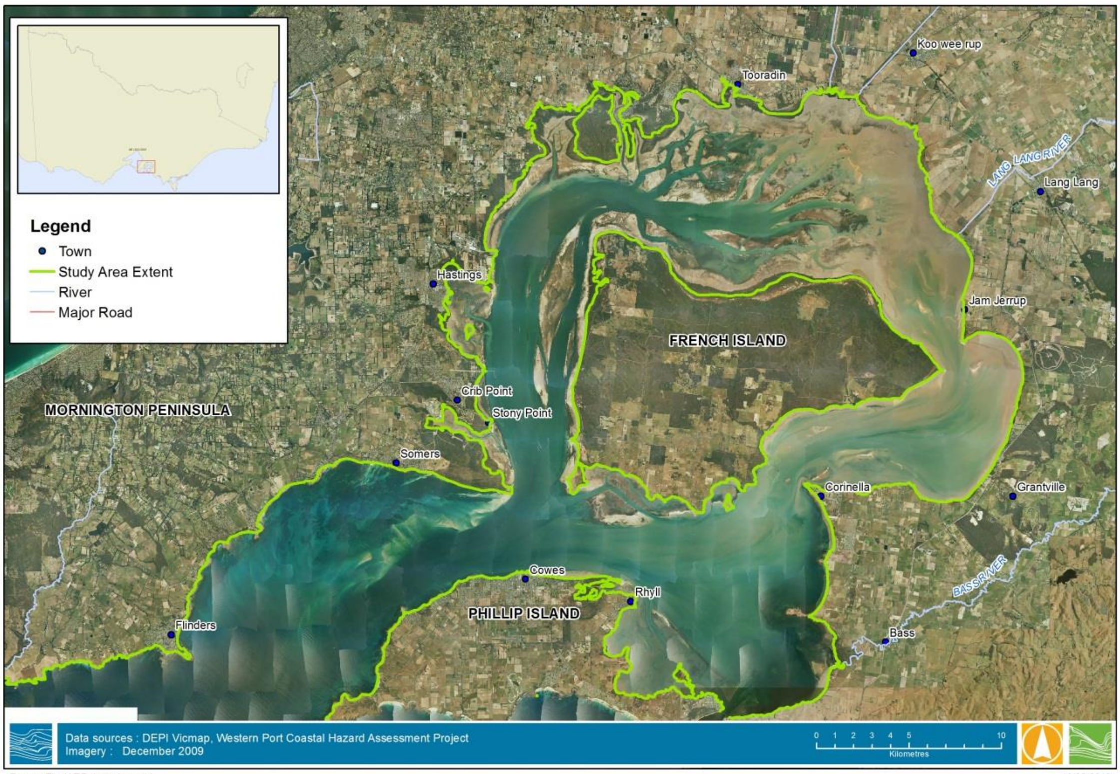
The information developed by the project will assist in planning for and managing coastal hazards. It will allow management agencies and other key stakeholders to identify and define triggers as the basis for short, medium and long term management responses. Specifically, the information will provide information, data and mapping to inform consistent policy and practice and support agencies in identification and management of risk, and undertake; strategic planning, statutory planning, infrastructure maintenance and replacement schedules, natural asset management, and business planning and budgetary processes that are responsive to a changing climate, its impacts and opportunities.

The boundaries of the study area for the WPLCHA project are defined as follows and displayed in Figure 1-1:

- Cape Schanck to West Head, along the shoreline of Western Port to the bridge at San Remo
- Inland from the Western Port shoreline will remain undefined enabling the assessment to be as far into the catchment as relevant
- All of the coast of French Island and the north side of Phillip Island from the bridge at Newhaven to the western extremity of Phillip Island (Seal Rocks), but excluding the south side of Phillip Island from Seal Rocks to the Bridge at Newhaven.

The study itself was split into two components:

- Part A - a broad scale Western Port wide coastal hazard assessment, and
- Part B - four local scale coastal hazard assessments.



Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

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Figure 1-1 Project Study Area Overview

1.3 Erosion Hazard Assessment Overview

The WPLCHA has broadly identified key coastal processes and hazards within the study area through extensive review of relevant literature, aerial photograph interpretation, terrain analysis using LiDAR, and the application of various tools including detailed wave and hydrodynamic modelling.

This report details the Part A broad scale analysis undertaken to assess the potential shoreline erosion hazards due to projected mean sea level rise this century.

Shoreline erosion within Western Port is a function of a range of key processes and different physical forcing factors, the relative importance of which vary considerably depending on the shoreline geology and geomorphology. Detailed assessments including hydrodynamic modelling have been used to integrate these processes to enable estimates of potential shoreline erosion to be developed taking into account how the processes respond to increased mean sea levels.

This report describes the Part A broad scale assessment of potential coastal erosion hazards undertaken for this study, and incorporates the following components:

- Identification of the physical, environmental and biological characteristics of the Western Port shoreline which contribute to or impact upon potential shoreline erosion hazards;
- Delineation of the Western Port shorelines into major shoreline classes based on key geomorphic characteristics, relevant processes and rates of change;
- Assess the potential for shoreline erosion of each of the major shoreline types both under present mean sea level and future sea level rise conditions.

- Definition and refinement of the potential coastal hazard extents throughout the study area for each major shorelines class with specific focus on potential future hazard extents under a series of sea level rise scenarios.
- An evaluation of the significance of uncertainty relating to the key processes and drivers of change within each major shoreline class on potential future extents of coastal hazards with sea level rise.

1.4 Reporting & Outputs

This document is part of a series of reports produced as part of the Western Port Local Coastal Hazard Assessment project. It should be read in conjunction with the following:

- Report 1: Summary Report (R01)
- Report 2: Data Review (R02)
- Report 3: Methodology Overview (R03)
- Report 4: Inundation Hazards (R04)
- **Report 5: Erosion Hazards (R05)**
- Report 6: Critical Locations (R06)

Accompanying these documents is a project geographical information system (GIS), which includes the following outputs from the erosion assessment:

- Digital geo-referenced data, including shape files of erosion hazard areas for the present mean sea level situation and for future sea level rise events.
- Digital field data acquired for the study, including location, elevation and summary output.
- Relevant model set-up and run files.

2. WESTERN PORT OVERVIEW

The characteristics and susceptibility of the shorelines of Westernport to coastal hazard impacts, including sea level rise, is integrally related to the nature and variations in geology, geomorphology, coastal vegetation and the hydrodynamic setting that exists in Western Port. The following sections provide a broad overview of the nature and variability of the physical environment of Western Port as a basis for understanding the potential type, extent and susceptibility of the shorelines of Western Port to coastal hazards.

2.1 Coastal Geology

The Western Port embayment is shaped broadly by a series of northeast-trending faults that define the Mornington Peninsula, the Western Port Sunkland and the western margin of the Strzelecki Ranges (Figure 2-1). Subsidiary east-west oriented faults have produced an elevated central block in the sunkland that is the basis for Phillip Island and French Island. A wide variety of interacting processes including tectonics, exposure of varied lithologies, accumulation of alluvial (river transported) and aeolian (wind transported) sediments and the development of a range of wetland plant communities including mangrove and saltmarsh has resulted in a diverse coastal and backshore environment. Figure 2-2 displays an overview of the geology of Western Port. The key geology of Western Port relevant to understanding the diversity of the Western Port shorelines are summarised in the following sections.

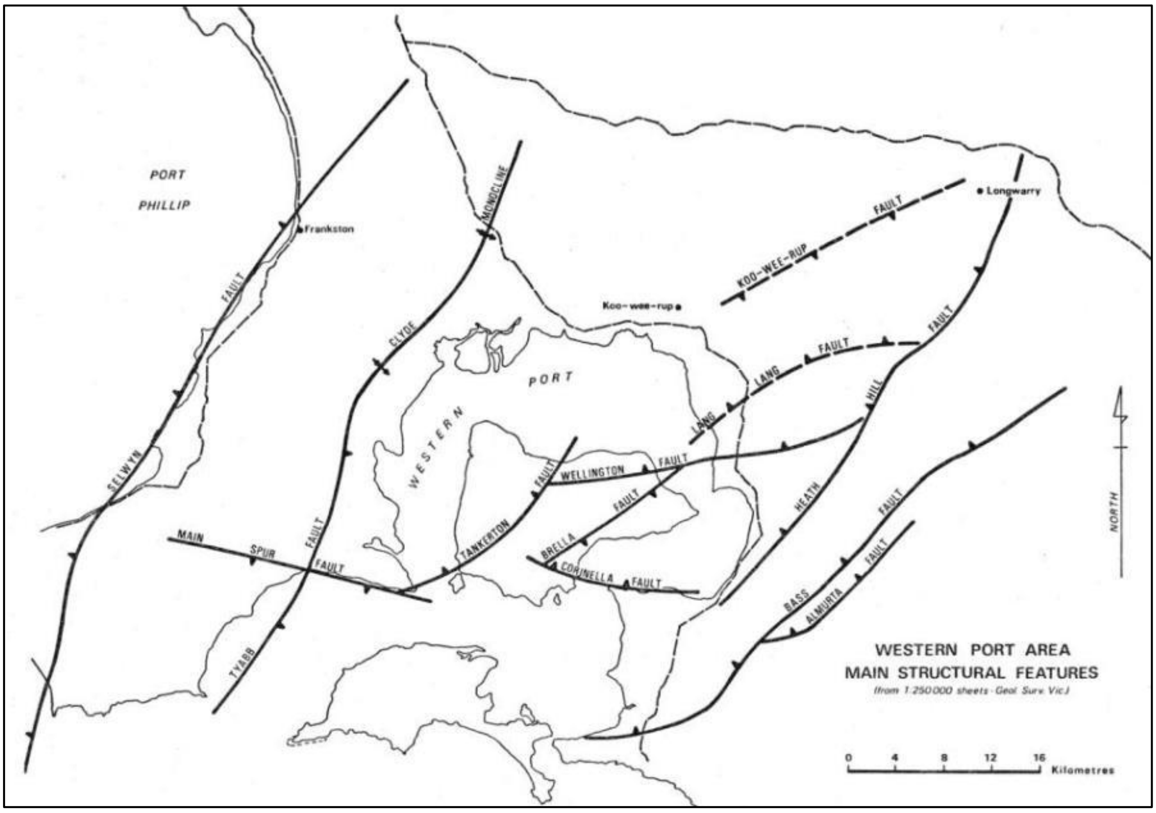
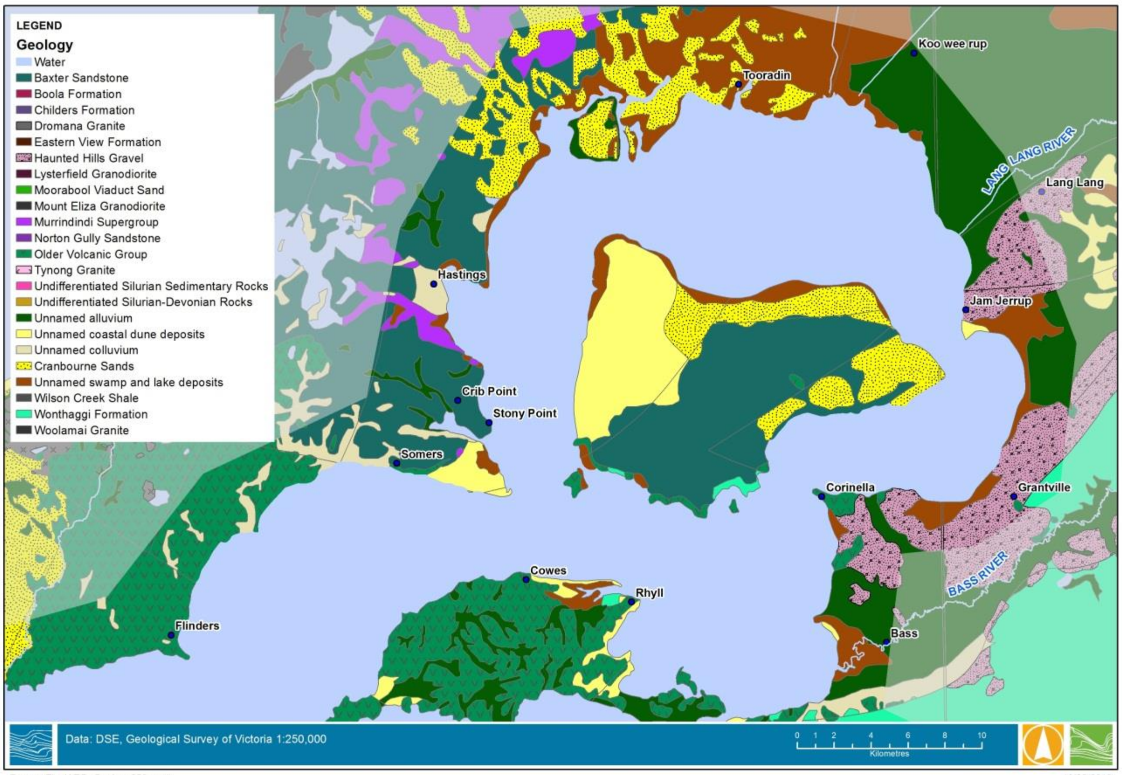


Figure 2-1 Structural Map of Western Port (from Spencer-Jones *et. al., 1975)*



Data: DSE, Geological Survey of Victoria 1:250,000

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Figure 2-2 Geology of Western Port

2.1.1 Palaeozoic (545 million to 248.2 million years ago)

The Palaeozic geological era comprises the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, and Permian periods. Marine Ordovician and Silurian sediments form the uplifted core of the Mornington Peninsula but are of limited extent on the Western Port shorelines. The most extensive outcrop is cliffs and shore platforms of Sandstone Island and a small area of shore platform between Hastings and Crib Point. Devonian granitic rocks occur at Cape Woolamai and Pyramid Rock on the southern coast of Phillip Island but are outside the present study boundary.

2.1.2 Mesozoic (248.2 million to 66 million years ago)

The Mesozoic geological era comprises the Triassic, Jurassic and Cretaceous periods. Limited outcrops of Lower Cretaceous arkose and mudstone occur along the eastern coast of Phillip Island, on the eastern San Remo Peninsula, the south coast of French Island and parts of Elizabeth Island.

2.1.3 Cainozoic (66 million years ago to present)

The Cainozoic geological era comprises the Tertiary and Quaternary periods. The most widespread hard rock materials around the Western Port coast are multiple flow units of Palaeocene to Oligocene age basalt and tuff (Older Volcanics). They are well-displayed as cliffs and shore platforms between Cape Shank and Flinders, Flinders to Somers, at Corinella and Cobb Bluff and the south coast of French Island.

Overlying the volcanic sequence is a widespread sheet of Upper Miocene sandy fluviatile beds termed the Baxter Sandstone by Keble (1950) and Jenkin (1962, 1974). Thompson (1974) noted the abundance of finer materials and preferred the term Baxter Formation. The formation is widespread on French Island and the western side of Western Port from Heath Hill south to Corinella. The sediments that outcrop are generally strongly discoloured by ferruginous cementation although this does not persist at depth (Thompson, 1974). This cementation is very marked in coastal outcrops at Crib Point and Reef Island where pebbles eroded from the ferruginized beds accumulate as gravel beaches. The sandy beds of the Baxter Formation are extensively quarried along the Heath Hill Fault scarp. Jenkin (1962) mapped a formation he termed the Warneet Beds which outcrops in Cannon Creek at Warneet and occurs in bores to the north. There has been some discussion as to the stratigraphic position of these beds (Cass, 1973; Jenkin, 1974; Thompson, 1974; Spencer-Jones et al., 1975). Thompson (1974) recognized a new formation, the Heath Hill Silts, which is exposed in the incised channel of the Lang Lang River between Lang Lang and Heath Hill. He regarded this as a fluviatile (floodplain) deposit of late Pliocene or early Pleistocene age and suggested the Warneet Beds are the marine equivalents. Jenkin (1962) mapped an extensive series of gravels draped along the scarp of the Heath Hill Fault, the Almurta Fault scarp and on French Island and proposed them as the Grantville Gravels, a Late Pliocene to Pleistocene formation of alluvial fan deposits. He discussed the lithological and structural differences between these and the older gravels of the Baxter Formation. Thompson (1974) and Spencer-Jones et al. (1975) regarded these as a unit of the Baxter Formation and not warranting separate formation status.

2.1.4 Quaternary (2.6 million years ago to present)

The Quaternary geological period is further subdivided into the Pleistocene (2.6 million to 11,700 years ago) and Holocene (11,700 years ago to present) geological epochs. Most of the Western Port coast is composed of or fringed by unconsolidated Quaternary sediments of beach, aeolian, fluvial, colluvial, paludal and deltaic origin and include a range of active and palaeo fresh-water and saline environment organic deposits. The Quaternary sediments can be summarised into the following main groupings.

Cranbourne Sand

A distinctive and significant sedimentary unit of the northern Western Port is the Cranbourne Sands (Jenkin, 1962), a series of siliceous sands forming north-west-trending ridges and swales. This terrain is a zone extending south of Cranbourne to Warneet and south-west to Tyabb. The dune swales are closed depressions originally occupied by wetlands although most of these have been artificially drained. The sands also occur south of Lang Lang towards Nyora and on north-east French Island where The Pinnacles are unusually high sand ridges. The sands were derived at lower sea-level and moved across the (now) Mornington Peninsula and extended across the northern part of Western Port. As they pre-date the Holocene marine transgression they may have been a major factor initiating the widespread impoundment of the Koo-Wee-Rup Swamp and other freshwater wetlands around the north and east of Western Port (Miles, 1976).

Freshwater wetlands

North of Koo-Wee-Rup and extending west to Heath Hill and south to Lang Lang Beach was an extensive freshwater wetland comprising reedswamp, paperbark, tea-tree and areas of open water (Hills 1942, Yugovic and Mitchell 2012). Beginning in the 1880's the area has since been entirely drained and claimed for agricultural land (Roberts, 1985) and, more recently, residential development, with the result that no major area representing the landscape of the former wetlands remains. At least three distinct swamp complexes the Koo-Wee-Rup or Great Swamp, the Dalmore Swamp to the east, and the Tobin Yallock Swamp to the south occurred. The swamps contained variable thickness of peat and clay, and these are exposed in the drainage channels and along the coast between the Bunyip River and Lang Lang Beach. The swamps were fed by the Bunyip River, Lang Lang River, Yallock Creek, Cardinia Creek and smaller streams. Traces of these streams, and of larger ancestral streams, in the form of abandoned channel segments and coarse sandy ridges are conspicuous, for example near Bayles and at Rythdale. The swamp deposits have been traced offshore (Miles, 1976) and underlie the tidal flats in the north-east of Westernport where they are exposed in the tidal channels.

Since the draining of the swamps there have been major physiographic changes in the channels of the contributing streams, notably the Bunyip River, Lang Lang River and Cardinia Creek. Deep incision of formerly swampy channels has exposed the underlying material and headward erosion has excavated sandy and gravelly prior stream and fan deposits and moved them down the drains to the coast. Extensive changes have also taken place on the coast at the fringe of the former swamp areas.

Deltas

The Bass River is the largest stream that has not been substantially modified by impoundment, diversion or drainage and has an active onshore and offshore deltaic zone with active and abandoned tidal meanders. An abandoned distributary of the Bass River entered a small embayment two kilometers east of Corinella so the modern stream delta is an anabranch that diverged two km southwest of Glen Forbes. The palaeochannel has similar channel dimensions to the modern stream but lacks bordering terraces and there are no large amplitude tidal meanders. A less obvious earlier outlet of the Bass River can be distinguished one kilometer east of Tenby Point.

2.2 Coastal Geomorphology

2.2.1 Overview

Western Port is a tidal embayment that developed its present configuration as the Holocene marine transgression drowned a broad plain and pre-existing drainage system (Marsden et al 1979). There are approximately 300 kilometres of shoreline included in the study area and a variety of coastal and intertidal landforms are present.

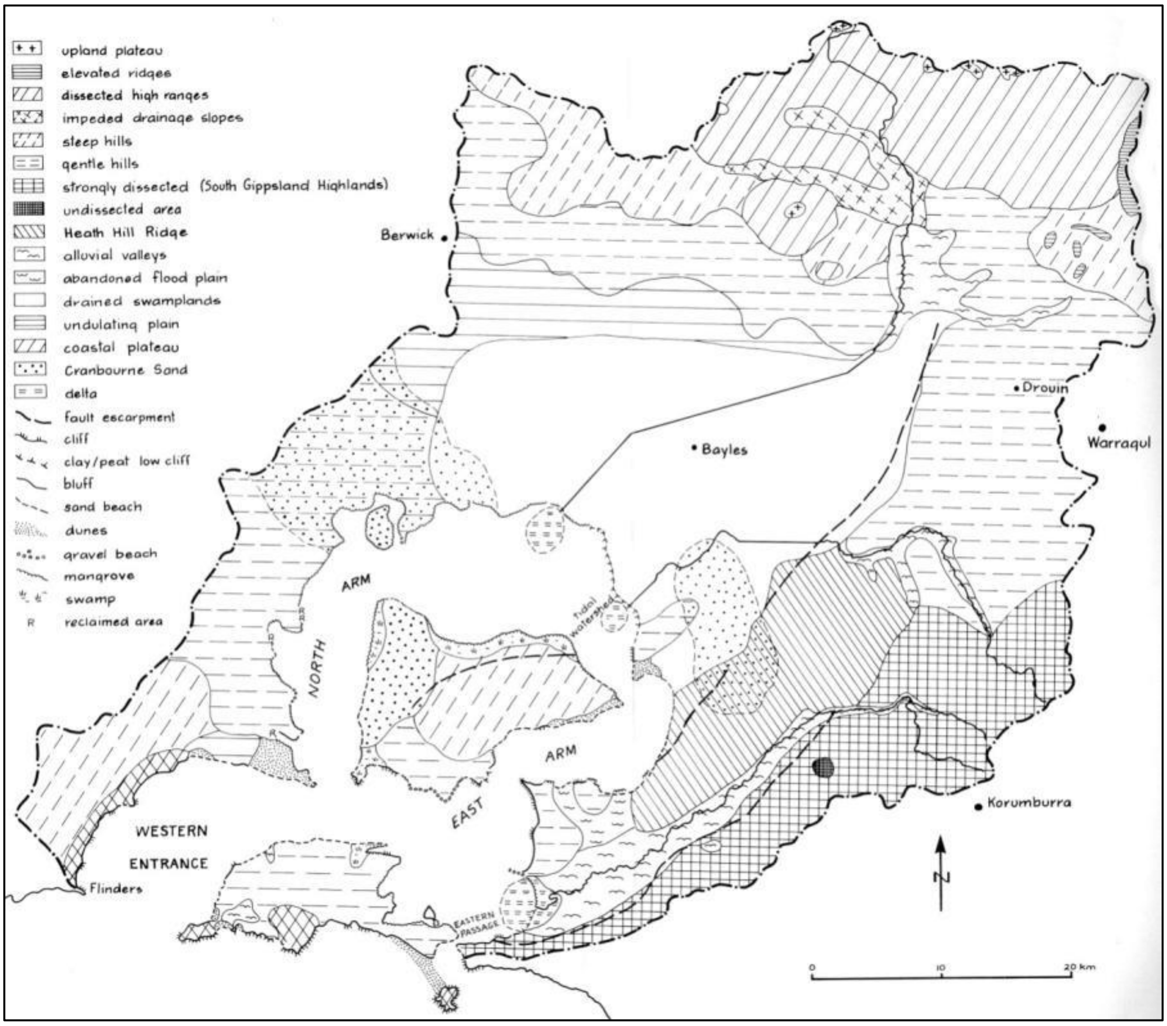


Figure 2-3 Geomorphology of Western Port Catchment and Coastline (from Rosengren, 1984)

The morphology of a particular sector of shoreline is determined principally by lithology of the coastal outcrops, the relief and topography of the backshore (hinterland) and the near-shore bathymetry. In broad terms, the southern shorelines of Western Port are characterised by bolder coastal relief and relatively resistant geology, whilst the northern shorelines are characterised by low backshore relief and unconsolidated or poorly consolidated sediments. Figure 2-4 displays the topographic and bathymetric elevations of Western Port. The nature of sediment delivered by streams, the tide range and prevailing wind, wave and current regimes also strongly influence the morphology of Western Port shorelines. In Westernport, these factors vary principally in relation to position in relation to the entrances to Bass Strait.

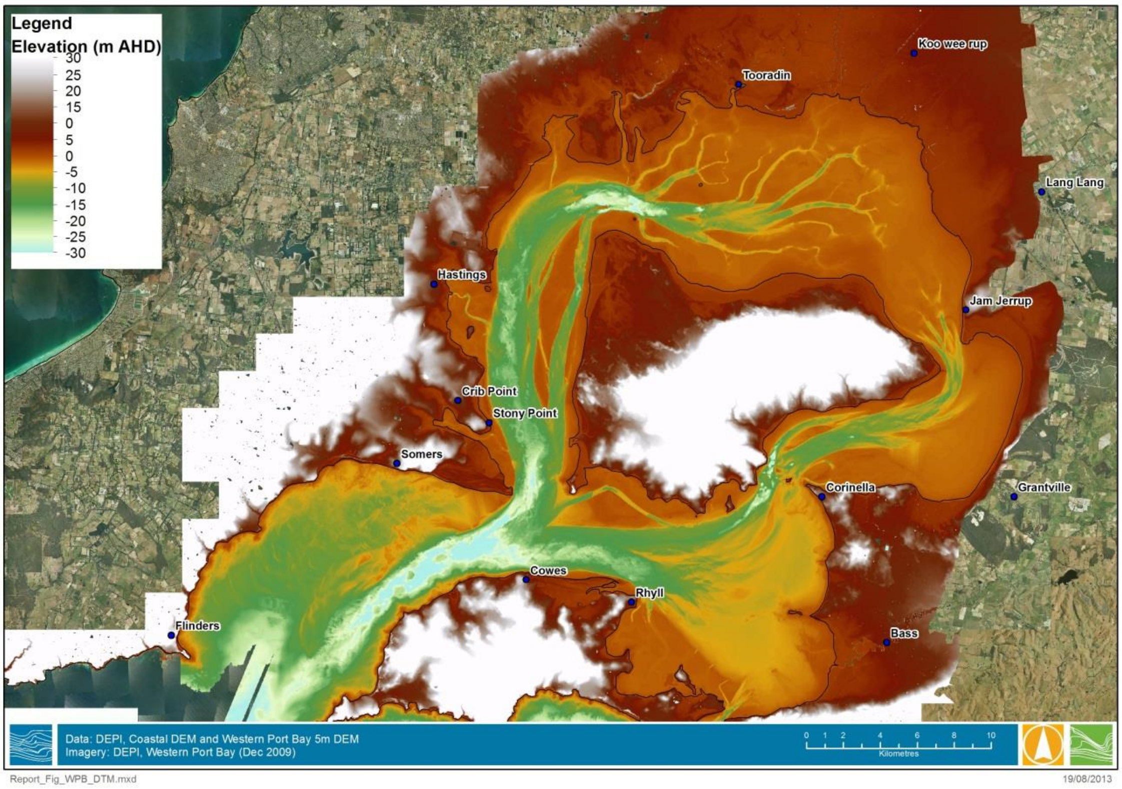


Figure 2-4 Topography and Bathymetry of the Western Port Study Area

2.2.2 Steep Coasts

Steep slopes that rise immediately from the shoreline, or are separated by a variable width of accumulation materials (gravel, sand, mud, vegetation) take many forms in Western Port. They are classified here according to the persistence of wave action effecting the cliff foot and face, and following Emery and Kuhn (1982), three main types are recognized:

- Active cliffs,
- Inactive cliffs, and
- Former cliffs.

The latter type corresponds to the coastal bluff described by Bird (1977). Active cliffs have frequent exposure to direct wave action (particularly at high tide and storms) and may continuously be receding due to the combined effects of marine and subaerial (surface) processes. Rock falls, slides and rotational slumps occur, and less resistant material in the cliff face are subjected to gullying and sheetwash. This material is removed by wave action and provides tools for marine abrasion and wave scouring. The detailed form of the cliff face is related to lithology and structure of the exposed material.

In Western Port the most common lithology of steep slopes is Older Volcanics basalt and tuff, and cliffs are developed in both hard fresh rocks, e.g. at Flinders, and on deeply weathered clays, e.g. at Cobb Bluff. Cliffs are developed in Mesozoic sediments, e.g. at Elizabeth Bluff, and Baxter Formation sediments west of Freeman Point on French Island. An unusual benched low cliff (usually less than two metres high) occurs for several kilometres north of Lang Lang beach. The cliffs are cut into the clays and peats of the seaward edge of the drained swamplands in areas where there is no mangrove fringe. They are low enough to be overtopped by storm waves, and ridges of coarse shelly sand (cheniers) are common a short distance inland from the cliff edge (Gell, 1974; Miles

1976). The cliff-foot - platform junction is marked by an abrupt angle and in some rocks a notch or undercut may be present. Most active cliff sectors are fronted by a shore platform which in places is over 100 metres wide and beaches if present at the cliff foot are typically of gravel.

Inactive cliffs have a veneer of weathered material on the cliff face and an accumulation of rock or sand at the cliff foot. Beaches are generally broader, and wave action is effective at the cliff foot only during storms and exceptionally high tides. The cliff profile may be partly vegetated with scrub or small trees extending down to the slope base. Inactive cliff sectors alternate with sectors of active cliffs along short stretches of coast, such as at Red Bluff south of Lang Lang, and between Shoreham and Balnarring. Former cliffs (abandoned cliffs, bluffs) are now removed from direct marine influences because they occur some distance inland. This isolation may be due to emergence i.e. the bluff was an active cliff during higher sea-level periods (Pleistocene or Holocene) and is now above the level of wave action. Bluffs of this origin occur between Long Point and Chambers Point on Phillip Island. The isolation of a former cliff may also be due to accumulations of sediment i.e. the buildup of beaches, spits, mangrove, marsh and deltaic deposits, which exclude waves from a former cliffed sector. Such accretion is responsible for the coastal bluff at Stockyard Point which is isolated by the growth of several recurving spits, and on the shores of Elizabeth and Churchill Islands where former cliffed sectors now lie well beyond wave attack behind a broad mangrove and salt marsh fringe. The various forms of cliffed coast are of particular scientific interest for the study of rates and processes of coastal recession, and for the evidence they provide of higher Pleistocene and possibly Holocene sea-levels.

Shore platforms are a feature of the basalt coast and are some of the broadest in Victoria – over 100 metres wide at Corinella and Cobb Bluff and provide excellent low tide exposures of geology and structures. The persistence of wide, hard rock platforms at the foot of deeply weathered cliff outcrops is a relatively unique coastal feature to Western Port.

2.2.3 Beaches

Many of the cliffed coasts are fringed by gravel beaches. Gravels are derived from the corestone and joint block weathering of the Older Volcanics basalt, and beaches of rounded even-size boulders of this origin occur at Corinella and at the entrance to Rhyll Inlet. Gravels are derived also from the Mesozoic sediments near San Remo. In the northern parts of the Bay, e.g. Chinaman Island, Barrallier Island and French Island, there are extensive beach accumulations of a hard red ferruginous sandstone shingle derived from weathering of the Baxter Formation sediments.

Sand beaches are predominantly of siliceous sand although there are calcareous rich sands on Cape Woolamai and at Cat Bay. Locally there are beaches with concentrations of shells, and the small embayments of the crenulate coastline cut into the swamp deposits north of the Lang Lang River have many beaches and chenier almost wholly of shell fragments (Gell, 1978). A number of prominent sand spits and forelands occur. Sandy Point east of Somers is almost five kilometers long and Stockyard Point south of Lang Lang is a tapering foreland over two kilometres long. Observation Point at Rhyll is an elongate barrier spit with a complex history and several episodes of spit growth are evident.

2.2.4 Coastal Dunes

The limited development of sand beaches, the amount of coarse material (gravel and shell fragments) in these, and the relative shelter of much of the coastline against onshore winds restricts the development of foredunes and transgressive dunes around Western Port. Multiple beach ridges occur in shallow embayments north of Flinders and there are elongate barrier and spit complexes at

Sandy Point, Stockyard Point and Between Freeman Point and Spit Point on French Island. Active transgressive coastal dunes are of limited occurrence within Western Port.

2.2.5 Emerged Shorelines

A variety of emerged shorelines are evident around parts of Western Port. An emerged shoreline shows depositional and/or erosional evidence of a former shoreline position. Emergence may be from one (or more) potential causes in Western Port:

(1) tectonic uplift/subsidence;
(2) Pleistocene high sea level (120,000 to 100,000 years before present); and
(3) Mid-Holocene higher sea levels (~7,000-3,000 years before present).

The locations and forms of these shorelines in Western Port provides important context and understanding to the evaluation of potential shoreline change and coastal hazard impacts due to projected 21st century sea level rise.

Approximately 18,000 years ago as the last glacial phase came to an end sea levels rose rapidly until the early Holocene. Initial submergence of Western Port began approximately 10,000 years ago. Local sea levels reached their maximum approximately 1.5-2.0 m higher than present in the early to mid-Holocene (approximately 7,000 years ago). The submergence of northern Western Port may not have occurred until this time. A possible combination of climate change and hydro-isostasy subsequently resulted in a local sea level fall to approximately present day sea levels 3,000 to 2,000 years ago.

Evidence of the location and characteristics of emerged shorelines in Western Port can be interpreted from close inspection of the high resolution terrain data (LiDAR) and other observational techniques. Review of these shorelines has been undertaken at the locations listed below to highlight the sensitivity of Western Port to recent, prehistoric sea level variations and to underscore the young and dynamic geomorphology of the current shorelines of Western Port.

Review and interpretation of the evidence of emerged shorelines have been undertaken for the following locations in Western Port:

- Watsons Inlet
- Bass Plain and Delta
- Cowes Rhyll Embayment
- Corinella Emerged Beach

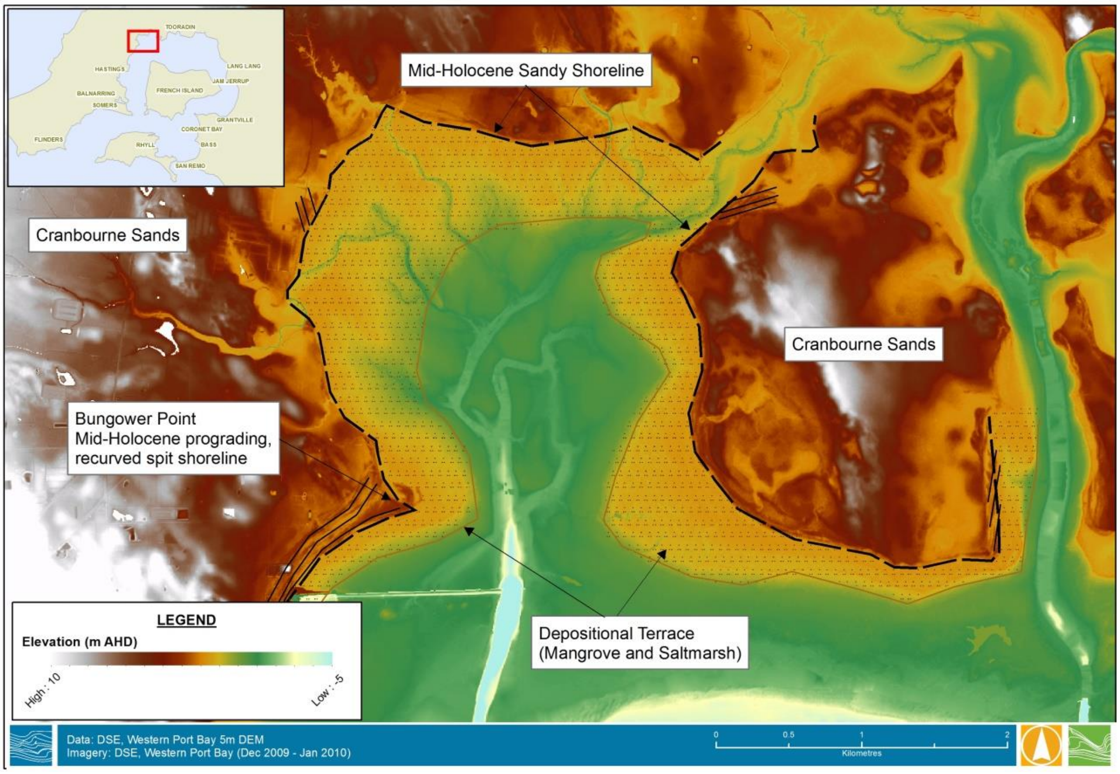
Watsons Inlet

The geomorphology of Watsons Inlet in the north western corner of Western Port from Yaringa to Quail Island reveals significant changes to the configuration and characteristics of the shorelines in this Inlet over the Holocene.

As the sea transgressed into the north western corner of the Western Port sunkland in the early Holocene, it encountered low ridge and swale topography associated with the Cranbourne Sands. Sandy shorelines evolved around a relatively broad and deep embayment during the mid-Holocene and wave action actively transported and rearranged the Cranbourne sands into a variety of sandy shoreline types including low cliffs, sandy beaches and spits (Bird E. C., 1974). Figure 2-5 delineates the approximate location of the sandy shorelines that existed around Watsons Inlet during the mid-Holocene as interpreted from the LiDAR survey. In a number of locations, multiple parallel dune ridges and recurved spit sequences can be seen. The recurved spits and parallel ridges at Bungower Point are the largest of these sandy landforms preserved in the morphology in this region. These features indicate extensive longshore drifting of sand and prograding shorelines occurred in this embayment during the mid-Holocene.

Following the relative fall in sea levels to present day levels and the establishment of mangrove and saltmarsh fringing vegetation, a broad depositional terrace has developed in front of these early sandy shorelines and these early shorelines are now not actively influenced by marine processes to any significant extent.

The changes in the shorelines of Watsons Inlet over the mid to late Holocene highlights the extent to which these shorelines are sensitive to minor variations in sea level as well as the significant influence of biological processes associated with coastal wetlands over this period.



Data: DSE, Western Port Bay 5m DEM
Imagery: DSE, Western Port Bay (Dec 2009 - Jan 2010)

Figure 2-5 **Geomorphology of Watsons Inlet**

Bass River Plain and Delta

The Bass River plain and delta displays significant marine and fluvial responses to mid-Holocene sea level variations and/or tectonic activity.

South of the Bass River delta, a striking succession of beach ridges originating from a series of scalloped knick points developed in the South Bass cliff line (Figure 2-7). The most landward breach ridge (R_1) has a base approximately 1.7 m above present high water level planes (Marsden & Mallett, 1974).

The stranded beach ridges are consistent with an emergent shoreline following the mid-Holocene high sea level still stand. During brief pauses in the rate of fall of the sea level post the mid-Holocene, active erosion of the weathered Basalt cliffs of South Bass controlled the location in which the beach ridges emanated from and extended across the Bass Plain.

Evidence of late-Holocene sea level fall may also be observed in the fields of large amplitude abandoned meanders at elevated levels on the floodplain and delta upstream to the township of Bass (Figure 2-7). Following the fall in sea level, the contemporary Bass River has entrenched into the delta, isolating these former tidal meanders. Other evidence of the rejuvenation of the modern

Bass River can be seen from its straightened course and series of terraces that have formed in this upper section of the delta (Marsden & Mallett, 1974).

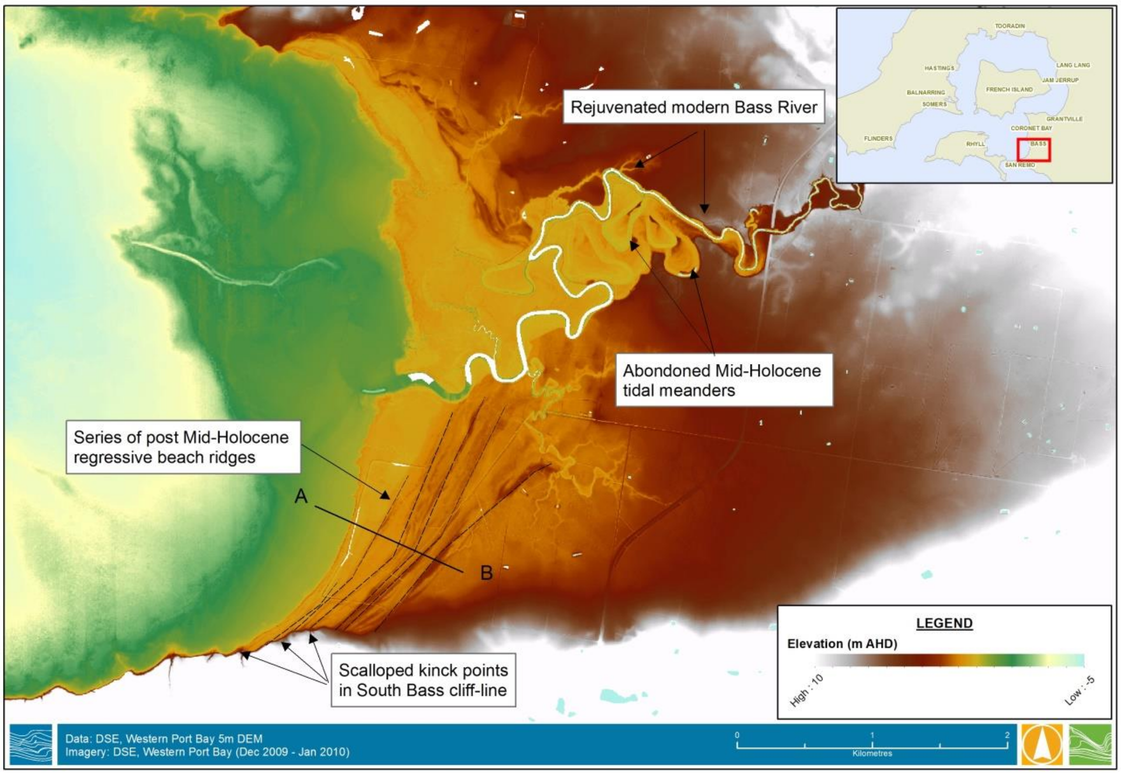


Figure 2-6 Geomorphology of the Bass River Plain and Delta

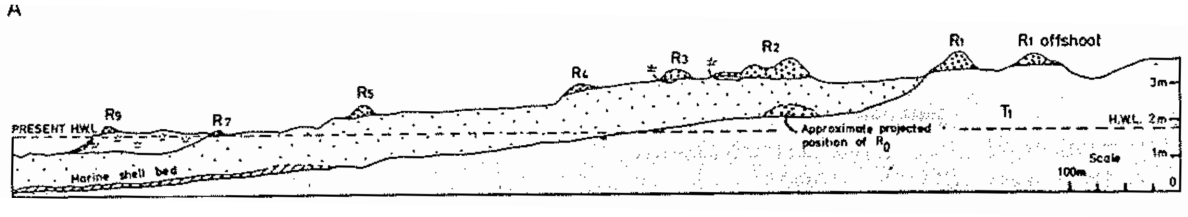


Figure 2-7 Geomorphology of the Bass River Plain and Delta (Marsden & Mallett, 1974)

Cowes Embayment/Rhyll Inlet

A region within Western Port that has shown particular variation and underlying sensitivity due to mid-Holocene sea level variations is the Cowes Embayment/Rhyll Inlet complex (Figure 2-8).

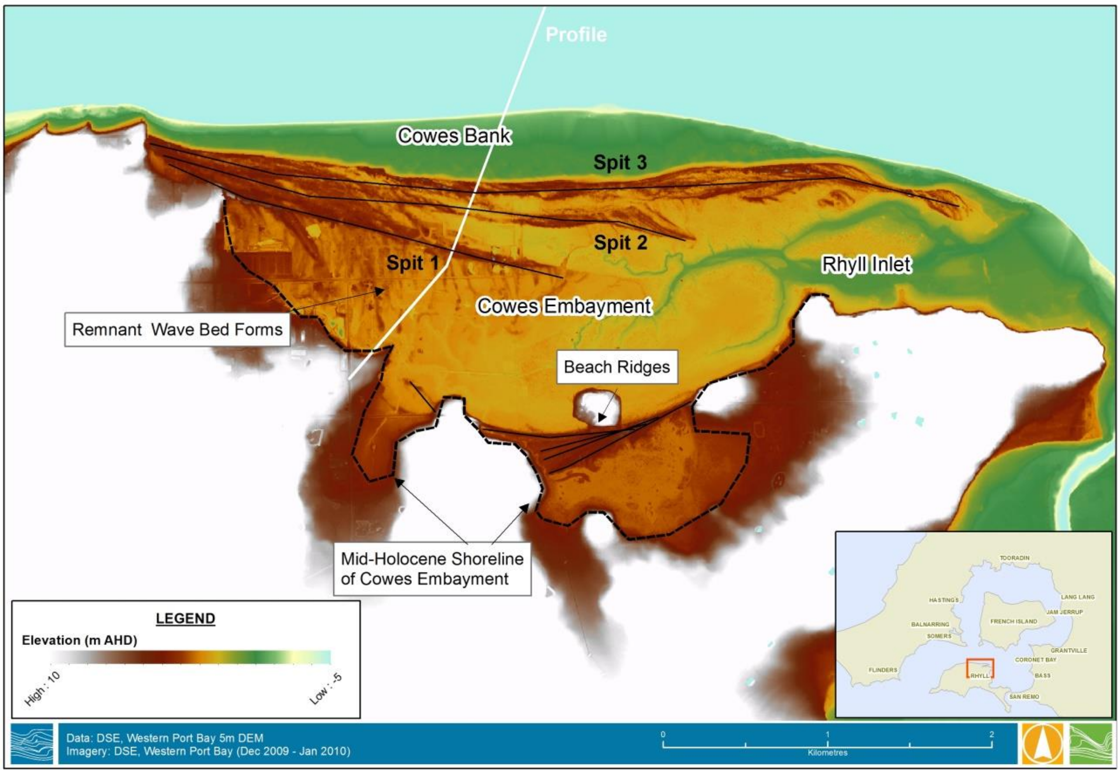
The area between Cowes and Rhyll initially previously existed as an open embayment during the mid-Holocene. The embayment was backed by sections of cliffed coastline where the mid-Holocene sea levels intersected outcropping Older Volcanic Basalt, Mesozoic arkose and Baxter Formation. The location of the initial mid-Holocene shoreline can be identified by the steep cliff and emerged shore platforms that occur around the margins of present day Rhyll Inlet.

Small beach ridge systems developed on the gently sloping shorelines of the embayment between the sections of active marine cliff coastline. The beach ridge systems subsequently sealed off minor inlets associated with the broader embayment. Rhyll Swamp was the most significant of these areas to be isolated from the broader embayment by beach ridge development. The configuration and orientation of the ridges systems along this mid-Holocene coastline suggest a pattern of wave and or current action that resulted in an east to west longshore transport within this earlier embayment (Marsden & Mallett, 1974).

Sediment supply from the east coupled with the fall in sea levels initiated the development of a succession of prograding sand spits which extended in an easterly direction from the Older Volcanic Basalt Headland at Erehwon Point. A corresponding succession of tidal inlets developed behind these spits and marine influence was gradually reduced within the embayment. Colonisation by mangroves and saltmarsh trapped and consolidated sediments and prograded the shorelines within Rhyll Inlet such that today the open water area is confined to a relatively small number of tidal channels.

Evidence of up to three former stages of evolution of the spit are apparent in the morphology (Figure 2-8) with the distill end of these earlier spits still preserved in the lee of the present day shoreward spit. The earliest spit (spit 1) trends more south easterly and is approximately 3.0 km long. A series of small, parallel ridges emanate from the inside edge of the spit orientated in a south-south easterly direction. It is speculated that these ridges are remnants of a sand bar feature caused by wave action across a subtidal sand sheet when this area was an open embayment, potentially similar to sand bar features that exist on present the day Cowes Bank (Marsden & Mallett, 1974) .

It is clear from the morphology preserved in this region of Western Port that the arrangement and position of the shorelines has been very dynamic over relatively recent geological history and is particularly sensitive to either sea level variations or a combination of sea level and sediment supply.



Data: DSE, Western Port Bay 5m DEM
Imagery: DSE, Western Port Bay (Dec 2009 - Jan 2010)

Figure 2-8 Cowes Embayment / Rhyll Inlet

Corinella Emerged Beach

Several features at the point west of the barge landing at Corinella area are potential emergence sites. A deposit of stratified sediments at the foot of the bluff includes a variety of minor gravel, sand, shell and clay. A section of the material in a low cliff includes two distinct horizons containing shells. The lower deposit rests on a buried planar surface in weathered Older Volcanic tuff and basalt. Jenkin (1961) and McMickan (1977) interpreted the lower shell bed as a former beach built at a sea level one to two metres above present sea level, and the upper bed as a kitchen midden.

Figure 2-9 **Corinella Emerged Shorelines**

2.3 Peripheral Vegetation Communities

2.3.1 Overview

Western Port is fringed by many different types of water-dependent vegetation, including mangrove (Avicennia marina) shrublands, coastal saltmarsh (of various species), Sea Rush (Juncus kraussii) marshes, and Swamp Paperbark (Melaleuca ericifolia) swamps. At least eight other less well-known vegetation types (i.e. Ecological Vegetation Classes) may also occur in the region.

2.3.2 Types of Peripheral Vegetation

Western Port has been listed as a Ramsar site on the basis of, among other things, the extent and diversity of its coastal wetlands. Large expanses of coastal wetland with such floristic and structural diversity are not common elsewhere in Victoria; mangroves line about 40% of the Western Port shoreline and, second only to the stands of 'bonsai' mangroves at Corner Inlet, are the highest-latitude mangroves in the world (Duke, 2006). Coastal saltmarshes are also extensive and, unlike the mono-specific mangroves that fringe Western Port, are floristically diverse (Boon *et. al, 2011* & Carr, 2012) ; they are also relatively undisturbed, unlike many other areas of coastal saltmarsh in south-eastern Australia (Laegdsgaard, 2006 & 2008). Figure 2-10 displays the extent of mangrove and coastal saltmarsh in Western Port.

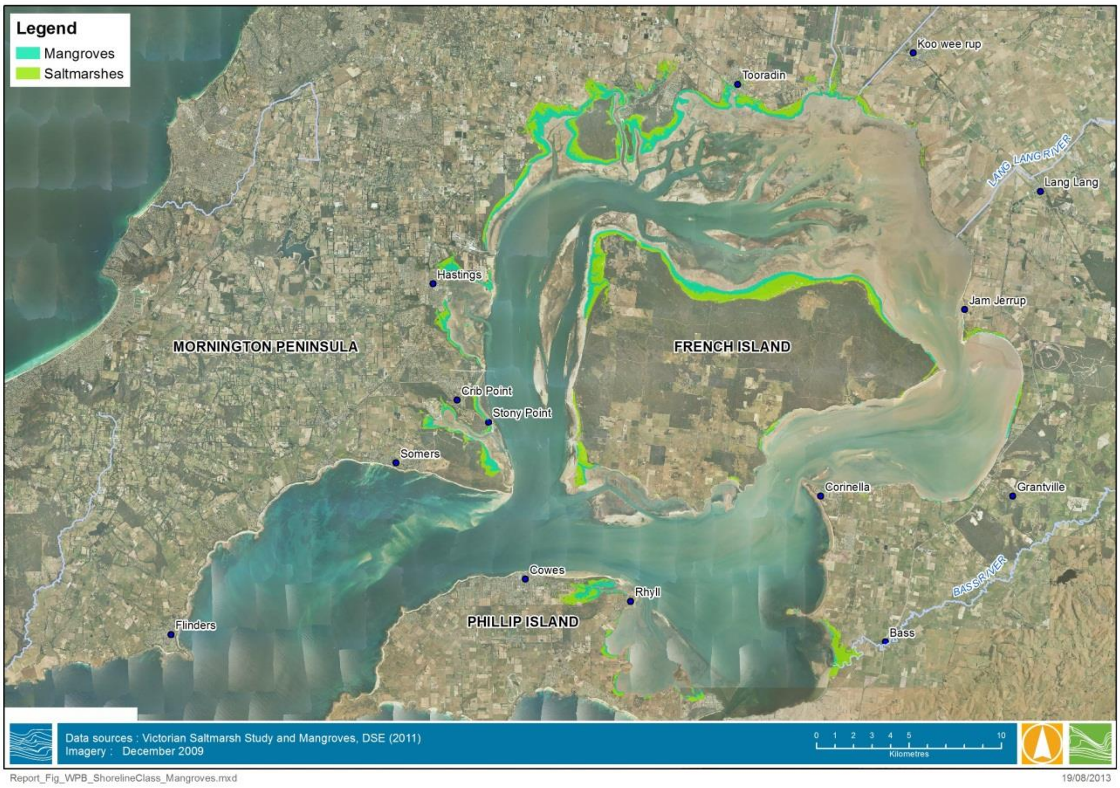


Figure 2-10 **Distribution of Peripheral Coastal Vegetation in Western Port (Saltmarsh: DSE (2011) *Victorian Saltmarsh Study,* Mangroves: DSE Arthur Rylah Institute (2011))**

Mangroves

Mangroves are trees, shrubs or palms, taller than 0.5 m, that grow above mean sea level in the intertidal zone of marine coastal environments and along the margins of estuaries (Woodroffe & Davies, 2009). Only one mangrove species, *Avicennia marina* var. *australasica*, is present in Victoria (Duke, 2006) and the vegetation community it forms is classified as Ecological Vegetation Class (EVC) 140 Mangrove Shrubland. Mangroves occur mostly as a dense mono-specific shrubland, with individuals growing as shrubs or small trees up to ~4 m tall, although at their most southerly extent the plants can be isolated shrubs only ~0.3–0.5 m tall (Harty, 1992; Duke 2006). Frost and/or low winter temperatures are believed to be the environmental factor that limits the distribution, vigour and productivity of mangroves in southern Victoria (Ashton, 1971; Oliver, 1982).

Figure 2-11 Fringing Mangroves, Tooradin (Photo: Paul Boon)

Coastal Saltmarsh

Because of its much greater structural and floristic complexity, it is harder to define coastal saltmarsh[2] than it is mangrove shrubland. Boon *et al*. (2011) reviewed the wide range of definitions that had been proposed in the past, and recommended that coastal saltmarsh be described as 'land that experiences regular low-energy inundation by seawater and which is vegetated by low-growing vascular plants (<1.5 m height), such as succulent chenopods and salt-tolerant monocots'.

Despite its floristic and structural diversity, coastal saltmarsh is currently allocated to a single EVC (EVC 9 Coastal Saltmarsh Aggregate) in Victoria. The recent State-wide assessment of Victoria coastal wetlands proposed that the current EVC be divided into seven new EVCs that better reflected the floristic and structural diversity in the vegetation (Boon *et. al.*, 2011) and this recommendation has been endorsed as a tentative typology in the 2nd edition of the DSE monograph on wetland EVCs (Department of Sustainability and Environment, 2012).

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[2] The term 'coastal' is used to differentiate these maritime-influenced saltmarshes from inland saltmarshes, which are also saline or hypersaline and often have similar species and/or genera, but are not subject to contemporary maritime/oceanic influences.

Figure 2-12 Coastal Saltmarsh at Hastings (Photo: Paul Boon)

Other Vegetation Types

Although mangroves and saltmarsh are the most obvious types of coastal wetland around Western Port, both are commonly found nearby, or in mosaics with, a range of other estuarine wetlands that similarly experience a mixture of tidal and freshwater influences. Research along other parts of the Victorian coast have shown that these other types of coastal wetland are often vegetated by dense stands of rhizomatous perennial monocots, including Sea Rush (*Juncus kraussii*) and Common Reed (*Phragmites australis*) in the seaward reaches, and Salt Club-sedge (*Bolboschoenus caldwellii*) and Sharp Club-rush (*Schoenoplectus pungens*) in areas further from the influence of sea water (e.g. Sinclair & Sutter 2008). Some of the other types of coastal wetlands around Victoria and possibly also around Western Port include:

- Estuarine Wetland (EVC 10), dominated by *Juncus kraussii*, occasionally with *Phragmites australis* or species of Cyperaceae.
- Brackish Sedgeland (EVC 13), dominated by *Gahnia trifida* (sometimes *Gahnia filum*) and *Baumea juncea*.
- Swamp Scrub (EVC 53), dominated by *Melaleuca ericifolia*, *Leptospermum lanigerum*, with aquatic or semi-aquatic spp. such as *Isolepis inundata*, *Triglochin procera*, *Villarsia* spp. and *Sphagnum* spp.
- Brackish Wetland (EVC 656), dominated by *Bolboschoenus caldwelli* and/or *Schoenoplectus pungens* and aquatic semi-aquatic species tolerant of at least moderate salinity.
- Tall Marsh (EVC 821), typically vegetated with *Phragmites australis*, *Typha* spp. and *Schoenoplectus tabernaemontani*.

- Estuarine Reedbed (EVC 952), dominated by *Phragmites australis*, with associated species variously including *Samolus repens*, *Juncus kraussii*, *Triglochin striatum*, *Bolboschoenus caldwellii* and *Suaeda australis*.
- Estuarine Scrub (EVC 953) *Melaleuca ericifolia* (in eastern Victoria), with other *Melaleuca* spp. (e.g. *Melaleuca lanceolata*, *Melaleuca gibbosa*) or *Leptospermum lanigerum* in marginal sites in western Victoria. Ground-layer includes *Samolus repens*, *Triglochin striatum* and *Selliera radicans*, variously with *Sarcocornia quinqueflora*, *Gahnia filum*, *Poa poiformis*, *Juncus kraussii*, *Disphyma crassifolium* and *Distichlis distichophylla*.

Figure 2-13 Coastal Saltmarsh at the northern shore of French Island (Photo: Paul Boon);

Sarcocornia-dominated herbland appears in the centre of the photograph: the shrub Tecticornia arbuscula in the front; and the rear is fringed by tall Swamp Paperbark Melaleuca ericifolia

2.4 Hydrodynamic Setting

2.4.1 Astronomical Tide

The lunar semi-diurnal tide is the principal driving mechanism for the water level variations observed in Western Port. Tidal range increases toward the head of the bay to a maximum of about 1.3 times the range at the entrance. This amplification of the tide towards the head of the bay is due to the one quarter wavelength resonance of the lunar semidiurnal tide within Western Port. Western Port subsequently experiences a meso-scale tidal range with the spring tidal planes (MHWS) varying from approximately 1.15 m AHD at Stony Point to approximately 1.5 m AHD at Tooradin as can be seen in Figure 2-14.

The western entrance is the largest of the two entrances and the dominant connection with Bass Strait (Lee, 2012), contributing approximately 85% of the tidal water entering over a tidal cycle (Marsden & Mallett, 1974). The tide propagates into Western Port primarily through the western entrance, before travelling around the western and eastern shorelines of French Island, meeting at a tidal divide in the north east corner of Western Port. Prevailing westerly winds result in a slight net clockwise circulation in Western Port. In the northern arm of Western Port there are broad areas of intertidal flats exposed at low tide crossed by an intricate network of ebb and flood channels.

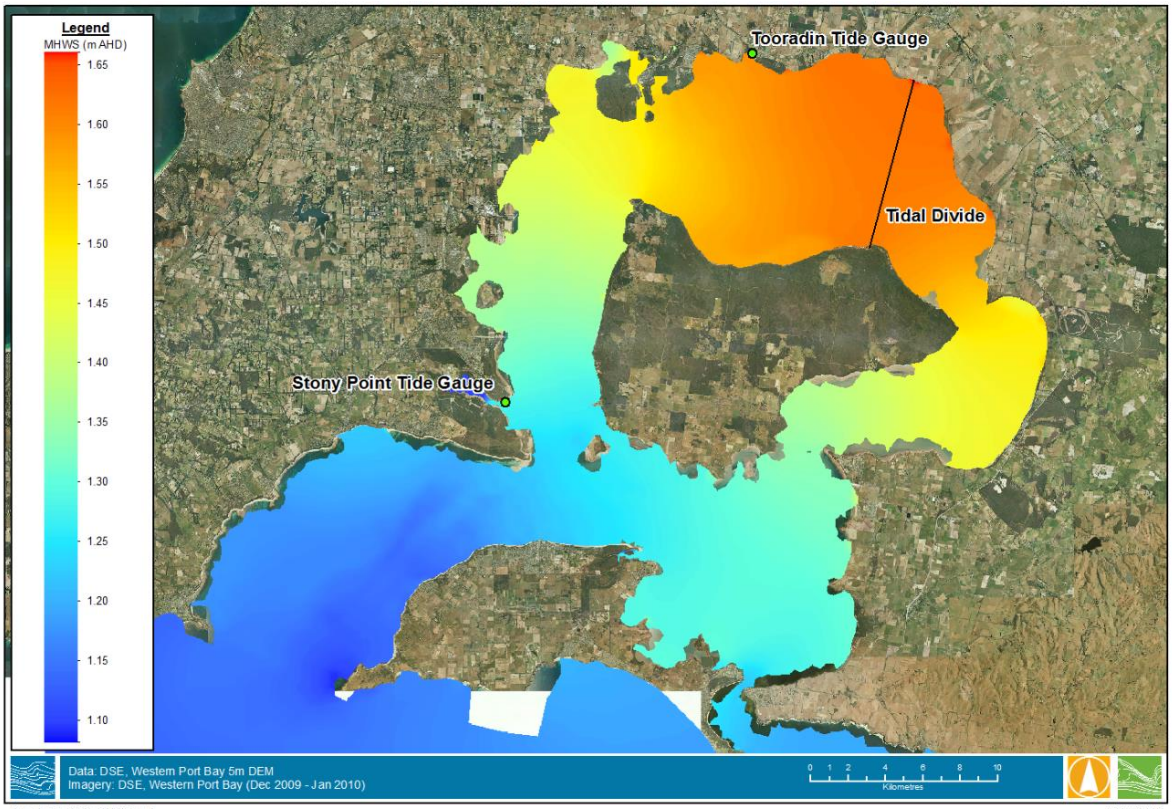

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Figure 2-14 Mean High Water Springs (MHWS) – Present Mean Sea Level

2.4.2 Wave Climate

The presence of Phillip and French Islands greatly modifies the passage of ocean swell from Bass Strait into Western Port. Figure 2-15 displays an estimate of the annual cumulative wave power (kW/m/year) in Western Port. As can be seen from Figure 2-15, the narrow eastern entrance and sheltering afforded by Cape Woolamai effectively limits ocean swell penetration to Cleeland Bight. Significant ocean swell energy does however propagate through the Western Entrance into Western Port. Ocean swells propagating through the Western Entrance are refracted towards the western and eastern shorelines of the Western Entrance resulting in very large gradient in wave energy through the western entrance and along these shorelines. Strong tidal flows cause significant wave-current interactions through the Western Entrance and ocean swells are significantly blocked during ebb tides. Low, residual ocean swells can be observed in Western Port as far as Sandy Point, Tortoise Head on French Island and as far east as Silverleaves along the northern shores of Phillip Island.

Away from the Western Entrance, the wave climate in Western Port is characterised by locally generated wind waves. The relative exposure of shorelines in Western Port to wind-waves is a function of their aspect in relation to prevailing wind directions and the extent of the available fetches and water depths. The relatively large tidal range and broad expanses of shallow intertidal areas in Western Port significantly influences the exposure of shorelines in Western Port to locally generated wind waves. The majority of shorelines in Western Port therefore experience a wave climate that is strongly modulated by the phase of the tide.

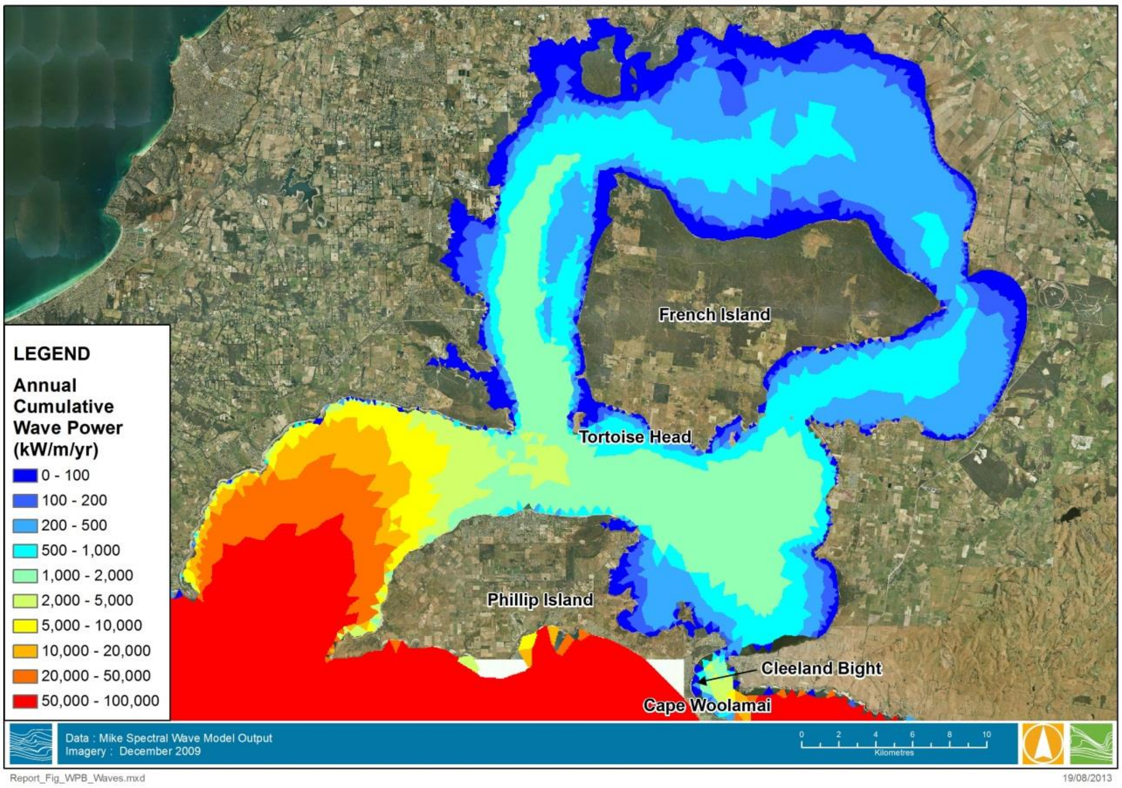

Figure 2-15 **Estimate of Average Annual Cumulative Wave Power in Western Port (kW/m/yr) from Ocean Swell and Locally Generated Wind Waves**

2.4.3 Water Movements & Sediment Transport

The movement of water through Western Port, as a result of tide and wave forces has previously been described by various authors (e.g. Marsden et al, 1979; Harris et al, 1979, Hinwood and Jones, 1979; and Hinwood, 1979). Harris et al (1979) characterise these movements in terms of four “systems” within the bay as follows (Figure 2-16):

1. High-energy channel/bank system (Western Entrance to just beyond the Confluence Zone) – an area of strong tidal currents, varying degrees of wave activity and a sandy substrate.
2. Ebb/flood areas with contrasting sandy and muddy sediments and intertidal sediment deposition (Lower North Arm, Corinella segment).
3. Subtidal, partly enclosed mud-deposition basin (Rhyll segment), comprising a shallow, subtidal, depositional basin collecting fine sediments. Circulation is weak and sediment transport minimal.
4. Extensive intertidal flat system, containing a web of minor channels. Localised flood and ebb-dominant transport paths.

Water Movements

Harris et al (1979) describes in detail the circulation and water movement throughout the “systems” within Western Port. In general, the currents in this system are oscillatory as they are generated by the astronomical tides propagating in from Bass Strait (i.e. Hinwood, 1979). Around 95% of the movement into the bay occurs through the Western Entrance segment. However complications develop at the Confluence Zone where the flood tide flow splits, moves up both the eastern side of French Island and part of the North Arm (Figure 2-16). Due to tidal lag, the incoming flood tide in the Eastern Entrance is pushed into the Rhyll segment. Part of this water leaves the bay through the Eastern Entrance on subsequent ebb tides. A small amount of water may enter the bay through the eastern entrance (Harris et al, 1979).

This complex behaviour has been replicated in the calibrated hydrodynamic model, detailed in Report 4 of this study. An example of the net water movements across Western Port is shown by the black arrows in Figure 2-16. These arrows represent the net magnitude and direction of velocity at each location over a representative 1 year hydrodynamic simulation. The model results have been mapped onto a 50 m grid across the whole study area. These results clearly show the recirculation of flows in the Western Entrance, particularly along the shoreline near Somers (across a large offshore sand deposit known as Middle Bank, Figure 2-17).

Sediment Transport

The tidal currents and circulation patterns drive the movement of sediment throughout the bay. Sediment transport paths (after Harris et al, 1979) are shown in Figure 2-17. General comments on the sediment movement in each of the “systems” are provided below (from Harris et al, 1979):

1. High-energy channel/bank system (Western Entrance to just beyond the Confluence Zone). This area is the most dynamic of Western Port, exposed to strong tidal currents and varying degrees of wave activity. Channel sediment, offshore banks and coastal deposits are almost entirely sand. The combination of net flow and wave induced transport make it a zone of strong inward movement of sand, providing a supply to Middle Bank and the beaches along Balnarring/Somers and along the northern shore of Phillip Island. The offshore sources and rates of sand supply to this system have not been quantified.
2. Ebb/flood areas with contrasting sandy and muddy sediments and intertidal sediment deposition (Lower North Arm, Corinella segment). In the Lower North Arm the intertidal sediments are much sandier than most other intertidal areas of Western Port. The Corinella segment is markedly different, with important depositional areas for mud towards the eastern embayments and limited deposition areas for sand.
3. Subtidal, partly enclosed mud-deposition basin (Rhyll segment), comprising a shallow, subtidal, depositional basin which collects fine sediments. Circulation is weak and sediment transport minimal. Strong current and sand transport only occurs at the eastern entrance.
4. Extensive intertidal flat system, containing a web of minor channels. Intertidal sedimentation processes associated with the channels dominate, resulting in significant deposition of suspended mud. Catchment sediment inputs have affected this area although volumes appear to be reducing (S. Brizga & Associates, 2001). Significant volumes of muddy sediments are being introduced to the system by the continued erosion of the eastern shoreline (described further in Section 3).

Sea Level Rise

Sea level rise may alter the water and sediment movements within Western Port through changes in the flow depths and velocities in different sections of the system. However, due to the potential interaction between many different physical forcings and feedback mechanisms throughout the system the future system-wide response to sea level rise is highly uncertain. Possible changes to water and sediment movements in different areas within Western Port as a result of sea level rise are discussed in general terms in the following sections of this report and in the Representative Locations Report (R06).

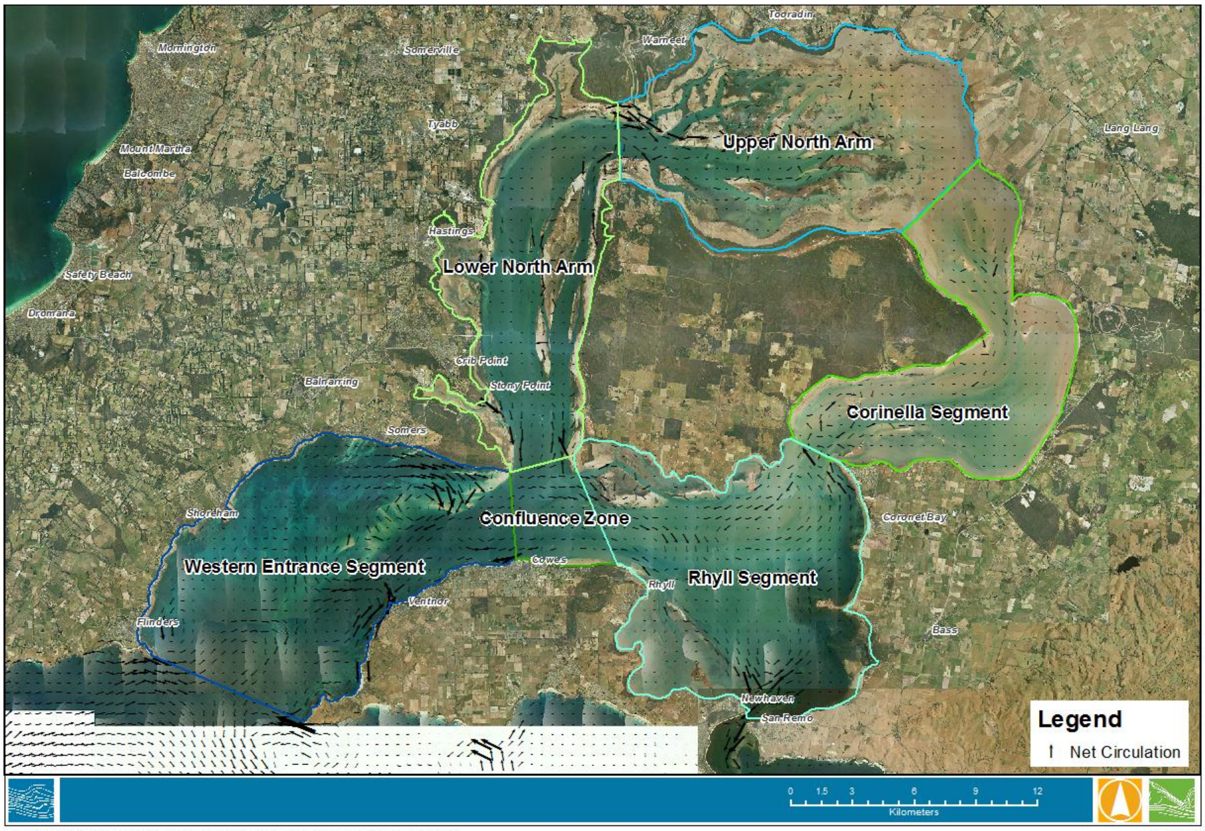

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Figure 2-16 Western Port Wave Movement and Sediment Transport Zones (after Harris et al, 1979) including Patterns of Net Circulation

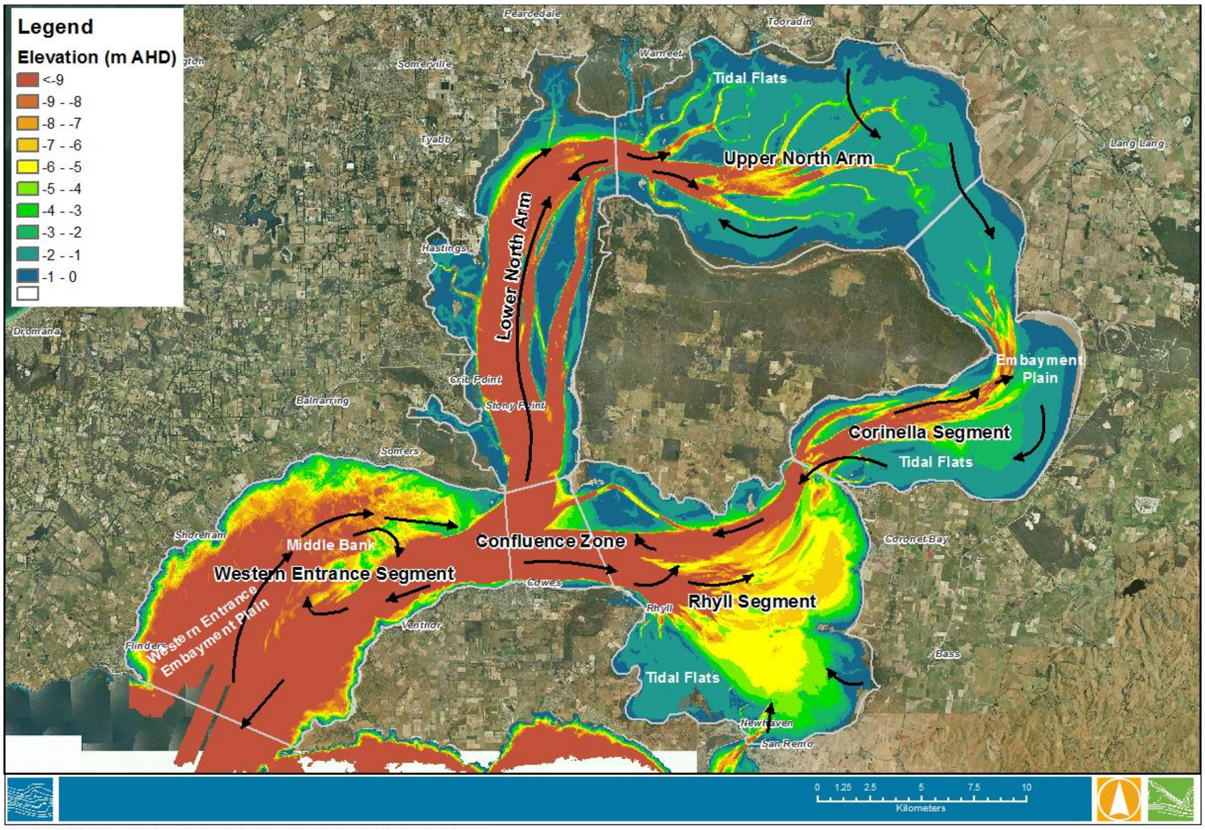

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Figure 2-17 Sediment Transport in Western Port (after Harris et al, 1979)

3. GEOMORPHIC SUB CELL DELINEATION

3.1 Overview

To develop an understanding of the potential extent of the shoreline response and therefore associated coastal hazard impacts around the entire Western Port shoreline due to sea level rise and/or climate change, the shorelines of Western Port have been characterised into seven major geomorphic shorelines classes.

The geomorphic shoreline class characterisation has used in part the Smartline terminology developed by Sharples *et al.* (2009) as the basis for describing backshore, coastal and intertidal features. For the current study, the geomorphic shoreline classes have however been independently identified utilising prior experience in Westernport, supplemented by additional references, aerial photograph interpretation, LiDAR data, and field work - including low-level aerial inspection of the shoreline of the study area.

The classification of shorelines and coastal landforms developed in this study is considered to best suit the unique environment of Westernport and provides a practical classification of shorelines and coastal landforms to support a Western Port wide assessment of potential coastal hazard impacts due to sea level rise.

The seven major geomorphic shoreline classes identified for Western Port to support the assessment of coastal hazard impacts due to sea level rise have been termed as follows:

- Coastal Wetland Fringed Shorelines
- Low Earth Cliffed Shorelines
- Hard Rock Cliff and Shore Platform Shorelines
- Platform Beach and Bluff
- Soft Rock, High Cliffed Shorelines
- Sandy Spit Shorelines
- Estuarine and Tidal Channel Shorelines

Figure 3-1 displays the delineation of the seven major geomorphic shoreline classes around Western Port. The total length of shoreline and percentage of the total study area shorelines of each major geomorphic shoreline class are displayed in Table 3-1.

Table 3-1 Summary of Geomorphic Shoreline Class Delineation of Western Port

Geomorphic Shoreline Class	Length (km)	Percentage (%)
Coastal Wetland Fringed Shorelines	155	45
Low Earth Cliffed Shorelines	30	9
Hard Rock Cliff and Shore Platform Shorelines	44	13
Platform Beach and Bluff	74	22
Soft Rock, High Cliffed Shorelines	5	1
Sandy Spit Shorelines	21	6
Estuarine and Tidal Channel Shorelines*	-	-
Infrastructure**	13	4
Total	**342**	**100**

* Length of Estuarine and Tidal Channel Shoreline Type not included

** Infrastructure dominated shorelines associated with major Port and Harbour Facilities

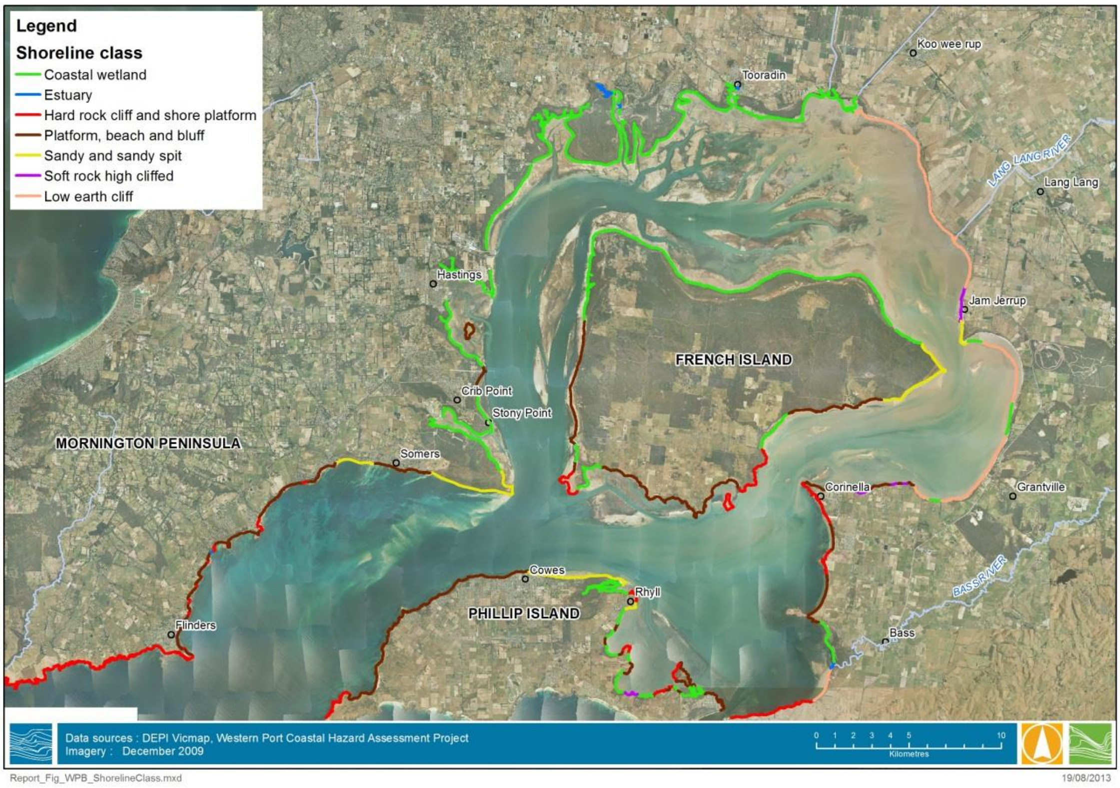


Figure 3-1 Overview of Shoreline Class Delineation for Western Port

Within each shoreline class, a number of sub-classes are identified that contain some variations in lithology, evolution and the physical processes operating on them but are considered likely to show similar responses and rates of change to sea level rise.

In order to provide an understanding of the potential extent of the shoreline response that may occur due to sea level rise and/or climate change and associated coastal hazard impacts within each geomorphic shoreline class, conceptual shoreline models have been developed for each shoreline and coastal landform class shown in Figure 3-1.

The conceptual shoreline models have been developed to provide an understanding of the following:

- Summarise the geology, processes and dynamics that characterise each shoreline type to develop an understanding of the historical evolution of these shorelines and their contemporary variability;
- Provide an understanding of the key response mechanisms of the shorelines to sea level rise and/or climate change and the relationship between these response mechanisms and potential rates of shoreline change and associated coastal hazard impacts; and
- Identify the extent of the knowledge, data and process gaps that exist for each shoreline type to enable the sensitivity of this uncertainty on the potential extents of shoreline change and coastal hazard impacts to be evaluated.

The classification of the Western Port shorelines necessitates the significant simplification of the spatial heterogeneity and geologic diversity of the shorelines of Western Port; however it provides a means for enabling a Western Port wide assessment of potential extents of coastal hazard impacts associated with shoreline change to be undertaken. It should therefore be noted that at any one specific location within Western Port, the shoreline may exhibit characteristics and contain physical components that partially reflect a number of the discrete geomorphic shoreline classes and associated conceptual models of change developed in this study. In many of these instances however, it is considered that the shoreline response to sea level rise and/or climate change will largely follow one of the seven main shoreline model types.

The following sections describe the major geomorphic features of each shoreline class, the key processes and dynamics that operate on these shorelines and the likely key drivers and rates of change that could be expected for each shoreline class due to sea level rise.

3.2 Coastal Wetland Fringed Shorelines

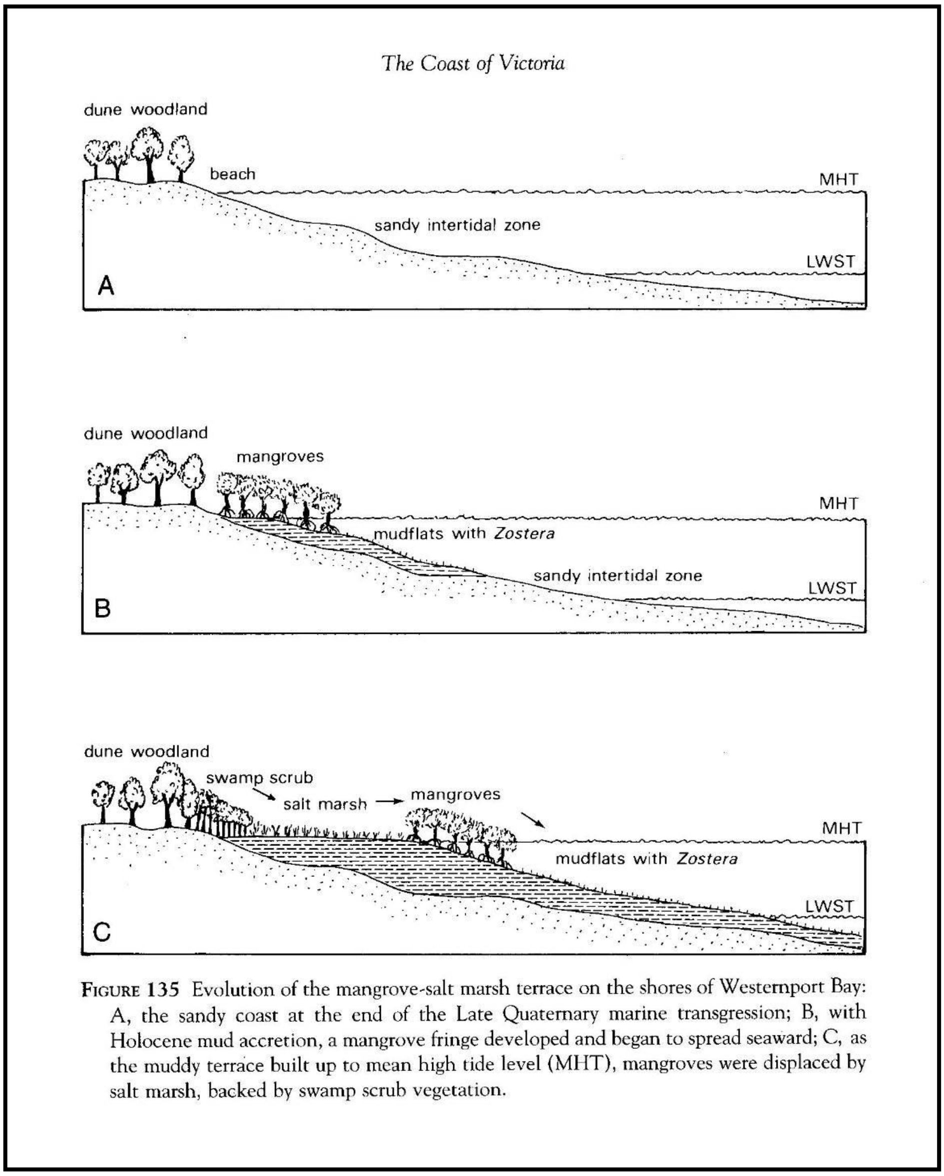
3.2.1 Class Overview

Approximately 38% of the shorelines of Western Port are fringed by coastal wetlands of which the predominant type is a mangrove fringed, saltmarsh terrace. These shorelines frequently display a clear zonation of vegetation type with elevation and with distance from the water as displayed in Figure 3-2. Typically this zonation progressed as follows:

- Seagrasses occurred in the subtidal and intertidal areas.
- Seagrasses gave way to mangroves in the higher parts of the intertidal zone.
- Mangroves gave way to coastal saltmarshes above the intertidal zone in most cases.
- Less salt-tolerant species of rhizomatous emergent plants such as *Juncus kraussii* and *Gahnia* spp occur landward of the saltmarshes, and
- Mixed *Melaleuca-Leptospermum-Eucalyptus* woodlands completed the transition to a terrestrial environment in the coastal hinterland. (Following European settlement however, much of the terrestrial vegetation has been cleared for agricultural production and grazing. Similarly, large areas of former paperbark woodland have been cleared (Bird 1993), as well as mangroves and coastal saltmarsh (Sinclair and Boon 2012)).

The clear zonation of vegetation types in Western Port are sometimes - but controversially - interpreted as evidence of seral succession. The succession is conventionally proposed to commence with pioneer mangroves colonizing bare mudflats. As the mangroves accumulate sediment, the sediment surface becomes elevated and less frequently inundated, which in turn creates conditions suitable for invasion by less flood-tolerant species such as saltmarshes, brackish-water taxa and, eventually, terrestrial plants. With increasing sediment elevation, the original pioneer species are able to colonise seaward. Implicit in the concept is that the earlier vegetation types modify the environment so that it becomes suitable for later vegetation types (Hogarth 2007).

Figure 3-2 shows this process in Western Port as outlined in Bird (1986, 1993).



The Coast of Victoria

FIGURE 135 Evolution of the mangrove-salt marsh terrace on the shores of Westernport Bay: A, the sandy coast at the end of the Late Quaternary marine transgression; B, with Holocene mud accretion, a mangrove fringe developed and began to spread seaward; C, as the muddy terrace built up to mean high tide level (MHT), mangroves were displaced by salt marsh, backed by swamp scrub vegetation.

Figure 3-2 Development of Peripheral Vegetation at Western Port, as Explained by Bird (1993)

Part C) shows the present-day plant zonation, with seagrass beds fronting a band of mangroves, which in turn fronts a saltmarsh community and behind it, a paperbark ('swamp scrub') community.

The clear-cut patterning of different plant types shown in Figure 3-2 is to some degree an idealized construction. In practice, the vegetation is not patterned as neatly as the model suggests, and this is because elevation is not related simply to distance from the sea. A large number of tidal channels cut across the fringing wetlands, and they introduce much spatial complexity into the peripheral vegetation (Figure 3-3). The simple and regular plant zonation that occurs with distance from the sea is thus made complex by the additional patterning that occurs at much smaller scales with distance (and thus elevation) from these tidal channels as can be seen below.

Figure 3-3 Example of the Zonation of Vegetation Types with Distance from the Sea

This photograph also shows mangroves growing along tidal channels far into the zone that, on the basis of distance from the sea, should be vegetated only by saltmarsh plants. Reproduced with permission of Neville Rosengren.

There are over 1,700 ha of mangroves in Western Port, of which a substantial proportion (475 ha, or ~20%) occurs on the northern shore of French Island. The combined area of the different types of coastal saltmarsh in Western Port is 1,088 ha, with an additional 860 ha on French Island, 10 ha on the Lang Lang coast, and 49 ha in The Inlets (refer to Figure 2-13). Figure 3-4 displays the extent of coastal wetland fringed shorelines of Western Port adopted for the coastal hazard assessment. These areas are typically located within the Lower North Arm and Upper North Arm segments of Western Port (refer Figure 2-16) and in sheltered embayments (Bass River Delta and Rhyll Inlet).

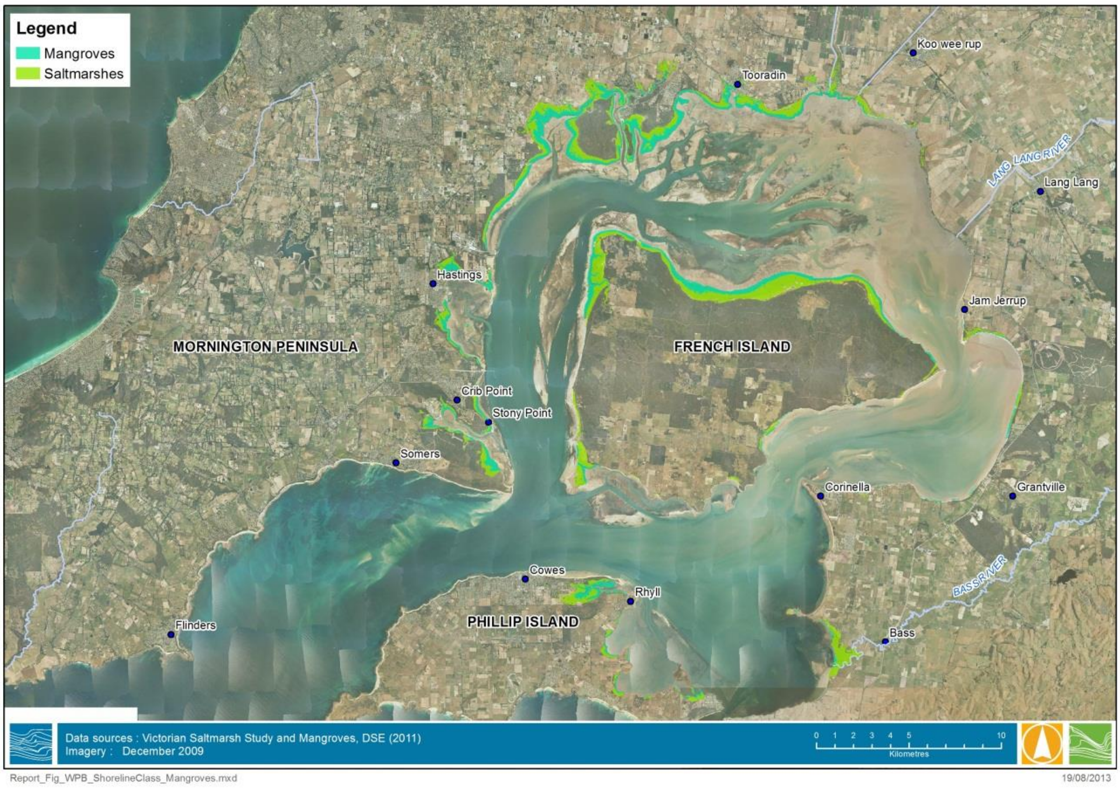


Figure 3-4 Extent of Coastal Wetland Fringed Shorelines around Western Port

3.2.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this conceptual shoreline type are displayed conceptually Figure 3-5 and are discussed in more detail below:

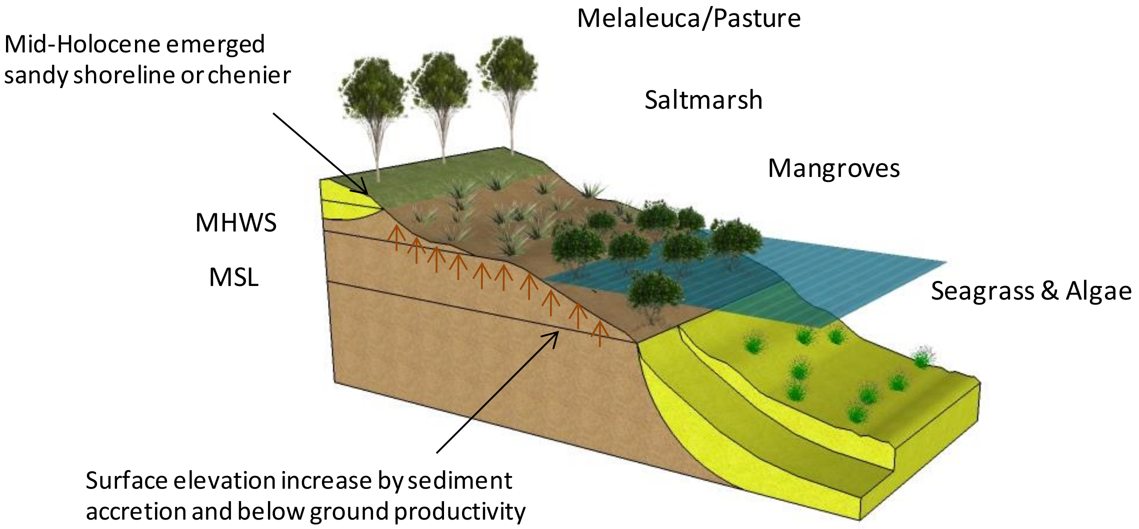


Figure 3-5 Coastal Wetland Conceptual Shoreline Type

Geomorphic Components

The key physical components of this shoreline type comprise the following:

- Predominately muddy or silty flats, channels and shoals existing below low water with seagrass and algae,
- A wide intertidal flat of silty mud and sand and partly decomposed organic material between mean low water and mean high water with mangroves,
- Shallow organic muds and peats above mean high water springs with saltmarsh, and
- Sandy terrace and mid Holocene chenier with Melaleuca or pasture or, in less developed areas, a hinterland of native eucalypts etc.

Inundation and Tidal Regimes

Mangroves are obligately intertidal plant species and die if they are not periodically inundated with the tides. Despite their extraordinary adaptations to episodic inundation (Saenger, 1982), they are also killed if their roots are kept permanently submerged, no matter whether the water is fresh, brackish or oceanic. The entry on *Avicennia marina* by the Queensland Department of Agriculture, Fisheries & Forestry, for example, notes that this species is killed if it is inundated for longer than ~14 days (http://www.daff.qld.gov.au/28_9226.htm, Viewed 12/04/2013). An example of *Avicennia*'s sensitivity to permanent inundation is provided below in Figure 3-6 which shows the death of mangroves after they had been permanently flooded as a result of sand movements along southern French Island.

Figure 3-6 Death of Mangroves after Ponding Created by Sand Movement, Southern French Island.

Source: Original photography by Dr Steve Sinclair and reproduced in Boon et al. (2011, Figure 1.46)

Roy E Lewis III, one of the leading (American) practitioners in the field of mangrove rehabilitation, recommended that *Avicenna marina* be planted in zones that were inundated by all medium–high tides, which in his categorization is equivalent to elevations that receive 45−59 tidal inundations per month (http://www.mangroverestoration.com/pdfs/mangrove_restoration.pdf Viewed 12/04/2013).

Previous modelling of potential climate-change impacts on Western Port's wetlands, Boon *et al*. (2010) argued, on the basis of the prior State-wide mapping project, that *Avicennia marina* typically occurred in the elevational range of about 0.3 m AHD to 1.2 m AHD around Western Port.

For this study, the State-wide mangrove mapping layer for Western Port has been intersected with a 5 m digital terrain model (DTM) based on the LiDAR topographic and bathymetric surveys to determine the distribution of surface elevations within mangroves in Western Port. A frequency histogram of the distribution of surface elevations and mangroves from this analysis is displayed in Figure 3-7 relative to key tidal planes at Stony Point.

From Figure 3-7 the analysis suggests that the majority of the mangroves exist between approximately mean sea level and the MHWS tidal plane in Western Port. The notable change in slope of the frequency histogram outside these two tidal planes suggest mangrove extents are strongly bound between these tidal ranges and associated inundation frequencies and depths. Some upward bias in the distribution of mangroves relative to the MHWS tidal plane at Stony Point is expected from this comparison as the tidal range increases towards the northern arm of Western Port where the significant percentage of the overall mangroves in Western Port exist.

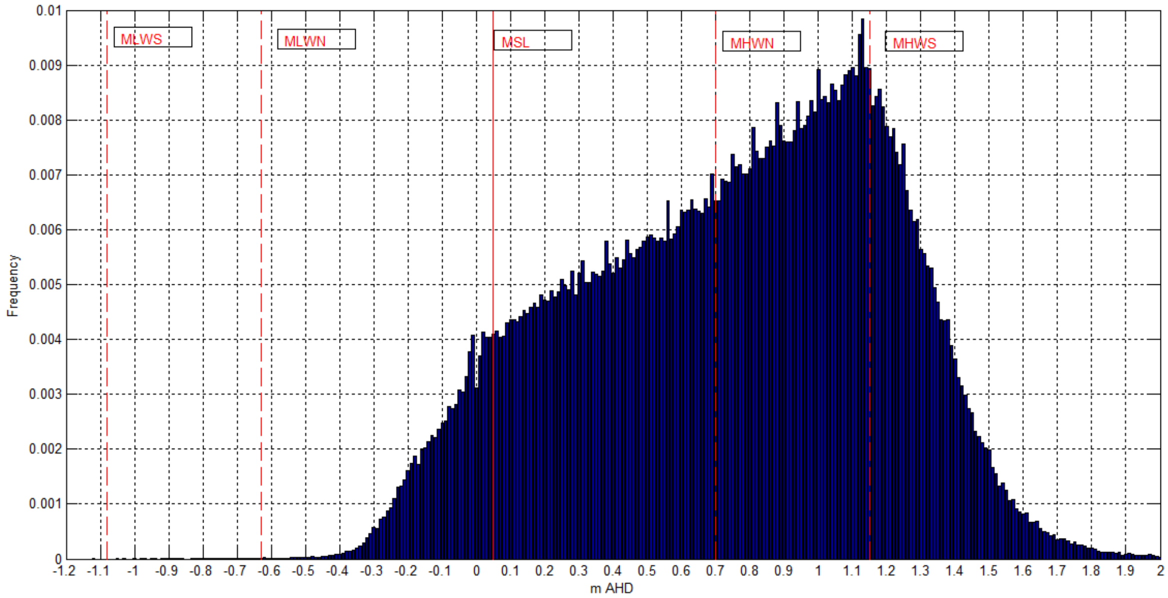


Figure 3-7 **Distribution of Mangrove Elevations Relative to Stony Point Tidal Plane Elevations**

Sedimentation

Significant differences of opinion exist within the literature and amongst contemporary researchers on the extent in which mangroves, and a lesser extent saltmarsh, facilitate sediment deposition and consolidation and therefore shoreline development/progradation, i.e. whether coastal wetland vegetation act as 'land-builders'.

The assumption that peripheral vegetation functions as land-builders is based on the following train of events:

i) the tidal waters that inundate coastal wetlands are commonly turbid;

ii) wetland vegetation reduces flow velocity and turbulence;

iii) those reductions allow suspended (inorganic) particles to settle out of the water column;

iv) sediments therefore accumulate as a result of the settling of these particles;

v) the slightly elevated mounds thus created around emergent plants facilitate further sediment deposition; and

vi) mangrove and saltmarsh plants therefore assist the sediment accretion and/or inhibit sediment erosion (Furukawa *et. al.,* 1997).

Mangroves are thought to be particularly important as land-builders, for two reasons. First, their position in the inter-tidal zone allows them to accumulate tidally-deposited sediments (*cf* saltmarshes, which are inundated far less frequently and thus cannot easily facilitate sediment deposition). Second, mangrove pneumatophores are believed to be especially important in trapping and retaining sediment (Bird 1971, 1980, 1986). In Western Port pneumatophores can attain densities of ~300 per m^2 (Bird 2008: see also Figure 3-8).

Figure 3-8 High Density of Pneumatophores Achieved by Mangroves in Western Port (Photo courtesy of Paul Boon)

Spenceley (1997) presented evidence that was counter to a number of these assumptions. He showed that although mangrove pneumatophores may promote sedimentation under low-energy conditions, under medium to high-energy conditions they caused the development of eddy currents, which initiated localized scour and erosion in the sediments. He concluded that when considered in isolation, *Avicennia* pneumatophores did not promote sediment deposition, and that other factors were required to explain the stabilization of sediments that occurs in mangrove swamps. The presence of fine rootlets in the upper layers of the sediment is probably a critical mechanism that makes mangrove sediments resistant to erosion. Bird & Barson (1982) similarly argued that the stabilising role of mangroves was limited to areas where the wave energy was low and that under higher-energy situations (e.g. after protective sand spits had been removed) mangroves were soon eroded away.

One of the reasons for confusion as to the roles played by mangroves in land-building is that it is often assumed the only geomorphological process involved in land-building is the settling onto the sediment surface of inorganic particles with incoming tides. In reality, the surface level of coastal sediments is controlled by two processes:

i) sediment trapping and/or loss; and
ii) the accumulation (or loss) of organic material built up by the roots and rhizomes of peripheral vegetation.

The latter process, often ignored or undervalued, is a result of the high rates of below-ground productivity of coastal plants, and can be due to accumulations either of dead plant remains (e.g. peat) or living plant roots and rhizomes. In turn, how the below-ground accumulation of dead organic matter behaves is controlled to a large degree by the degree of water-logging, and this is controlled by tidal inundation and by the behaviour of local ground waters as displayed conceptually in Figure 3-9.

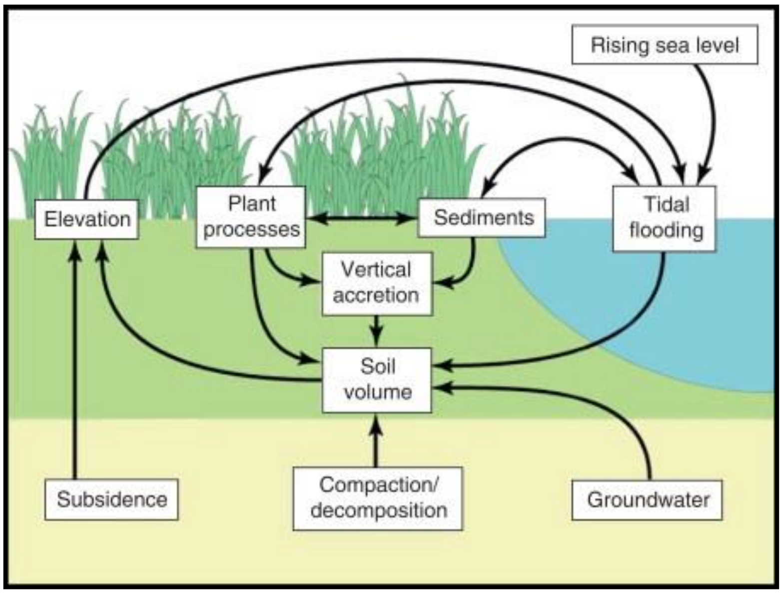


Figure 3-9 **Interactions Between Above and Below Ground Productivity, Sediment Deposition, Peat Accumulation, Tidal Inundation and Groundwater Behaviour in Controlling Sediment Elevations in Coastal Wetlands**

Source: Spencer & Möller (2013, Figure 13).

In summary, mangroves − and to a lesser extent other types of peripheral vegetation in less tidally inundated zones, such as coastal saltmarsh − can facilitate sediment deposition and stability in four ways:

- The fine mat of surface roots and deeper roots/rhizomes bind sediment and limits erosion.
- Emergent shoots and roots (e.g. pneumatophores in mangroves, shoots in rhizomatous taxa) decrease current velocities and encourage the deposition of fine particles, at least under low-energy conditions (but probably not under high-energy conditions).
- Plants add organic matter to sediments via below-ground productivity (i.e. roots, buried leaves etc), thus building up the sediment surface. If material is accumulated for long enough in a stable environment, peat deposits can form.

- Plant roots and rhizomes form a dense, sometimes impenetrable mat, which as well as protecting the sediment from physical erosion (dot point 1 above) deters burrowing invertebrates that would otherwise rework the sediments.

Given the operation of these four processes, under stable sea level conditions, mangroves should slowly increase sediment elevations in coastal wetlands. The simplest evidence for this process taking place is where individual mangrove trees occur on locally raised mounds (Figure 3-10), or where coastal areas vegetated with mangroves are steeper than nearby unvegetated areas (Woodroffe 1992).

Figure 3-10 Example of a Mangrove Tree on a Locally Raised 'Sediment Mound', Near Grantville, Western Port

Waves/Extreme Events

Mangroves and coastal saltmarsh are susceptible to excessive sedimentation and to erosion associated with waves and extreme events, and the effects can occur at both the establishment phase of young plants and on adult specimens. As a generalization, it is well known that young wetland plants are particularly susceptible to breakage by wind or by waves during their establishment. Wind and wave induced disturbance and toppling were identified as significant factors limiting the establishment of young mangrove plants along the eastern shore of Western Port by Kirkman & Boon (2012).

Despite their ability to build-up sediments and rapidly colonize areas that are actively sedimenting, *Avicennia marina* is susceptible to smothering by sediments and to erosion. There are examples of both processes at Western Port (Figure 3-11).

Figure 3-11 ***Increased sedimentation (by sand) and potential smothering of mangrove pneumatophores (left-hand photograph) and severe erosion (right-hand photograph) of mangroves near Grantville, Western Port (Photographs: Paul Boon, February 2010)***

3.2.3 Key Drivers and Rates of Change

Coastal wetlands are very dynamic environments that change and evolve in concert with a suite of external pressures, orchestrated by complex synecological relationships[3] and by random or stochastic events[4].

Rises in mean eustatic sea level, however, are not the only aspect of climate change that will affect coastal wetlands and other types of peripheral shoreline vegetation around Western Port. Sea-level rise is only one manifestation of climate change, and ecological impacts are likely to occur as a consequence of other physical and chemical components of the climate-change phenomenon, such as higher temperatures and altered atmospheric CO_2 concentrations. Moreover, impacts will probably occur as a result of societal responses to climate change, such as the creation of sea walls and other structures built to protect the hinterland (Burley *et. al.,* 2012*)*.

Inundation and Tidal Regime

A large number of studies, undertaken mostly on wetlands in the Northern Hemisphere, have concluded that changes in mean sea level will have drastic impacts on coastal wetlands (Day *et al.,* 2008; Gilman *et. al.* 2009, 2008; Woodroffe & Davies 2009).

In one of the first analyses of climate-change impacts on Victorian coastal vegetation, Vanderzee (1988) argued that the well-defined pattern of plants in Victorian saltmarshes reflected strongly the extent, timing and duration of inundation by seawater, and therefore that even small changes in tidal inundation would have large consequences for saltmarsh floristics and, probably, plant productivity. Vandezee's study was centred on changes in saltmarsh communities at Corner Inlet, and he argued that likely changes included the landward migration of plant species in response to tectonic submergence of the coastline. Such naturally occurring changes were proposed to be a good model for predicting possible impacts arising from climate-induced rises in sea levels. The

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[3] Synecological relationships are ecological interactions among suites of organisms.

[4] Stochastic events are non-deterministic, often random. Erfanzadeh *et al*. (2010) explains the critical role they play in coastal wetlands.

model developed to explain the response by vegetation to changes in sea levels is shown in Figure 3-12.

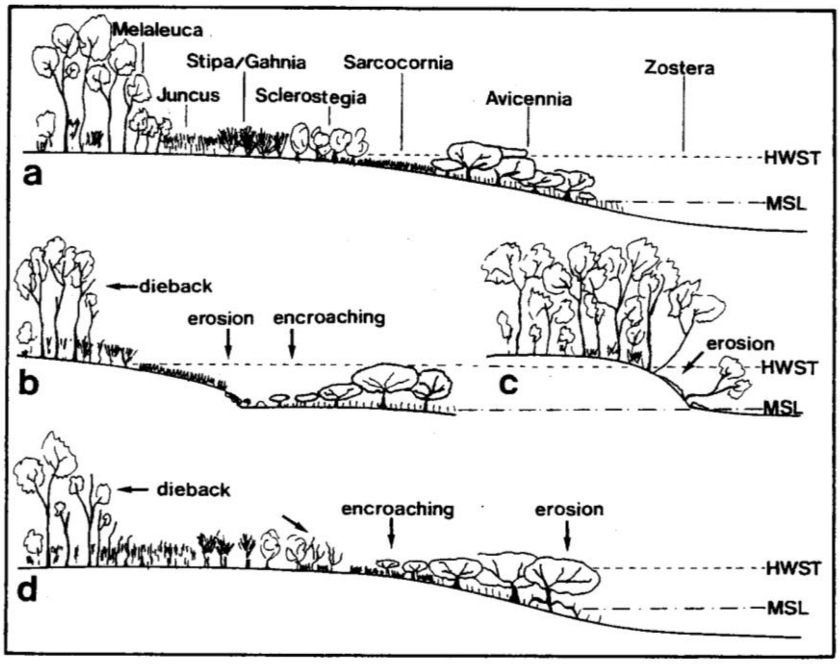


Figure 3-12 Impacts of Sea-Level Rise on Peripheral Vegetation in Corner Inlet as Explained by Vanderzee (1988).

Part a) shows an idealized sequence with species characteristic of each zone; b) Avicennia marina encroaching into saltmarsh; c) erosion of saltmarsh back to the Melaleuca ericifolia zone; and d) a typical sequence in response to sea-level rise. Source: Vanderzee (1988, Figure 2).

Rates of Sedimentation

Most of the early analyses (i.e. in the 1980s) of the likely impacts on rises in mean sea levels on coastal wetlands similarly concluded that there would be a large-scale loss of wetland habitat (Pratolongo *et. al.,* 2009). More recent studies have come to slightly different conclusions, as it has been recognized that that changes in the *relative* sea level will be the fundamental determinant of ecological and geomorphological responses by fringing vegetation. In other words, if coastal wetlands can maintain their elevation by accumulating sediment and by laying down peat, they can possibly keep up with – as opposed to catch up with – sea-level rise (Pratolongo *et. al.,* 2009; Rogers *et. al.,* 2012).

If changes in the level of the sediment surface can therefore meet or exceed average rates of sea-level rise, peripheral vegetation may possibly maintain itself in the face of this aspect of climate change (Morris *et. al.,* 2002). Limited data is however available on the rates of sediment elevation changes around Western Port in coastal wetlands.

The limited available data, summarized in Table 3-2, indicate that rates of sediment elevation around Western Port can be up to ~5 mm year^{-1}, in some saltmarsh environments but, conversely, can be −2 mm year^{-1} in some areas of mangrove.

Alternative estimates of sedimentation rates determined by 210 Pb activity over the last 100–150 years suggests rates of between (1.4 –2.5 mm per year) (Rogers *et al.* 2005). These latter rates would suggest coastal wetland surface elevations have approximately kept pace with observed rates of mean sea level rise over the last century.

Table 3-2 *Mean (± standard errors) rates of change in surface elevation at four sites around Western Port (2001-2003), Source: Rogers et al. (2006, Table 3)*

Site	Vegetation type	Change in surface elevation (mm year^{-1})
French Island	Mangrove	−2.13 ± 1.66
	Saltmarsh	5.27 ± 0.96
Kooweerup	Mangrove	−0.03 ± 2.23
	Saltmarsh	−0.16 ± 0.94
Quail Island	Mangrove	−2.60 ± 2.07
	Saltmarsh	−0.68 ± 1.18
Rhyll	Mangrove	0.92 ± 1.87
	Saltmarsh	0.64 ± 0.75

Alternative, indirect measures of potential changes in sediment elevation can be inferred from review of the pattern of changes in mangrove extents and size (ages) around Western Port. In some locations, small individuals are observed advancing in front of more mature mangrove stands. Whilst in other areas, the seaward margin of mangroves is abruptly defined by mature stands of mangroves, with smaller (younger) mangroves observed to be distributed landward of the main mangrove fringe amongst saltmarsh. The spatial variability observed in mangroves in Western Port suggests that the future responses of mangroves to sea level rise will not be uniform within Western Port. Research elsewhere in Australia, particularly in New South Wales and south-east Queensland, suggests that alternating wet and dry periods affect patterns of mangrove recruitment and expansion, but the precise relationship has yet to be identified.

In order for coastal wetlands to survive anticipated rises in mean sea levels this century, increases in surface elevation of between 2–8 mm year^{-1} and up to >10 mm year^{-1} by the end of the century will be required.

Figure 3-14 displays the projected rates of sea level rise this century compared with the previous century as well as the surface elevation deficit that would exist by the end of this century if coastal wetlands could only continue to increase their surface elevations at historical rates of approximately 1 and 2 mm/yr in Western Port. From Figure 3-14 it can be seen that substantial surface elevation deficits could be expected by the end of the century unless coastal wetlands can consistently increase their rates of sedimentation/surface elevation above those observed under historical sea level rise conditions in Western Port.

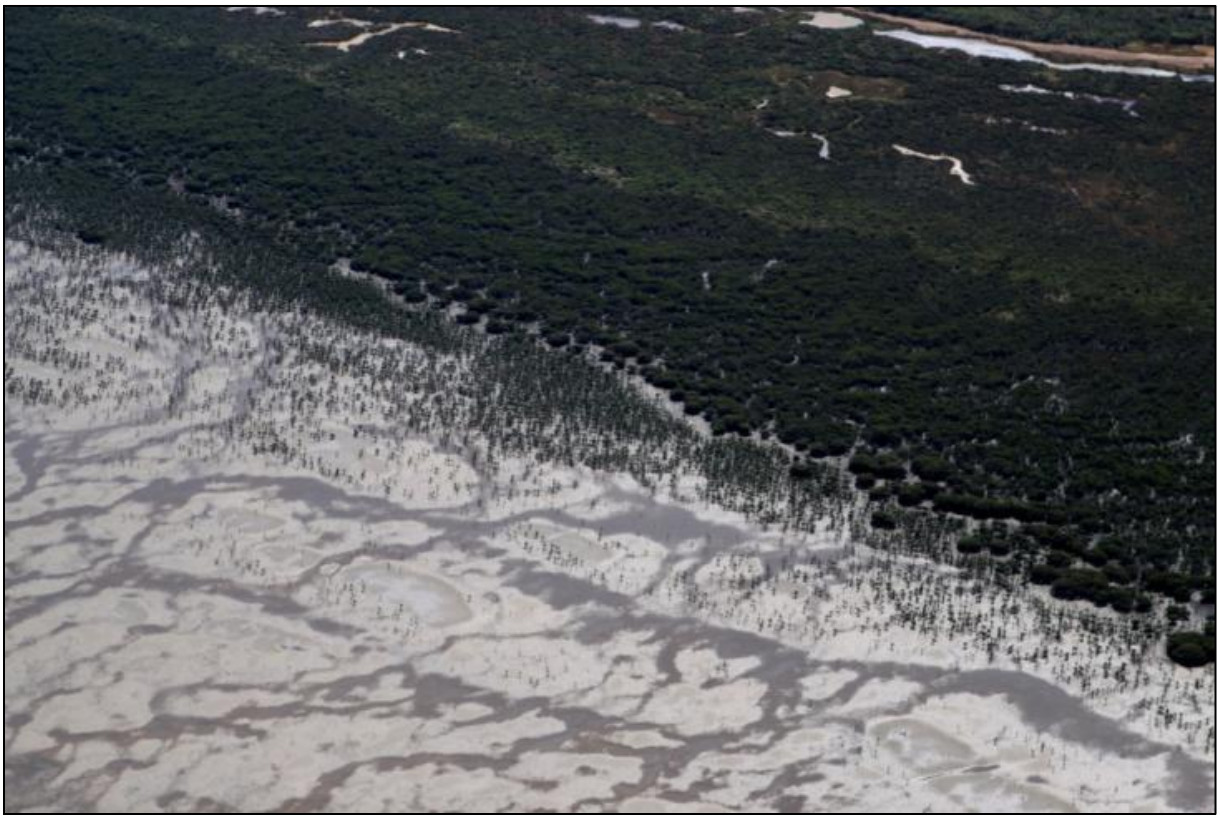


Figure 3-13 **Juvenile Mangroves Advancing Seaward in Front of Mature Mangrove Fringe East of Tooradin (Photo courtesy of Neville Rosengren)**

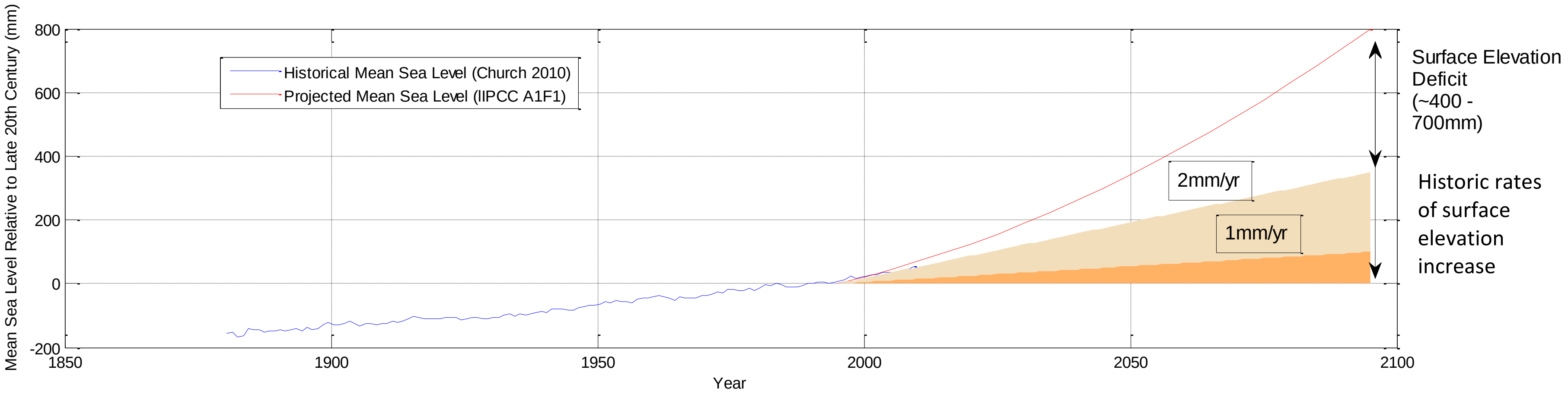
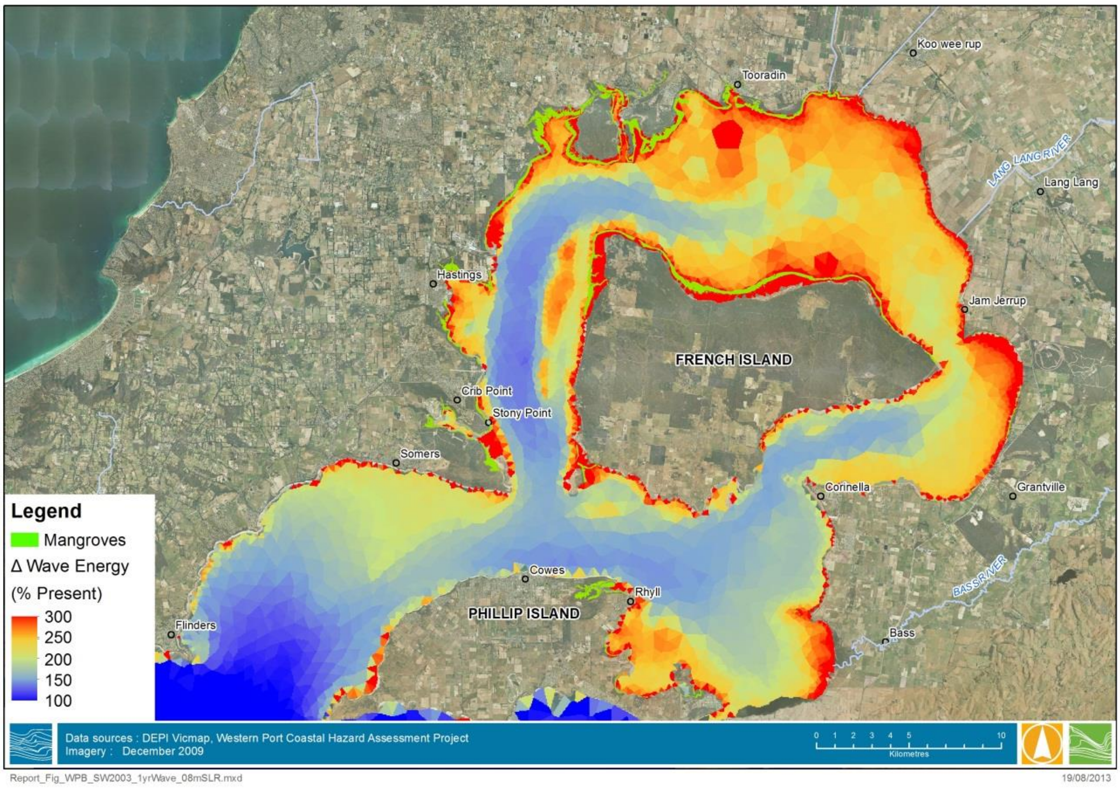


Figure 3-14 Projected Future Rates of Sea Level Rise Compared to Historical Rates of Surface Elevation Increase of Coastal Wetlands in Western Port

Waves

The amount of wave energy that coastal wetland fringed shorelines are exposed to could be expected to increase significantly with sea level rise in Western Port. Exposure to waves along these shorelines is currently limited by the duration of tidal inundation and water depths across the intertidal flats fronting the mangrove fringe. As sea level rises, both the duration of tidal inundation and water depths could be expected to increase, allowing waves to impact the outer fringe of mangroves for longer periods each tidal cycle and with larger heights (energy) due to the greater depths.

Figure 3-15 displays the predicted percentage change in annual average cumulative wave power in Western Port for the +0.8 m sea level rise scenario. Figure 3-15 also overlays the extent of the coastal wetland fringed shorelines in Western Port. From Figure 3-15 it can be seen that the percentage change in annual cumulative wave power along these shorelines under the +0.8 m sea level rise scenario is predicted to at least double and in many locations increase by a factor of as much as three times existing sea level conditions. The magnitude of the potential changes in annual cumulative wave power along the outer edge of mangrove fringe could be expected to significantly change the rates and patterns of sediment transport in these areas. Rapid erosion and/or accretion of sediments due to increased wave action along the mangroves fringe could be expected to destabilise the mangrove roots and pneumatophores and increase rates of smothering. In combination, these processes could be expected to lead to the loss of mature mangroves and limit the ability for future mangrove recruitment along the seaward fringe.



Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

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Figure 3-15 **Predicted Percentage Change in Annual Average Wave Energy for a +0.8 m SLR Scenario Relative to Coastal Wetland Fringed Shorelines**

Summary

Climate change is highly likely to have wide-ranging impacts on mangroves, saltmarsh and other types of peripheral water-dependent vegetation around Western Port, including:

- Higher temperatures will probably affect the phenology of almost all the area's biota, including the timing of flowering and germination of plants, and may facilitate the spread of mangroves into coastal saltmarsh as winters get warmer and the incidence and severity of frosts decreases.
- Predicted large changes in wave energy due to sea level rise along the seaward fringe of mangroves has the potential to mobilise sediments and may lead to varying patterns of erosion and accretion that are in aggregate likely to lead to a loss of mature mangroves and limit the potential for future mangrove recruitment on the seaward edge of the existing mangrove fringe.
- The primary impact of rises in relative sea levels on coastal wetlands and other types of peripheral vegetation is expected to be associated with the changes in inundation frequency and depths.

The relative changes in inundation frequency and depths in coastal wetlands may be somewhat less than the absolute change that would be attributed to eustatic sea level rise due to the response of coastal wetlands in increasing sediment elevation as sea levels rise. However, the limited (both limited in time to a few years, and spatially restricted to only a few sites) data for Western Port on changes in sediment elevation and the poor knowledge of potential future responses is such that a conservative assessment approach has been adopted; it is assumed that the sediment accretion by coastal wetlands (specifically mangroves) will be significantly less than the rates of sea level rise in the future and therefore the depth of inundation of the wetlands is equal to sea level rise.

The initial response of coastal wetlands to sea level rise, therefore, has been assessed as fundamentally associated with the landward migrations of mangroves into saltmarsh as displayed conceptually in Figure 3-16. This process effectively results in the saltmarsh zone being narrowed between an advancing front of mangroves and the already terrestrially vegetated elevated backshore region. Coastal erosion hazards are expected to be limited to the seaward edge of the mangroves as they are progressively drowned and increased wave action is able to mobilise sediments on the seaward edge of the depositional terrace.

Depending on the sea level rise scenario and the slope of the mangrove-saltmarsh depositional terrace, it is possible that the inundation regime, depths and wave energy may become progressively unsuitable for coastal wetland vegetation on these shorelines. At shorelines where future MHWS tidal planes extend completely across the depositional terrace and intersect backshore sandy landforms and/or bluffs, it is expected that erosion hazards may evolve along this interface due to the combination of the loss of coastal wetland vegetation, frequent tidal inundation and significantly increased wave action. This shoreline response under this scenario is displayed conceptually in Figure 3-17.

In order to assess the likely coastal wetland response to sea level rise and extent of associated coastal hazards around the Western Port shorelines for each sea level rise scenario, the modelled changes to the MHWS tidal plane extents, including sea level rise, have been intersected with the DTM around the coastal wetland fringed shorelines.

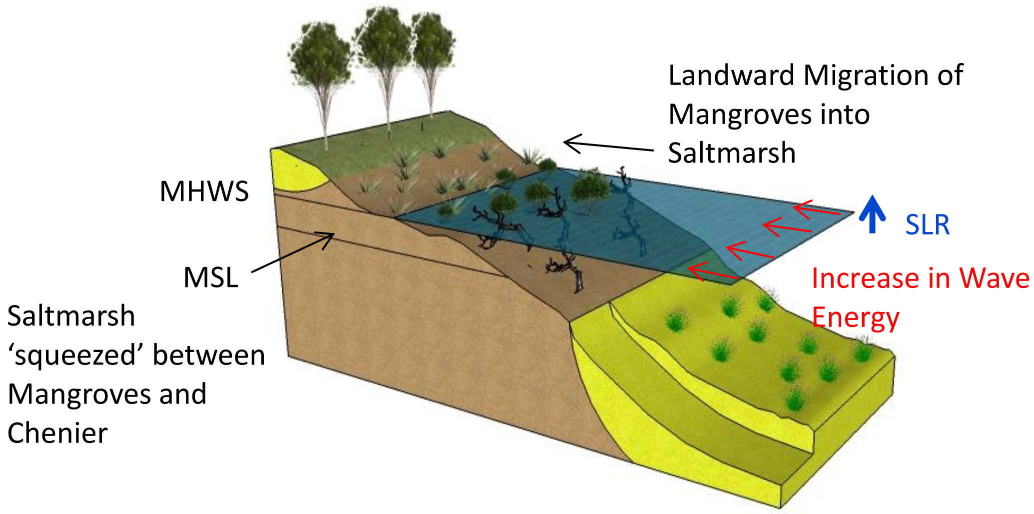


Figure 3-16 Intermediate Mangrove Retreat into Saltmarsh SLR Response

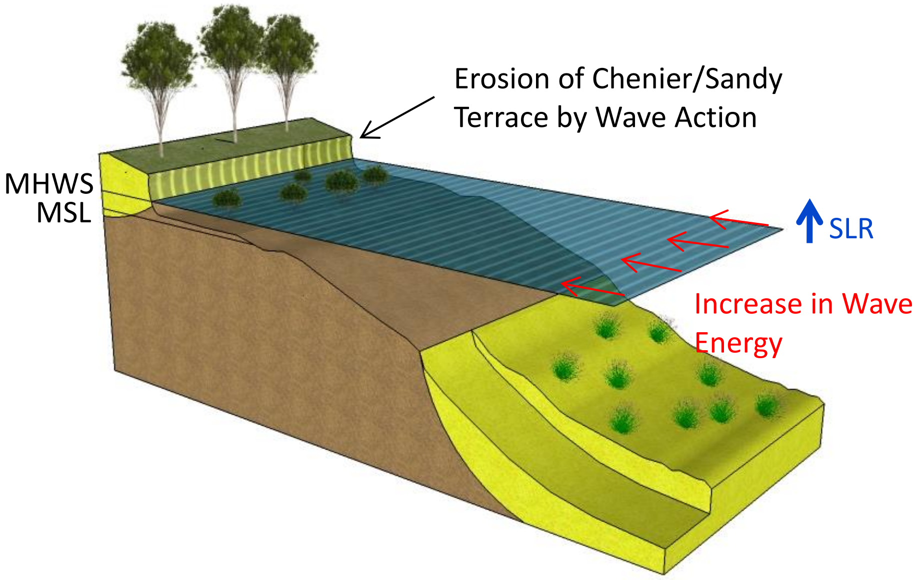


Figure 3-17 Back Shore Erosion Ultimate SLR Response

3.3 Low Earth Cliff Shorelines

3.3.1 Class Overview

This geomorphic shoreline class incorporates a relatively wide grouping of low, earth cliffed shorelines within Western Port. This class is differentiated from high cliff shorelines because the processes resulting in shoreline change are largely driven by marine processes and the backshore terrain is very low and vulnerable to coastal inundation. Low cliffed shorelines have been defined as those with cliff heights approximately less than or equal to two metres in Western Port.

A relatively consistent characteristic of this geomorphic shoreline class is that shorelines are generally undergoing active shoreline recession. Two significant sub classes, described below, are recognised within this overall class.

The most well-known subclass is the receding peat cliff shorelines at Lang Lang. Table 3-3 summarises the classification of the peat and mud shoreline sub class. Figure 3-18 displays an example of this shoreline sub class at Lang Lang.

Table 3-3 Peat and Mud Shoreline Sub Class

Examples	Backshore	Geology	Intertidal	Geomorphology
Lang Lang north to Yallock Creek	***BackProx***: Active Cliff	Peat and mud (Tobin Yallock Swamp)	Intermittent sand beach in embayments, no or minimal sand beach on headlands, firm mud shore platform	Simple to compound cliff profile with local overhangs. Low Elevation backshore plain , generally leveed
	BackDist: Plain			
	BackProf: ***S***teep slopes			

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

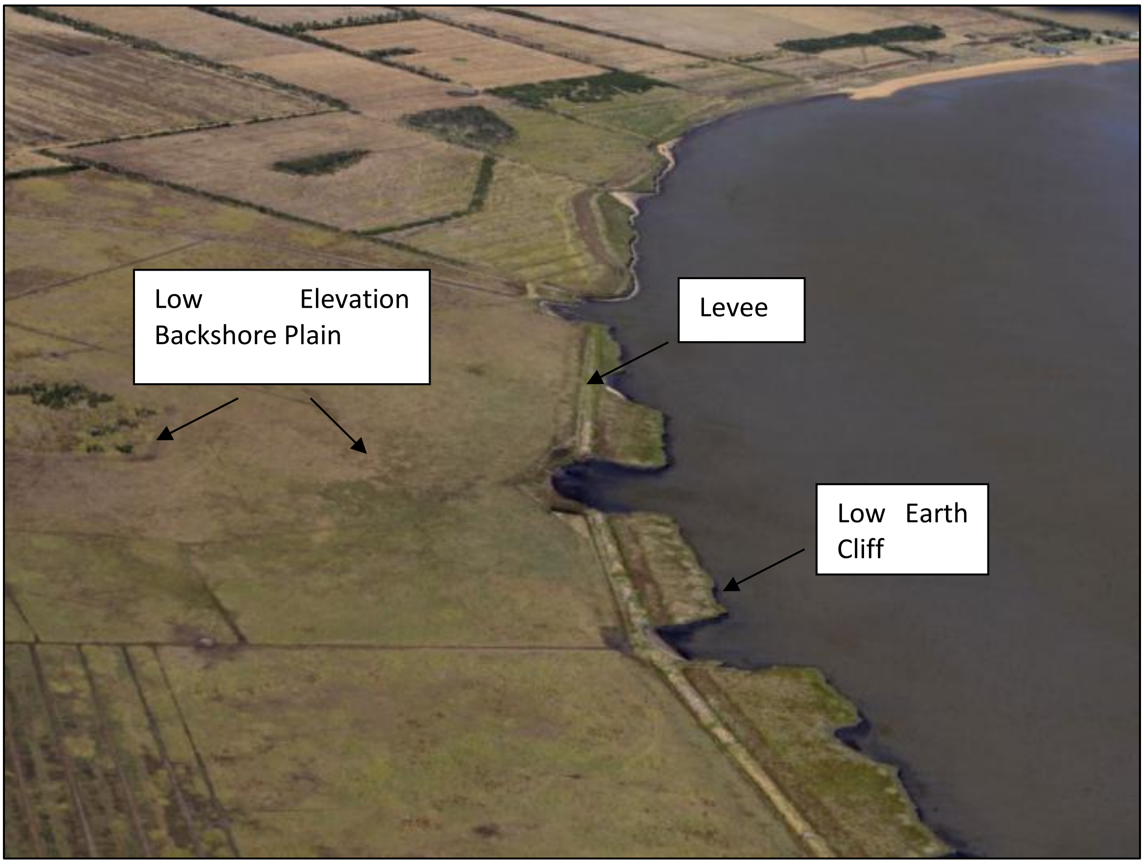


Figure 3-18 Peat Cliffed Shoreline at Lang Lang (photo: Neville Rosengren)

The second significant sub class of shorelines are a range of low cliffed shorelines cut into a variety of Quaternary sediments along the eastern shorelines of Western Port. Table 3-4 summarises the characteristics of this shoreline sub class. Figure 3-19 displays an example of this shoreline class north of Grantville. These shorelines are typically located within the Upper North Arm and Corinella segments of Western Port (refer Figure 2-16) where sediment movement within the intertidal areas is limited. Contributions of fine sediment to the these areas are provided from the inflowing rivers and drains but the volumes are insufficient to reduce the current rates of erosion and appear to be reducing due predominantly to changes in catchment management (Brizga et al, 2010).

Table 3-4 Mixed Quaternary Sedimentary Shoreline Sub Class

Examples	Backshore	Geology	Intertidal	Geomorphology
Grantville north	***BackProx***: Active Cliff ***BackDist:*** Plain ***BackProf:*** Steep slopes	Unconsolidated to weakly cemented grit, sand, mud and peat.	Minimal sand beach. Evidence of former mangrove fringe	Benched cliff profile with local overhangs. Shoreline often modified by shore protection works

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

Figure 3-19 Receding Low Earth Cliffed Shoreline at Grantville (photo Tim Womersley)

Figure 3-20 provides an overview of the delineation of the extent of the low, earth cliff shoreline class in Western Port.

Figure 3-20 Delineation of Low Earth Cliffed Shoreline Class in Western Port

3.3.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this shoreline class are displayed conceptually in Figure 3-21 and are discussed in more detail below:

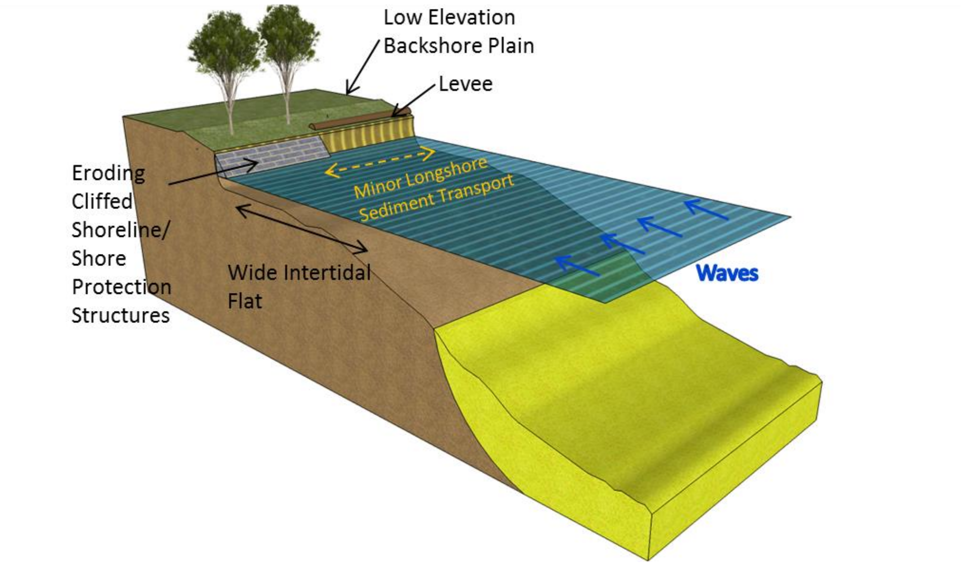


Figure 3-21 Low Earth Cliff Conceptual Shoreline Type

Geomorphic Components

The key geomorphic components of this shoreline class comprise the following:

- A wide intertidal flat of silty sand or peats and mud, mangroves are generally not present but where they persist coverage is sparse;
- An intermittent, narrow sandy beach or rounded peat pebbles may exist;
- A low, active cliff cut into Quaternary sediments of poorly consolidated and unconsolidated peat, mud, cemented sand and/or gravel. A range of formal and informal shoreline protection structures including rock revetments and seawalls are often present; and
- A low elevation backshore plain of former swampland, often leveed, or remanent Melaleuca woodland.

Waves

This geomorphic shoreline class generally occurs on the eastern shorelines of Western Port and are subject to wind-waves generated by prevailing westerly winds. The eastern shorelines are particularly susceptible to the relatively frequent combination of large storm surges and strong westerly winds which can amplify erosion.

In soft rock cliffs, the energy delivered to the cliff toe and face by breaking waves has been identified as a key driver of coastal recession. It has been suggested (e.g. Hackney et al, 2013; Trenhaile 2011) that undercutting of the cliff toe by wave action and subsequent mass failure is the mechanism by which most cliffs are eroded, regardless of lithology.

Sub-Aerial Processes

A range of sub-aerial processes contribute to erosion of the low active cliffs including groundwater pore pressure and seepage, shrink-swell detachment, and chemical interactions with the soil material which contribute to slope failure through block or slumping type movements.

Surface runoff and rain impact can affect the stability of the cliff face through mechanisms such as sheet flow across the surfaces or concentrated runoff which can deeply indent the cliff surface.

If the cliff undergoes repeated wetting by salt spray or surface runoff, interspersed with periods of drying the heating weathering of the cliff-material can occur. This makes the cliff more susceptible to erosion but weathering effects are normally overshadowed by wave erosion or slope failure.

Sediment Transport

In some locations within this geomorphic shoreline class, narrow, low beaches exist. These beaches may be located in front of the eroding cliff or may form low dunes where an actively eroding cliff is not present.

The sediments comprising these beaches are predominantly derived locally from the erosion of Quaternary sediments forming the low cliffs and locally, erosion of Baxter Formation sandstones. The beach sediments are relatively coarse, angular and poorly sorted. Limited volumes of sediment may be derived from catchment inflows from the adjacent rivers and drains (e.g. Harris et al, 1979).

A beach may provide protection to the underlying platform, where and when it is sufficiently thick relative to the waves passing over it.

3.3.3 Key Drivers and Rates of Change

The key drivers and potential rates of change on these shorelines due to sea level rise or underlying process variability is discussed below and displayed conceptually for this shoreline type in Figure 3-22.

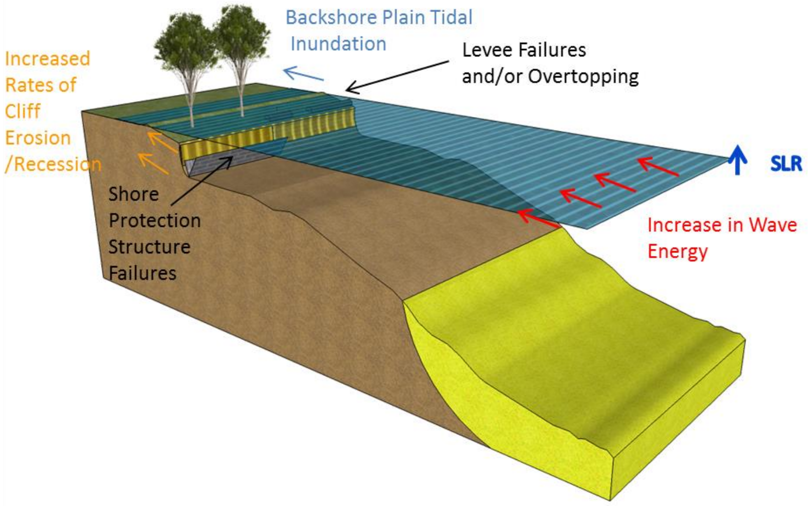


Figure 3-22 Low Earth Cliff Sea Level Rise Response

Current Rates of Shoreline Change

Recent detailed erosion monitoring of the peat cliffed receding shorelines at Lang Lang has yielded estimated rates of cliff recession of the order of 3 cm / month, although some parts of the cliffs have been observed to erode much faster at > 10 cm / month (CSIRO, 2013). These estimates provide annual erosion rates of 0.36 m - ~1.2 m on these shorelines and are relatively consistent with rates or recession inferred from comparisons of historical aerial photography (pers. comm. Neville Rosengren). The on-going investigations undertaken by the CSIRO confirm that the erosion is predominantly occurring through the physical processes of abrasion and detachment of sediment from the cliff face associated with wave action at Lang Lang.

Available historical aerial photography of low earth cliff shorelines at Grantville has been reviewed (Figure 3-23). The comparisons of the photography reveal a relatively dynamic shoreline. Coastal structures including rock revetments and storm water outlets have captured and/or altered longshore transport processes resulting in local shoreline changes over the photographic record. However, comparison of the vegetated shoreline extents delineated from the 1974 and 2010 photographs reveal an underlying recessionary shoreline trend of approximately 20-35 m from 1974 to 2010 over significant lengths of the shorelines in the vicinity of Grantville. This corresponds to an approximate average annual shoreline recession rates of between 0.5 and 1.0 m/year.

The review of available information and previous and current studies of shoreline erosion within this shoreline class in Western Port suggests that low earth cliffed shorelines in Western Port are generally receding at a rate of approximately 0.3 – 1.2 m/year. These annual average erosion rates have been adopted for consideration of potential rates of erosion including the impacts of sea level rise as discussed further in the following section.

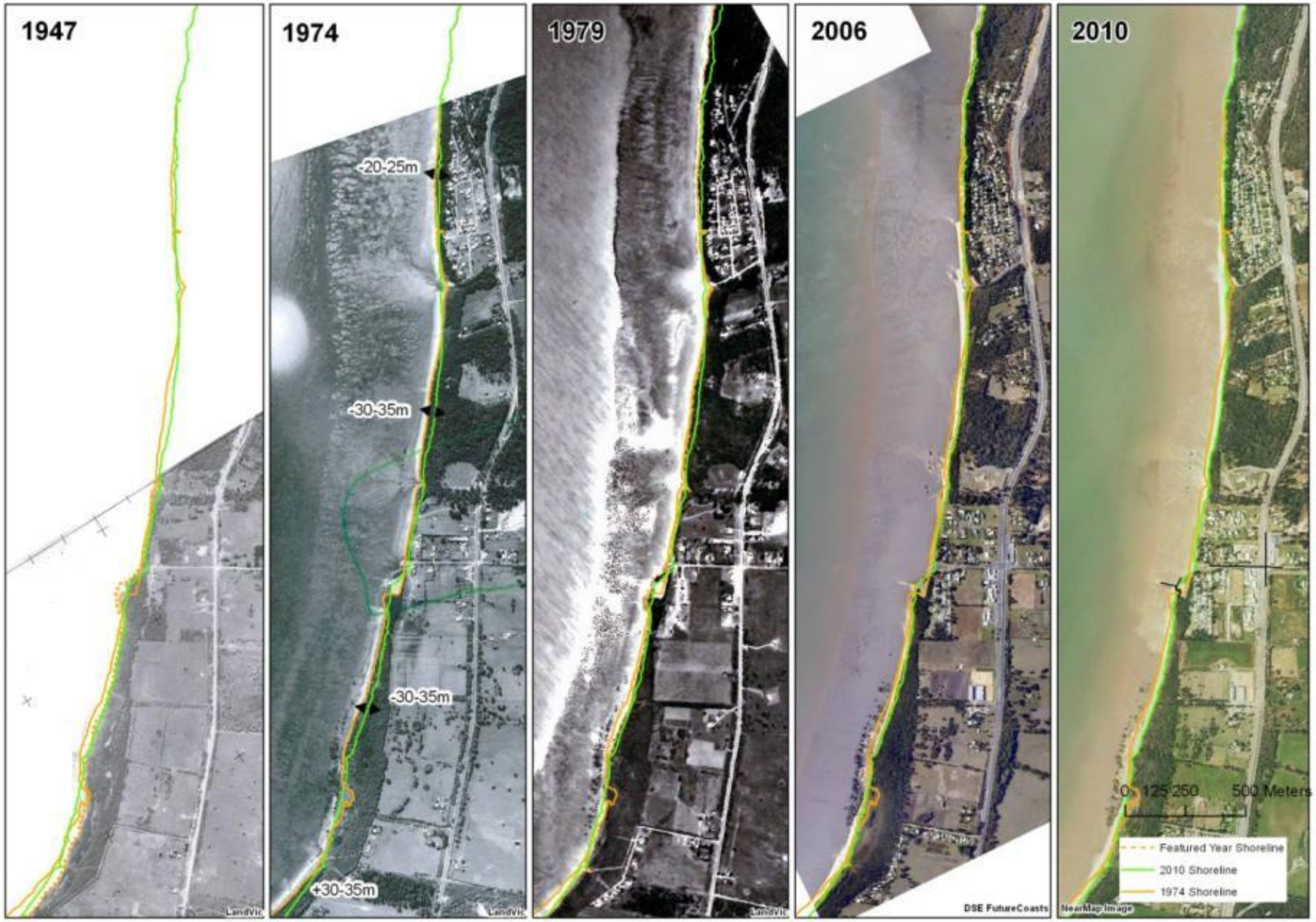


Figure 3-23 Comparison of Historical Shorelines in Low Earth Cliff Shorelines at Grantville

Future Rates of Shoreline Recession

Various authors have attempted to analyse and predict the response of soft and hard rock shorelines to sea level rise (e.g. Trenhaile, 2004, 2009; Ashton et al, 2011; Hackney et al 2013; Castedo, 2012; Walkden and Hall, 2005). There appears to be a general consensus that there will be faster soft rock cliff recession with rising sea level as a result of the increase in water depth, reduced rates of wave attenuation and breaker zones which move closer to the shore.

A simple predictive model of potential future rates of shoreline change on these shoreline types is to assume the rate of erosion is proportional to incident wave energy. Future rates of shoreline erosion can then be estimated by determining the percentage change in wave energy along these shorelines due to various sea level rise scenarios. This approach is supported by Trenhaile (2011) whose also suggests that there will be a consistent increase in the amount of cliff recession with rising sea level during the present century, relative to the amount that would be accomplished over the same period with stable sea level.

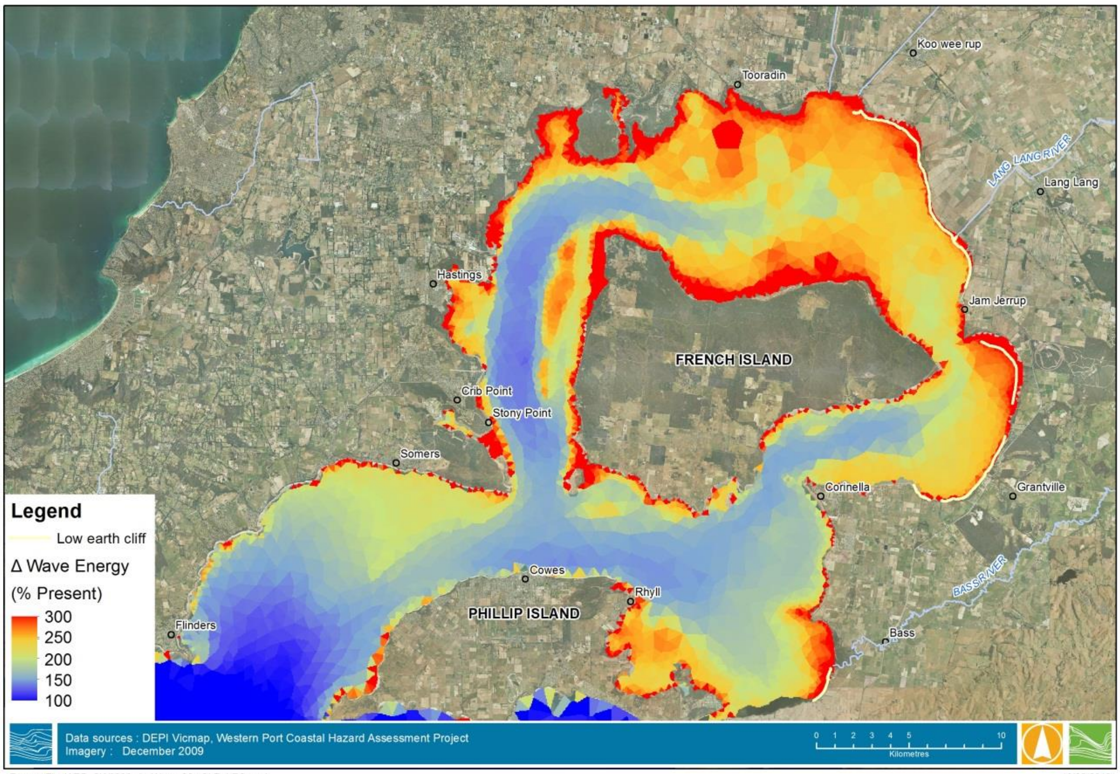
Figure 3-24 displays the predicted percentage change in annual average wave energy for the +0.8 m sea level rise scenario relative to the distribution of low earth cliffed shorelines in Western Port. From Figure 3-24 it can be seen that in general, this shoreline class is predicted to be exposed to significantly greater wave energy than occurs under present sea levels. The greater wave exposure is primarily associated with the greater duration of tidal inundation and greater depths that would occur along these shorelines.

Table 3-5 summarises the relative change in wave energy predicted by the spectral wave model for the different sea level rise scenarios as well as the subsequent estimate of the associated potential increase in average recession rates at two representative locations within this shoreline class. From Table 3-5 it can be seen that average recession rates are predicted to increase by a factor of almost three for the +0.8 m sea level rise scenario.

The average predicted recession rates for each sea level rise scenario have been linearly interpolated across the associated timeframes to provide a potential coastal hazard distance along this shoreline class.

It should be noted that the modelled change in wave energy on the shoreline does not take into account any increase in the below water level sediment elevations as a result of the shoreline erosion. There are no measured deposition rates offshore of these locations currently available and no obvious increases in elevation of the below high tide areas have been noted during site visits by members of the project team. As the material eroded from the low earth cliffs is fine grained (mud) the annual rate of deposition and subsequent accretion of the intertidal areas is likely to be very low over an annual to decadal time scale.

An additional factor that may impact erosion of these shorelines into the future was identified in the review of impacts on groundwater as a result of sea level rise (Report 4). The review found that increases in groundwater levels may alter shoreline erosional processes for cliffed shorelines around Western Port, increasing the rate of erosion. Insufficient information is available on either current or potential future groundwater conditions on these shorelines and therefore the potential impact of groundwater on erosion hazards has not been assessed further.



Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

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Figure 3-24 **Predicted Percentage Change in Annual Average Wave Power for +0.8 m SLR Scenario Relative to Low Earth Cliffed Shorelines**

Table 3-5 **Summary of Predicted Future Rates of Shoreline Recession on Low Earth Cliffed Shorelines**

Location		Sea Level Rise Scenario			
		Existing	+0.2 m (2040)	+0.5 m (2070)	+0.8 m (2100)
Lang Lang	Percentage Change in Annual Cumulative Wave Energy Relative to Existing Sea Level (%)	-	135	190	240
	Annual Shoreline Recession Rate (m/yr)	0.4-1.2	0.5-1.6	0.8-2.3	1.0-2.9
	Cumulative Recession (m)	-	13-39	32-98	59-176
Grantville	Percentage Change in Annual Cumulative Wave Energy Relative to Existing Sea Level (%)	-	140	200	270
	Annual Shoreline Recession Rate (m/yr)	0.5-1.0	0.7-1.4	1.0-2.0	1.2-2.7
	Cumulative Recession (m)	-	17-34	42-85	76-156

Backshore Plain Inundation

Future rates of shoreline change are expected to vary relatively linearly with sea level rise so long as the shoreline cliff and backshore terrace are of sufficient height to prevent frequent backshore inundation associated with tidal variations. However, at some locations within this geomorphic shoreline type, it is likely that for certain sea level rise scenarios, the relatively linear shoreline recession may transition to more dynamic and variable rate of change where sea level rise results in the potential for frequent, extensive backshore inundation along these shorelines.

Presently, extensive networks of raised embankments or levees associated with drainage works have been constructed adjacent to these shorelines. Whether originally intended or not, these ‘levees’ now prevent ingress of saline coastal water across the backshore plain during large storm tide events. These general informal structures could however be expected to become increasingly vulnerable to erosion associated with shoreline recession and overtopping due to sea level rise. Examples of the MHWS tidal planes including +0.8m of sea level rise relative to low lying backshore plains along these shorelines have been extracted from the digital terrain model and are displayed in Figure 3-26. This shows that extensive, fortnightly inundation of the backshore plains could be expected on these shorelines under sea level rise scenarios of approximately +0.8 m or greater, should the structures fail or be overtopped at low points.

Where sea level rise results in frequent, tidal backshore inundation, the persistent flood and ebb tide flows through failed levees and/or natural depressions in the backshore landscape could be expected to result in relatively rapid dissection of the shoreline as tidal channels develop and expand in response to the extent of backshore inundation generated by tidal water level variations along these shorelines.

The extent to which significant lengths of informal levee and bank systems and range of shoreline protection measures including groynes, informal seawalls and revetments are maintained and/or upgraded to mitigate future sea level conditions will significantly influence the extent of shoreline change and coastal hazard impacts along these shorelines.

Given the informal construction and management status of the majority of these levees, it is considered prudent to assess the extent of future coastal hazards assuming they will not be maintained or upgraded to a significant standard to mitigate future impacts associated with sea level rise.

The potential extent of the coastal hazard impacts along these shorelines have therefore been assessed as for each sea level rise scenario as potentially extending to the intersection of the MHWS tidal plane and the backshore topography.

Figure 3-25 Examples of the MHWS Tidal Planes Including 0.8m of Sea Level Rise Relative to Low Lying Backshore Plain.

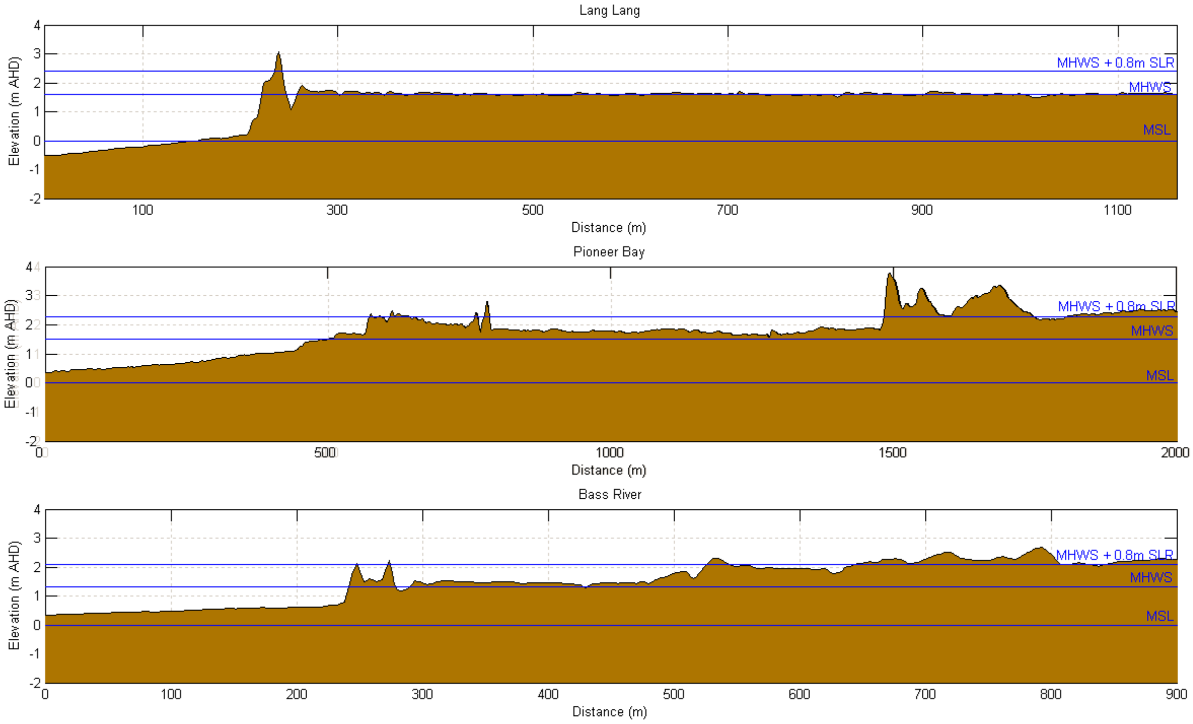


Figure 3-26 Topographic Cross-sections at Low Earth Cliffed Shorelines Relative to Key Tidal Planes incorporating the +0.8m Sea Level Rise Scenario

3.4 Hard Rock Cliff and Shore Platform Shorelines

3.4.1 Class Overview

Active, hard rock cliff and shore platform coasts occur relatively extensively within the Western Port study area.

Steep and high coastal slopes fringing Western Port are developed in rocks of Cainozoic age. The most extensive and highest and steepest slopes are in Palaeogene volcanic basalt and tuff with lesser areas of Mesozoic sedimentary and Baxter Formation sediments. The most resistant materials are thick units of horizontally layered basalt and locally strongly cemented Mesozoic arkose and ferruginous Baxter Formation sandstones. The profile form is related to the detailed stratigraphy and exposure to wave energy. Between Cape Schanck and Flinders multiple lava flows have developed as vertical slopes above a narrow shore platform (Figure 3-27).

Figure 3-27 Vertical Cliffs East of Cape Schanck (Photo N. Rosengren 8 June 2013).

This major shoreline class includes two sub-classes that are associated with variations in geology between Older Volcanic basalt and Mezsozoic mudstones. Table 3-8 summarises the characteristics of the Older Volcanic basalt shoreline sub class. Figure 3-28 displays an example of this shoreline class at Tortoise Head.

Table 3-6 Older Volcanic Basalt Shoreline Sub Class

Examples	Backshore	Geology	Intertidal	Geomorphology
Flinders, Shoreham, Corinella, Tortoise Head, San Remo	***BackProx***: Active Cliff and Slope ***BackDist:*** Plain ***BackProf:*** Moderate to steep slopes	Older volcanic basalt and tuff	Very narrow sand beach and/or gravel festoons and talus overlying wide rock shore platform	"Slope over wall" profile. Deeply weathered and/or poorly consolidated regolith. Basal cliff where hard rock exposed

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

Figure 3-28 **Example of Older Volcanic Shoreline Sub Class, Tortoise Head (French Island)**

Table 3-8 summarises the characteristics of the Mesozoic mudstone shoreline sub class. Figure 3-29 displays an example of this shoreline sub class at Red Bluff on French Island.

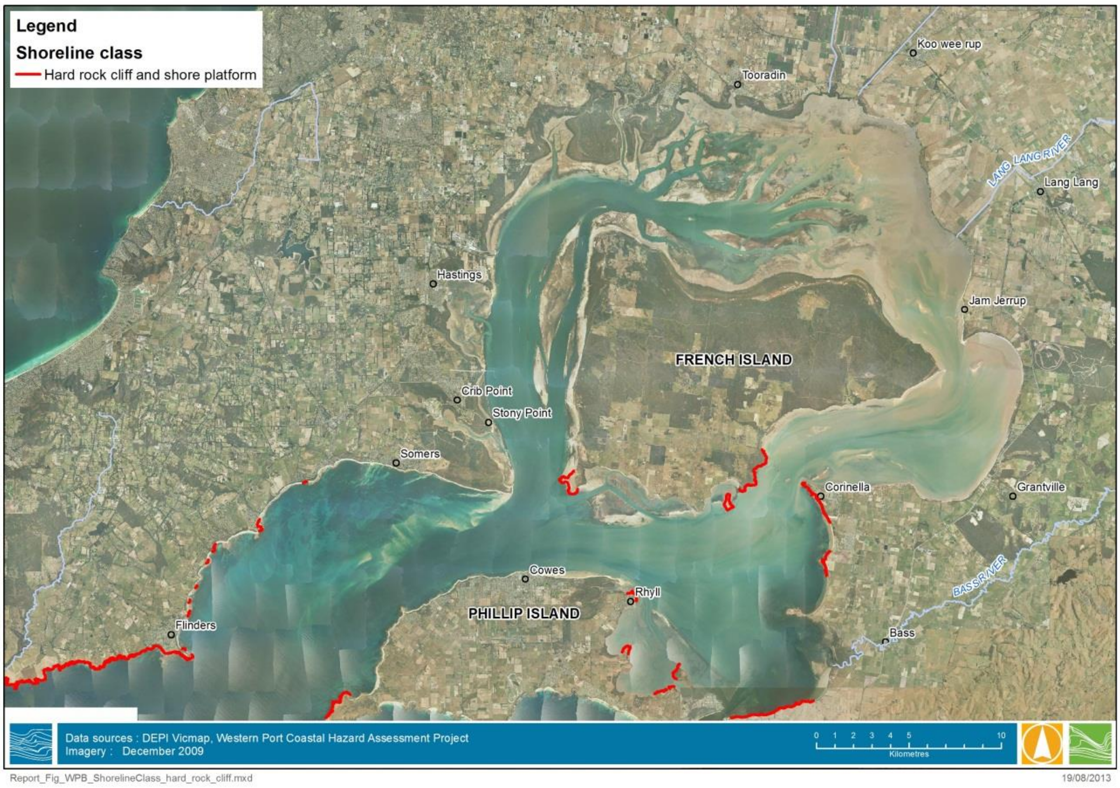
Table 3-7 **Mesozoic Sedimentary Shoreline Sub Class**

Examples	Backshore	Geology	Intertidal	Geomorphology
Red Bluff (French Island)	***BackProx***: Active Cliff ***BackDist:*** Plain ***BackProf:*** Steep slopes	Mesozoic sedimentary	Minimal sand beach overlying rock shore platform	Steep slope of exposed regolith and partly weathered Mesozoic rocks. Narrow shore platform with variable sand cover. Narrow intermittent beach at cliff base.

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

Figure 3-29 Example of Mesozoic Sedimentary Shoreline Sub Class, Red Bluff on French Island

Figure 3-30 provides an overview of the delineation of the extent of the hard rock cliff and shore platform shoreline class in Western Port.



Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

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Figure 3-30 Delineation of Hard Rock Cliff and Shore Platform Shoreline Class in Western Port

3.4.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this geomorphic shoreline class are displayed conceptually in Figure 3-54 and are discussed in more detail below:

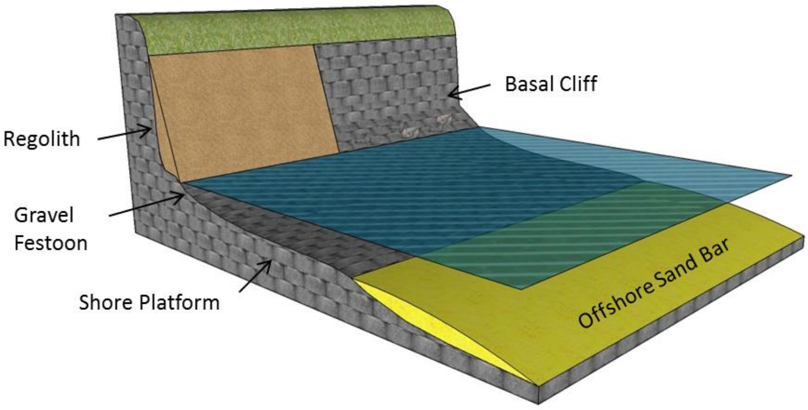


Figure 3-31 Hard Rock Cliff and Shore Platform Conceptual Shoreline Type

Geomorphic Components

The key physical components of this geomorphic shoreline type comprise the following:

- A shore platform of variable width and generally well defined outer edge that is exposed at low spring tides
- Very narrow sand/ gravel or boulder beach and/or gravel festoons and talus are occasionally present at the base of the cliff
- A steep slope of exposed regolith and/or partly vegetated surface on weathered hard rock.
- Basal cliff where hard rock is exposed.

Key Processes

The rate of slope retreat and profile re-shaping is determined by the accumulation and rate of removal of slope-foot debris by wave action. Other primary structures including lava tubes also influence the rate of lower slope retreat.

Where the upper flows are tuffaceous and/or deeply weathered, the profile is “slope over wall” with a concave upper form above steep mid-to lower slopes (Figure 3-32). The upper slope is often shaped by deep-seated mass movements including rotational sliding and bulk detachment while the lower slopes are shaped by joint orientation and spacing in the lava beds.

In lower energy environments, such as inside Western Port, similar geology produces a more subdued profile as wave action is less effective in removing the cliff-base debris (Figure 3-33). In lower wave energy environments mass movements may extend as colluvium festoons and talus onto the shore platforms or end abruptly as small vertical cliffed sections where wave action has eroded the material away.

Figure 3-32 Mass Movement on the Upper Slopes has Developed a Concave Profile above a Steep to Vertical Lower Slope (Photo N. Rosengren 8 June 2013).

Figure 3-33 Simpler Coastal Slope on Similar Geology as Figure 3-32 in a Lower Wave Energy Environment, Phillip Island (Photo N. Rosengren 8 June 2013).

3.4.3 Key Drivers and Rates of Change

The key drivers and potential rates of change on these shorelines due to sea level rise or underlying process variability are discussed below and displayed conceptually for this shoreline type in Figure 3-34.

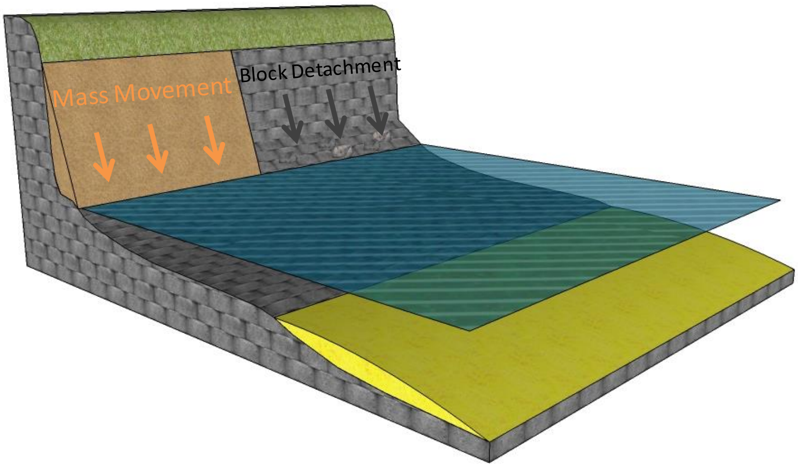


Figure 3-34 Hard Rock, Cliff and Shore Platform Sea Level Rise Response Mechanism

Cliff recession processes are caused by a combination of the internal structure, joints, fractures and faults of the rocks, rates of sub-aerial weathering and associated mass movements including slumping, cliff falls and landslides and the rates of basal erosion and the removal of collapsed material from the cliff base by the hydraulic action of waves.

The rates of change on these shorelines are generally highly episodic and may be associated with extremes of wet and dry climatic conditions and phases of strong wave attack and elevated coastal water levels. The rates of change are also highly variable laterally and vertically based on the resistance and other properties of the rock formations.

Mass movements are the most significant process for assessment of the potential extent of hazards along these shorelines. Mass movements or slope failures can occur due to variety of mechanisms including rotational and translation slips, soil creep, and rock slides. Detailed, site specific knowledge of the geology, geomorphology, hydrogeology and the soil and rock mechanics is required to assess the site specific soil and rock slope stability and potential failure mechanisms on these shorelines.

Increases in mean sea level will increase both the duration over which the cliff base is exposed to wave action as well enable larger waves to impact these cliff bases due to the greater depths available across the shore platforms. The increase in wave energy is likely to both increase the rates of hydraulic weathering and abrasion processes on the basal cliff sections and the rates at which slumped material can be removed from the regolith steeped sloped cliff sections.

The extent of the hazards associated with mass movements is however not expected to be significantly influenced by sea level rise over the time frames considered in this assessment for this shoreline class. Sea level rise could however be expected to increase the likelihood/frequency of mass movements in these shoreline types.

A small number of significant mass movement/slope failures have been documented within this shoreline class in Western Port (Bird E. C., 1993). These include major slope failures in weathered basalts at San Remo and Tortoise Head on French Island.

The slope failure at San Remo occurred in 1985 along a slippage plane formed by percolated water adjacent to a cliff of deeply weather basalts (Geological Socitey of Australia, 1996). The slope failure resulted in the destruction of several houses. The festoon of colluvium from this slope failure has been armoured at the shoreline and can be clearly seen in Figure 3-35.

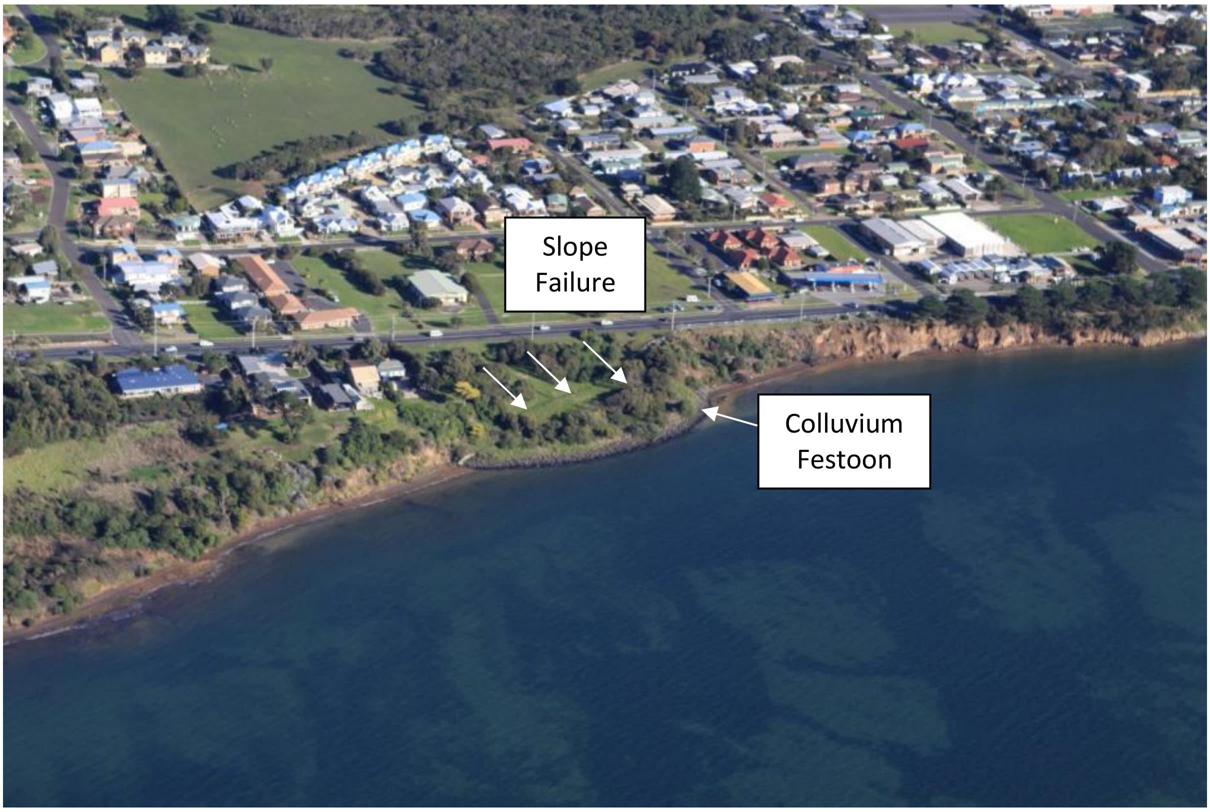


Figure 3-35 Historical Slope Failure at San Remo (photo: Neville Rosengren)

Cross sections through the San Remo slope failure and prehistoric slope failure at Tortoise Head on French Island have been extracted from the LiDAR survey. Comparison cross sections have been extracted in cliffed shorelines immediately adjacent to the slope failures. These cross sections are displayed for both locations in Figure 3-36. The following observations can be drawn as to the significance of the mass movements on potential hazard extents along these shorelines:

- The extent of influence of the slope failures can extend landward to a distance of approximately 3 – 5 times the height of the cliff; and
- Slope failures/mass movements can result in the shoreline prograding seaward due to the transport of colluvium and development of gravel festoons at the base of the slumped sections.

Another major mass movement in the deeply weathered upper slopes of high basalt cliffs east of Bush Rangers Bay on the high wave energy Bass Strait coast can be observed (Figure 3-31). A cross section of the ‘slope over wall’ cliff profile at this location has been extracted from the LiDAR survey and is displayed in Figure 3-37. As the lower slope is hard basalt at this location, the slope failure does not extend the full height of the cliffed profile. This effectively results in a relatively smaller ratio (~2H) between the landward extent of the slope failure and height of the cliff profile at this location. It should however be noted that the absolute landward distance over which the slope failure hazard has extended at this location is still relatively large and in the order of 70-80m landward of the lower slope.

The absolute extent of the slope failures identified in the hard rock cliff and shore platform shorelines in the study area highlight the potential susceptibility of this shoreline class to major hazard impacts associated with mass movement/slope failure processes. The observed variability in the type and extent of the slope failure hazards due to local variations in the weathering profile or other contributing factors and processes that can be observed in the study area also emphasises the difficulty in defining an appropriate hazard extent at a study area scale for this assessment. Of particular importance however when considering an appropriate hazard extent for this hazard process is the fact the mass movements/slope failures can occur with little to no warning and therefore require a conservative approach to be adopted.

Based on extensive prior experience in the study area, supplemented with aerial photography and LiDAR survey interpretation as well as low-level aerial inspection of the hard rock cliff and shore platform shorelines, the following hazard extents and variations in the study area have been adopted for the mapping assessment:

Western Port Shorelines

- In general the extent of slope failures in the hard rock cliff and shore platform shorelines is considered greater within Western Port as the lower wave energy environment is less efficient at removing regolith and weathered material from the slopes such that slope failures can occur through the entire profile.
  The hazard extent has therefore been considered to extend landward from the base of the cliff by a factor of 5 times the height of the cliff along these shorelines in Western Port. This results in a final failure slope of approximately 11^0 along these shorelines.

Bass Strait Shorelines

- In general, the high energy wave environment has removed unconsolidated material from the lower slopes of these shorelines exposing a basal cliff. Slope failures are therefore more likely to be limited to the weathered upper slopes.
  The hazard extent has therefore been considered to extend landward from the base of the cliff by a factor of 3 times the height of the cliff along the Bass Strait shorelines. This results in a final failure slope of approximately 18^0 along these shorelines.

The extent of the hazards resulting from slope failures on this shoreline class is not expected to change significantly over the timeframes and rates of sea level rise projected this century, and therefore, the hazard extents remain constant over the sea level rise scenarios.

An additional factor that may impact erosion of these shorelines into the future was identified in the review of impacts on groundwater as a result of sea level rise (Report 4). The review found that increases in groundwater levels may alter shoreline erosional processes for cliffed shorelines around Western Port, increasing the rate of erosion. Insufficient information is available on either current or potential future groundwater conditions on these shorelines and therefore the potential impact of groundwater on erosion hazards has not been assessed further.

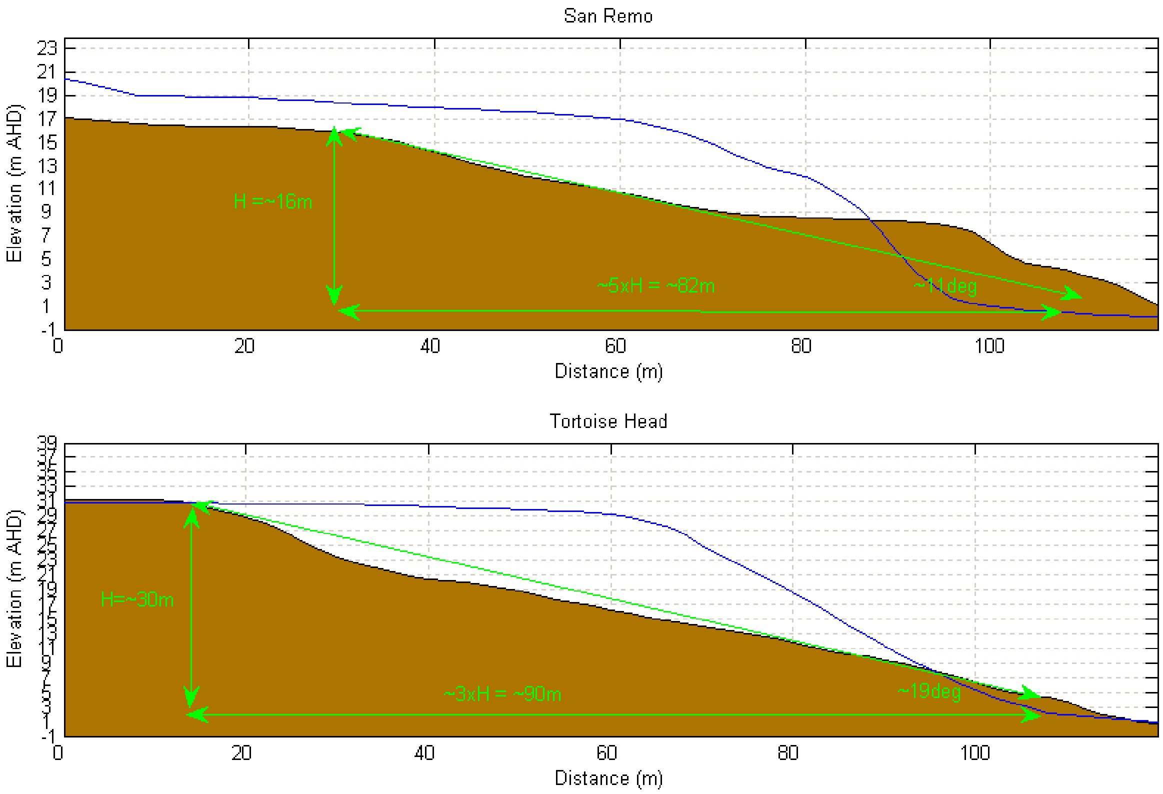


Figure 3-36 **Analysis of Slope Failure in Low Wave Energy Western Port Shorelines**

The green lines show the slope failure geometry and the blue lines show the neighbouring section of cliff where a slope failure has not occurred.

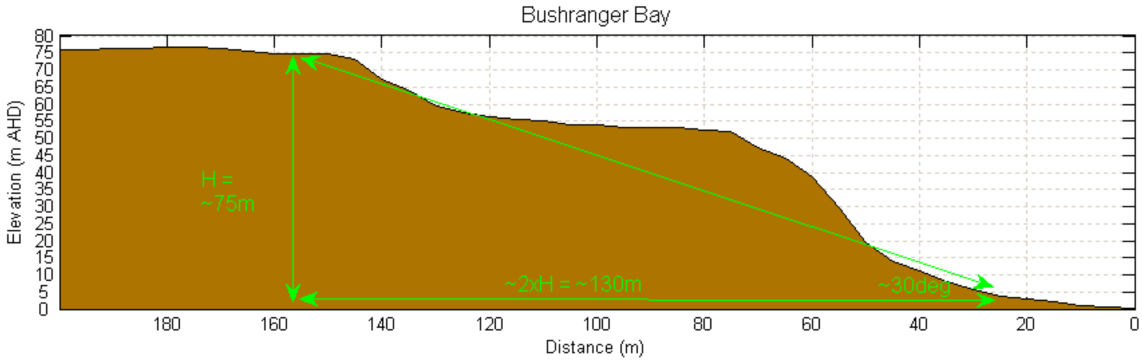


Figure 3-37 **Analysis of Slope Failure in High Wave Energy Bass Strait Shorelines**

3.5 Platform Beach and Bluff

3.5.1 Overview

This broad shoreline type occurs extensively along the western shorelines of Western Port and Phillip Island. These shorelines abut the major geologic formations that define the planform of the Western Port sunkland.

During previous interglacial high sea level still stands and as recently as the mid-Holocene high level still stand (~7,000 years before present), many of these shorelines existed as active marine cliff and shore platform shoreline types.

Following the 1 - 1.5 m fall in sea level following the mid-Holocene high sea level still stand in combination with the onshore flux of sediments from the floor of Bass Strait into Western Port, sandy platform beach and plain shorelines gradually emerged in front of the active marine cliffs.

The platform beaches protected the cliffs from the influence of direct marine driven processes and the cliffs have subsequently been sub aerially weathered and colonised by vegetation to form marginal bluffs that are now located some distance shoreward of a sandy platform beach shoreline.

These sandy shorelines however differ significantly from geologically unconstrained sandy shorelines in that the sediment volumes are limited in depth and seaward extent by the underlying shore platforms.

Theses shorelines also generally show a high degree of spatial heterogeneity and complexity associated with the underlying geologic structure and controls. The width of the sandy platform beach and plain can vary significantly laterally and the platform beaches frequently give way to headlands comprising active marine cliffs and shore platforms.

Table 3-8 summarises the characteristics of this shoreline class. Figure 3-38 displays an example of this shoreline class at Flinders.

Table 3-8 Platform Beach and Bluff Shoreline Sub-Class

Examples	Backshore	Geology	Intertidal	Geomorphology
Flinders, Shoreham	***BackProx*** Stable Bluff	Older volcanic basalt and tuff	Variable width beach of mixed sand and gravel overlying wide rock shore platform	Deeply weathered regolith with soil and vegetation cover. Variable width accumulations – sand and gravel beach ridges and locally with low established foredunes. Bluffs are remnant of higher Holocene and Last Interglacial sea-level. Now have wide fringing beach plain and are isolated from waves.
	BackDist Plain			
	BackProf Moderate to steep slopes			

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

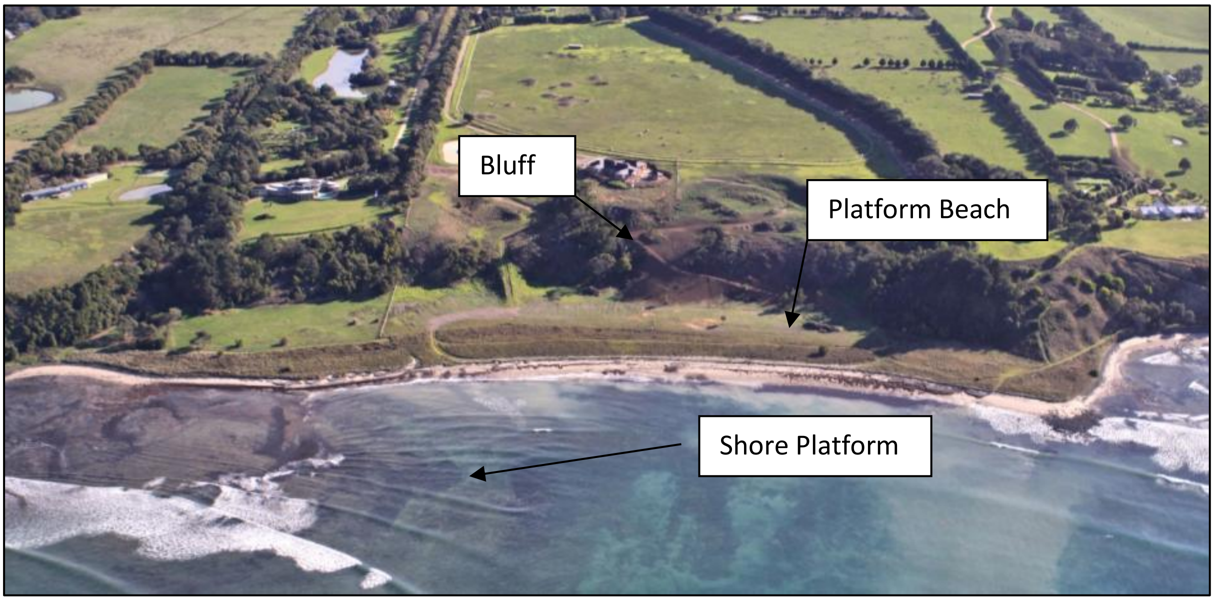


Figure 3-38 **Example of a Platform Beach and Bluff Shoreline, Flinders (Photo: Neville Rosengren)**

Figure 3-39 provides an overview of the delineation of the extent of the platform beach and bluff shoreline class in Western Port. Sand inputs to these shorelines are derived predominantly from the Western Entrance segment (refer Figure 2-16) as the channel sediment, offshore banks and coastal deposits are almost entirely sand.

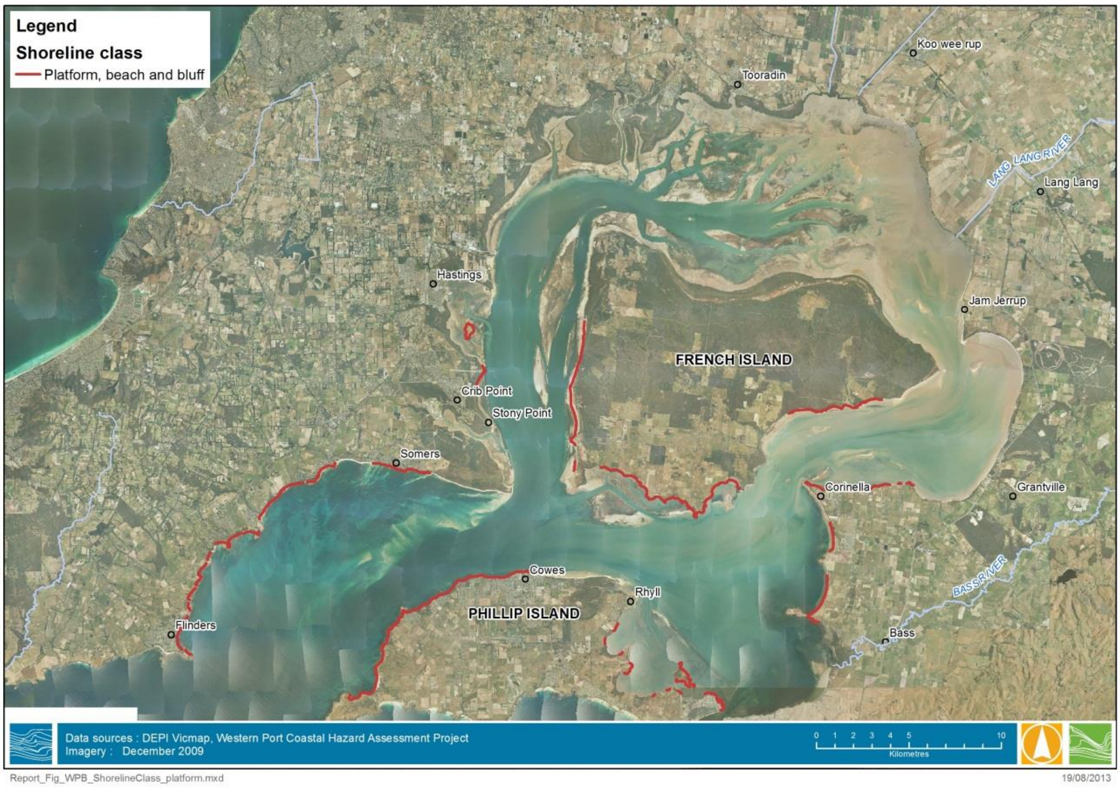


Figure 3-39 **Delineation of Platform Beach and Bluff Shoreline Class in Western Port**

3.5.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this geomorphic shoreline class are displayed conceptually in Figure 3-40 and are discussed in more detail below:

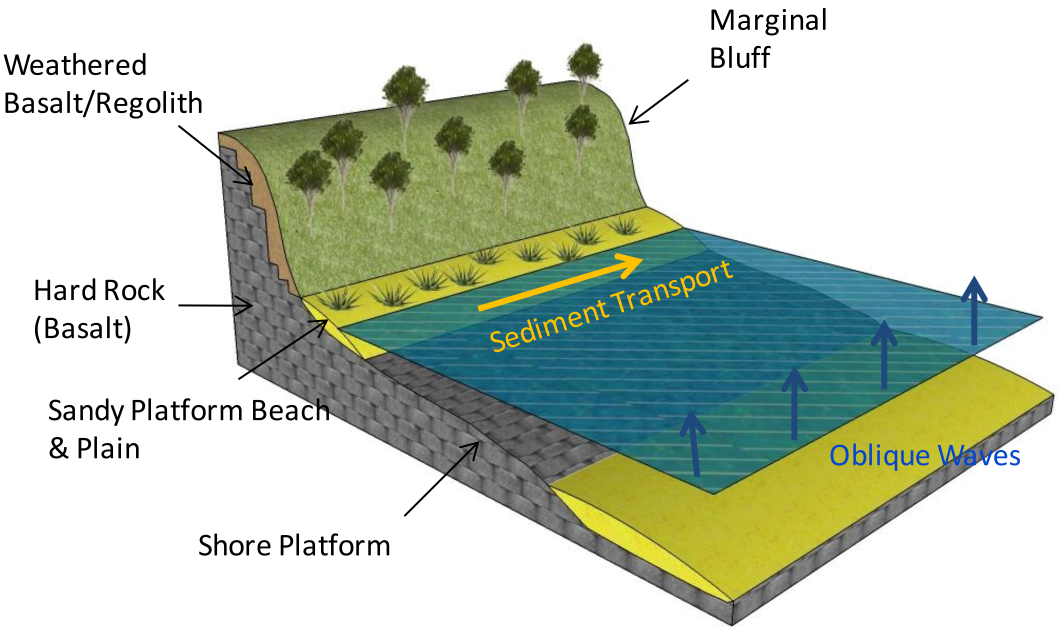


Figure 3-40 Platform-Beach and Bluff Conceptual Shoreline Type

Geomorphic Components

The key physical components of this shoreline type comprise the following:

- a shore platform that is exposed at various stages of the tide and significantly modifies the incident wave energy to the shoreline;
- a sand/gravel platform beach and plain of finite volume that lies discontinuously over the shore platform and extends to the base of a marginal bluff; and
- a marginal bluff, generally vegetated with a weathered slope of regolith

Shore Platform

Shore platforms comprise the upper surfaces of resistant rock formations that are generally associated with an active marine cliff of the same geology. They are shaped by a variety of processes including but not limited to the hydraulic action of waves and generally display a high degree of spatial heterogeneity due to variations in rock resistance and underlying structure.

Waves

These shoreline types are generally exposed to ocean swell energy that refracts into the western arm of Western Port and can be observed at times on the shorelines through to Somers on the western shores of Western Port and Cowes on the western shores of Phillip Island.

The waves arrive obliquely along these shorelines and transport sediment along these shorelines further into Western Port.

The amount of wave energy available to transport sediment along theses shorelines is strongly controlled by the width, slope and elevation of the shore platforms fronting the sandy platform beaches.

Sediment Transport

The sediments comprising the sandy terraces on these shorelines is generally comprised of fine quartose sands that has been transported into Western Port, off the floor of Bass Strait (Marsden, Mallet and Donaldson, 1979; Harris et al, 1979). Low refracted swell waves are slowly working these sediments northwards along the western shorelines of Western Port to Sandy Point and from Seal Rock to Observatory Point along the western shorelines of Phillip Island. The weathering of the Older Volcanic basalt cliffs does not generate significant quantities of beach material to these shorelines. However, rounded pebbles of basalt and/or core stones are often observed locally on these shorelines and can form an armouring layer.

Marginal Bluff

The marginal bluff marks the location of a previously active marine cliff, the majority of which were active during the mid-Holocene high sea level still stand. The bluffs of this shoreline type are principally comprised of Older Volcanic Basalts in Western Port. Sub aerial weathering and vegetation growth has resulted in a regolith of weathered basalt and clays that overlies harder basalt.

3.5.3 Key Drivers and Rates of Change

A critical control on both the rate and potential landward extent of shoreline change on these shorelines is expected to be related to the width and subsequent volume of the sandy platform beach and plain that exists between the existing sandy shoreline and the toe of the marginal bluffs. Where the plain is wide, recession of the sandy shorelines may proceed relatively linearly with sea level rise. However, where the sandy plain is narrow such that sea level rise results in marine influences impacting the toe of the bluffs, then the reflection of wave energy from the bluffs is likely to dramatically increase the rates of potential sand transport in front of the bluff. This scenario is analogous to the frequently observed impact to beaches following the construction of seawalls, where the reflection of wave energy from the seawall results in rapid sediment transport and lowering of the beaches in front of the seawall.

A rapid, non-linear loss of the sandy platform beach fronting the bluffs along these geomorphic shoreline types is possible where sea level rise results in significant reflection of wave action from the base of the bluffs. Once the sandy shorelines are removed from the toe of the bluff, marine processes could be expected to begin to erode the material comprising the bluff.

The width, slope and elevation of the shore platforms seaward of the sandy platform beach shorelines also provides a critical control on the processes and rates of change that may be observed on these shorelines. The slope of the shore platform controls both the potential and location along the platform in which sandy sediment can accumulate (Trenhaile, 2004). The shore platform also significantly attenuates the amount of wave energy that can impact the sandy shorelines as they are generally exposed at low tides and provide a focus for wave breaking at higher tides.

Increases in mean sea level will increase both the duration over which the platform beach shorelines are exposed to wave action as well enable larger waves to impact these shorelines due to the greater depths available across the shore platforms. The increase in wave energy may potentially both modify the equilibrium beach slope and increase the rates of longshore sediment transport.

The potential shoreline response and coastal hazard impacts for this conceptual shoreline type is therefore considered to comprise two potential sea level rise response mechanisms that would be expected to evolve in series depending largely on the existing width of the sandy platform beach and plain in front of the bluffs along these shorelines.

The two sea level rise response mechanisms and potential rates of change are discussed below:

Sandy Platform Beach Shoreline Recession

Figure 3-41 displays an overview of the key geomorphic processes and drivers of change associated with sea level rise that are expected on this shoreline type whilst the width of the sandy platform beach and plain prevents marine influences from significantly impacting with the marginal bluff. Figure 3-41 displays the following key processes:

- Increases in mean sea level could be expected to result in the landward translation of the sandy shorelines to a new equilibrium position that varies as a function of the underlying shore platform gradient.
- Sea level rise will increase the amount of wave energy that impacts the sandy terrace shorelines due to greater durations and depths of inundation across the shore platform.
- The increase in wave energy could be expected to modify the equilibrium beach slope and increase the rates of longshore sediment transport and the rates of offshore sediment transport.

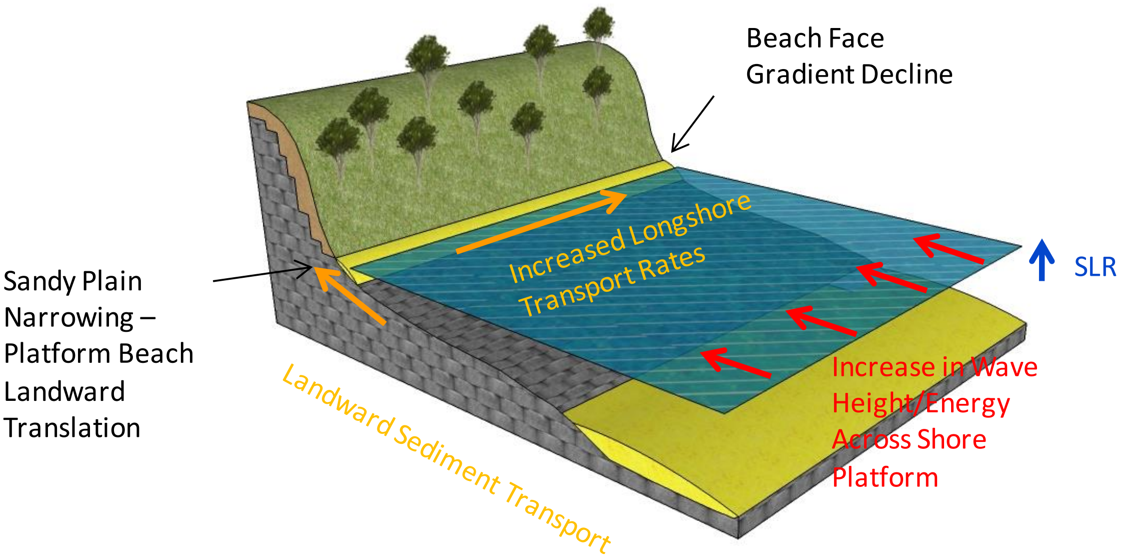


Figure 3-41 Platform Beach Shoreline Sea Level Rise Response Mechanism

The rate at which the platform beaches may translate landward due to sea level rise is highly uncertain. The uncertainty stems largely from the high degree of variability in the underlying geology of the shore platforms along these shorelines. However, by analysing slopes at different shore locations and at locations where slope failures or changes have occurred in the past provides a means for estimating the potential magnitude of shoreline change that could be expected due to sea level rise.

The relative slope of the shore platform compared to the equilibrium beach slope imparts a significant control on the accumulation and volume of sandy sediments on these shorelines. As shore platform gradients increase sandy beach volumes decline. Beach gradients also decline with increasing breaker wave height and period and decrease in sediment grain size. Where the slope of the platform is greater than the equilibrium beach slope, sandy sediments cannot accumulate and the shore platform terminates as an active marine cliff (Trenhaile, 2004).

To provide broad estimates of shore platform and beach slopes for Western Port, a number of representative cross sections have been extracted from the LiDAR survey to enable estimates of average shore platform and beach slopes and variability to be established for this geomorphic shoreline type.

Cross sections were extracted from representative locations at Flinders and Shoreham (Figure 3-42) and on Phillip Island at Ventnor (Figure 3-43). From these cross sections the average shore platform and beach slope have been estimated and are displayed on these figures.

The profiles show that shore platform slopes are generally observed between 0.1^0 and 1.0^0. As a general observation, shore platforms on the western shorelines of the Mornington Peninsula appear wider and flatter than shore platforms observed on Phillip Island, despite the same underlying geology.

Beachface slopes of 3^0 are generally observed but can be as steep as 5^0.

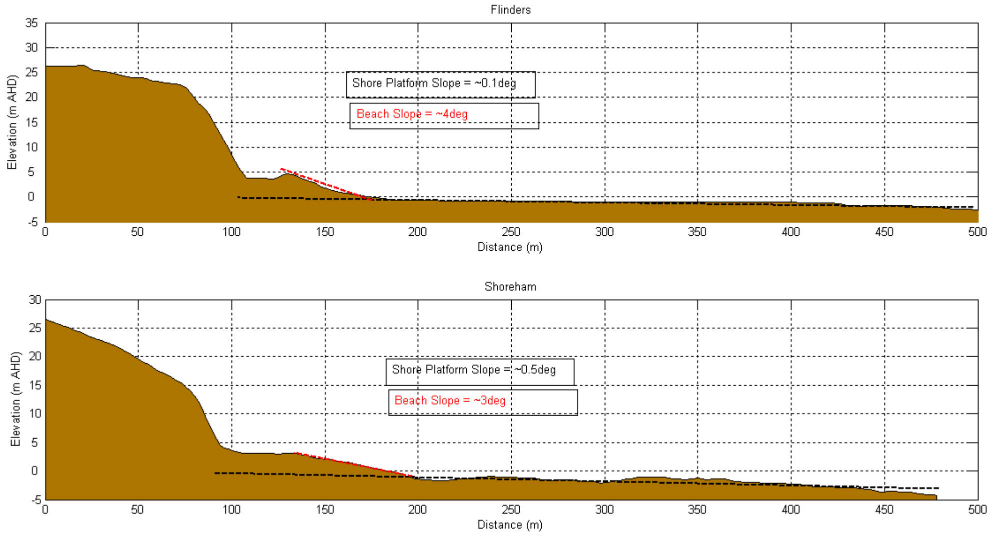


Figure 3-42 Shore Platform and Beach Slopes (Flinders and Shoreham)

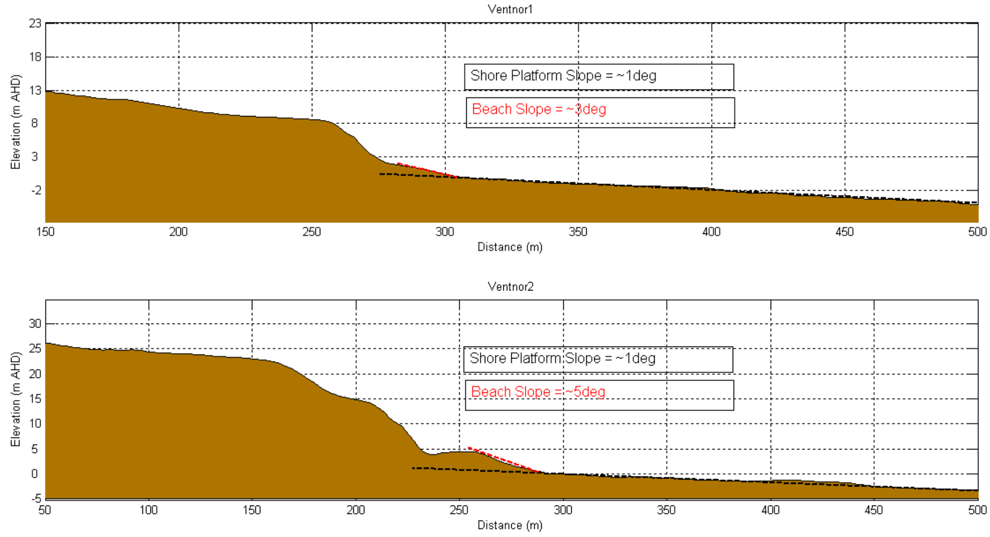


Figure 3-43 Shore Platform and Beach Slopes (Phillip Island – Ventnor)

Considering the fundamental geometric features of these shorelines and the assumption that beaches develop along these shorelines because sediment is transported landwards by asymmetrical wave-generated currents (Trenhaile, 2004), a basic geometric model can be developed and used to estimate the potential landward translation of the sandy platform beach due to sea level rise.

Figure 3-44 displays the fundamental geometric features conceptually for a shore platform slope of 1^0 and beach face slope of 3^0. Equilibrium translation of the platform beach due to +0.8 m increased in mean sea level rise results in the position of the beach face translating laterally along the shore platform by approximately 46 m.

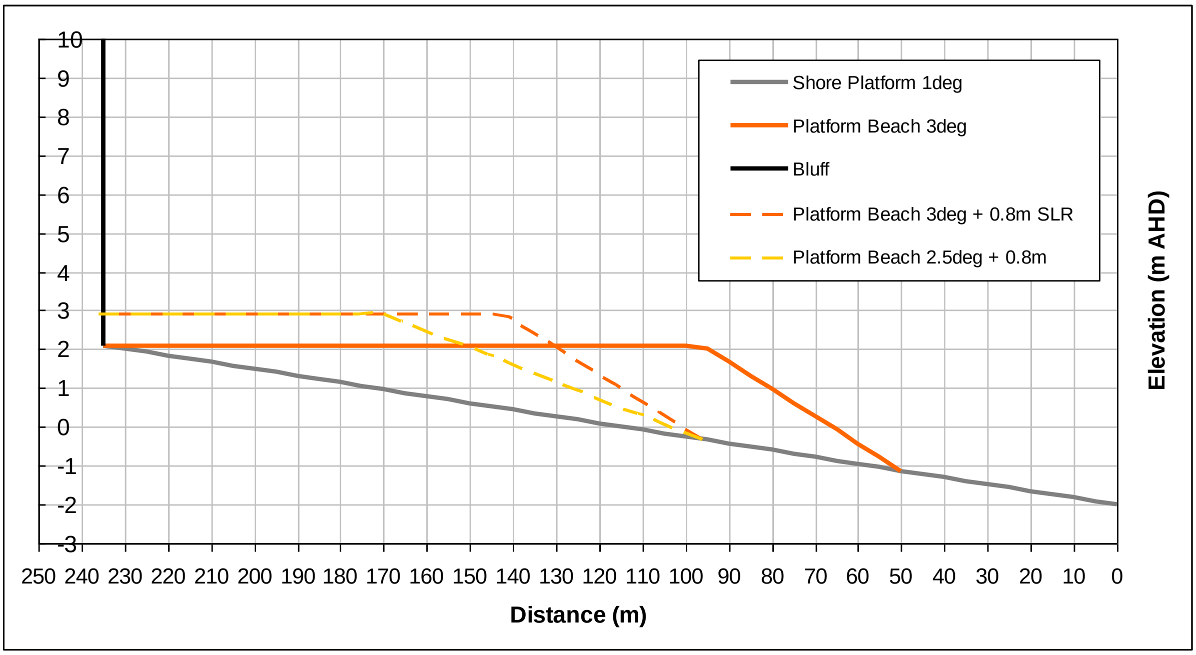


Figure 3-44 **Influence of Beach Face Slope on Potential Shoreline Recession Profiles**

Beachface slopes have been shown to vary as a function of wave height, wave steepness and grain size (Sunamura, 1989). As depths across the shore platforms increase due to sea level rise, the height of waves that can impact the sandy shorelines will increase. This could be expected to reduce the beachface slopes along these shorelines. The empirical expression for beach face slopes developed by (Sunamura, 1989) provides a means for assessing the potential sensitivity of beachface slopes to sea level rise on shore platforms in Western Port:

$$\tan \propto = \frac{0.12}{(H_b/(g^{0.5}D^{0.5}T))^{\quad 0.5}}$$

Where:

H_b = Breaking Wave Height

g = Gravitational Acceleration

D = Sediment Grain Size

T = Wave Period

Sunamura's expression results in a 25 % increase in breaking wave height predicting a 10% decrease in beach face slope. For the typical beachface slopes observed in Western Port, this results in a potential reduction in beach face slopes of approximately 0.3^0. Taking a conservative estimate of a maximum reduction in beach face slope of 0.5^0 (2.5^0 beach face gradient) due to increases in breaking wave heights on these shorelines, Figure 3-44 displays an additional shoreline recession of

30 m could be expected. This sensitivity test potentially highlights how sensitive platform beach shoreline positions are to wave heights (wave energy).

Table 3-9 summarises the recession estimates for shore platform slopes of 1^0 and 0.5^0 and for each sea level rise scenario.

Table 3-9 Summary of Predicted Future Rates of Platform Beach Recession

Shore Platform Slope (degree)	Sea Level Rise Scenario		
	0.2m	0.5m	0.8m
1	10m	30m	45m
0.5	25m	60m	90m

Marginal Bluff Re-Activation

Depending on the sea level rise scenario and the initial width of the sandy plain, it is considered likely that at some point, the linear, landward translation of the platform beach shorelines will transition to a different shoreline response mechanism. The transition will occur when marine influences associated with storm tides and wave action being to interact with the material comprising the toe of the marginal bluff. At this point, the dissipation of wave energy afforded by the platform beaches will cease and the reflection of wave energy from the toe of the marginal bluff would be expected to rapidly lower the remains of the platform beach in front of the marginal bluff.

The lowering of the sandy shoreline and erosion of the material comprising the toe of the marginal bluff would then be expected to reactivate the marginal bluff as a marine cliff. Cliff erosion processes, including mass movements would then dominate further shoreline response to sea level rise along these shorelines.

The risk of significant mass movements of material comprising the marginal bluffs due to reactivation by marine processes at their base is a possible consequence of the transition to this shoreline response mechanism. Sub-aerial weathering of the bluffs could be expected to have formed regoliths of weathered basalt and basaltic clays that may be vulnerable to mass movements once the material at the base of the bluff is removed or destablised due to wave action.

Figure 3-45 Platform Beach and Bluff Susceptible to Reactivation due to Sea Level Rise, Flinders/Shoreham (Photo N. Rosengren 8 June 2013).

Figure 3-46 displays the key geomorphic processes and drivers of change once sea level rise results in marine processes interacting with the toe of the marginal bluff.

Due to the potential for significant mass movements/slope failures to develop on the bluffs of these shorelines due to sea level rise, the same potential slope stability hazard extent of 5 times the height of the bluff/cliff with Western Port has been adopted for this shoreline class as was adopted for the hard rock cliff and shore platform class.

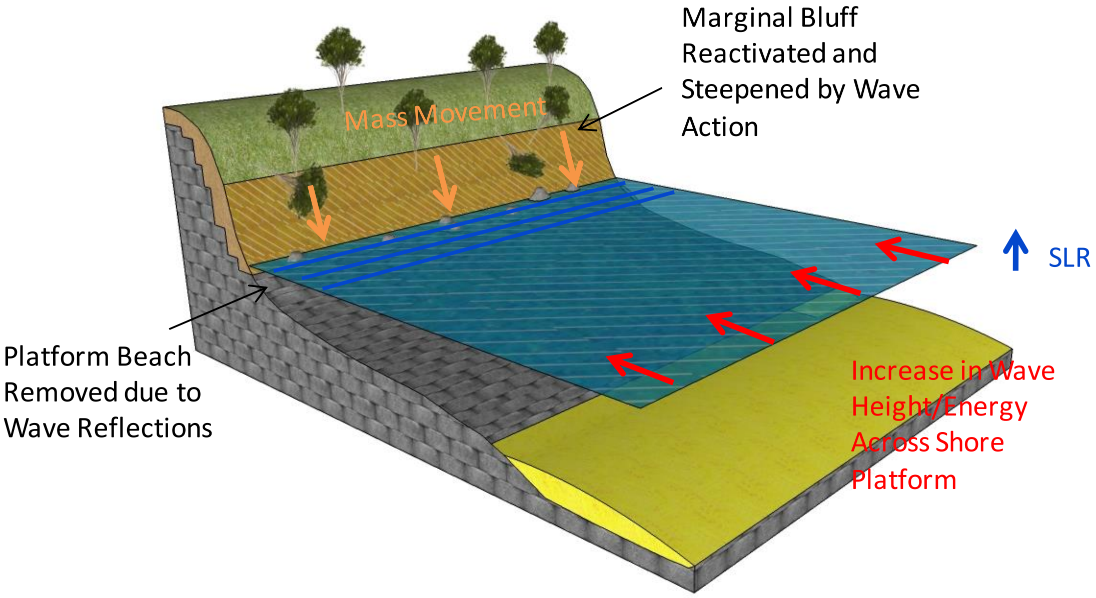


Figure 3-46 **Marginal Bluff Reactivation Sea Level Rise Response Mechanism**

3.6 Soft Rock, High Cliff Shorelines

3.6.1 Class Overview

Deeply weathered and/or weakly consolidated sediments are exposed as high cliffs at some relatively localised locations in Western Port. Sediments comprising these cliffs are subject to sub-aerial processes and intermittent marine erosion.

There are typically two sub classes of this shoreline class in Western Port; Older Volcanic and Tuff, and Pliocene Baxter Formation classes.

Table 3-10 summarises the characteristics of the Older Volcanic basalt and Tuff shoreline sub class. Figure 3-47 displays an example of this shoreline class at Swan Corner. Swan Corner is located on the southern and south-eastern shore of Swan Bay, five kilometres west of Newhaven.

Table 3-10 **Older Volcanic Basalt and Tuff Shoreline Sub Class**

Examples	Backshore	Geology	Intertidal	Geomorphology
Cobb Bluff, Swan Corner	***BackProx*** Active Cliff	Older volcanic basalt and tuff	Minimal beach of mixed sand and gravel overlying wide rock shore platform	Steep slope of exposed regolith and deeply weathered volcanics. Local overhangs at cliff top. Very little beach development – shore muddy of coarse sand and gravel. Wide, planar shore platform with irregular outline. Outer edge exposed at low spring tide in some places or may be mud-covered.
	BackDist Plain			
	BackProf Steep slopes			

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

Figure 3-47 Older Volcanic Basalt and Tuff Shoreline Sub Class, Swan Bay

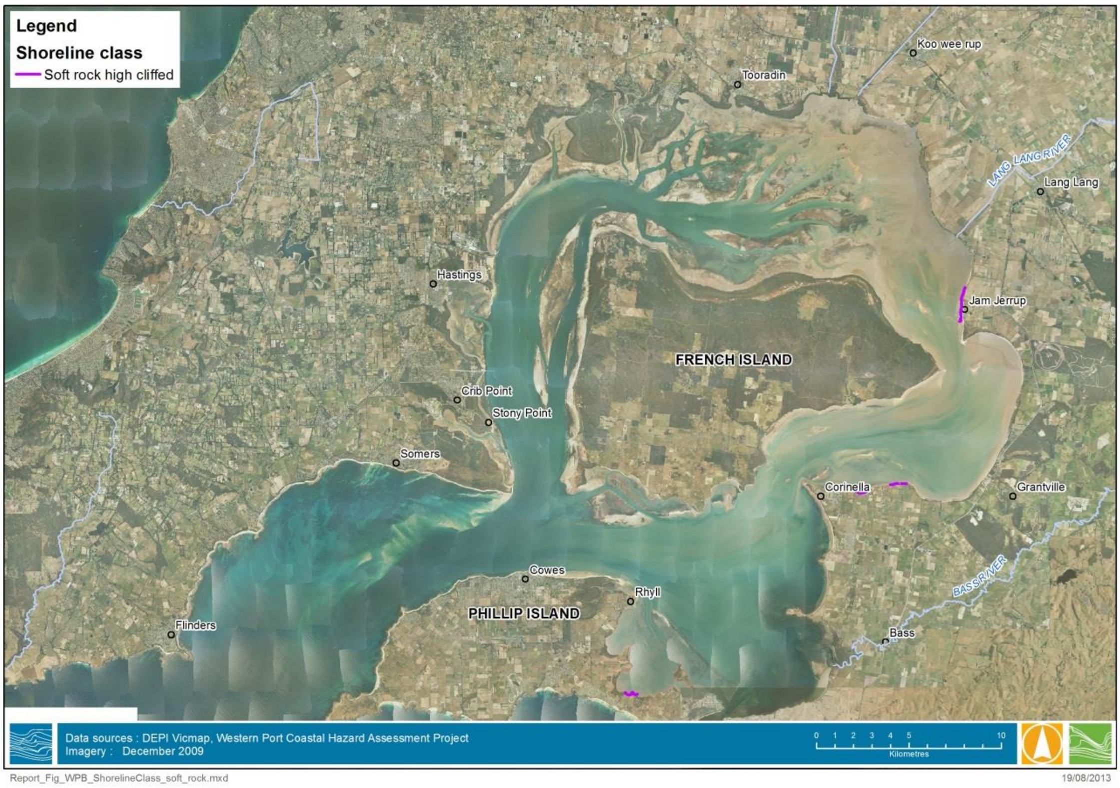
Table 3-11 Pliocene Baxter Formation Shoreline Sub Class

Examples	Backshore	Geology	Intertidal	Geomorphology
Red Bluff (Jam Jerrup)	***BackPro*x** Active Cliff	Pliocene Baxter Formation sediments	Sand beach, local gravel and boulders, nearshore bars, minimal rock platform	Steep slope of exposed regolith and deeply weathered and ferruginised Baxter Formation. Local overhangs at cliff top. Intermittent sand beach with local boulders fallen from cliff. Minimal shore platform – wide intertidal beach – fine sand and mud.
	BackDist Plain			
	BackProf Steep slopes			

The backshore zone classifications are based on the Smartline Project, and full definitions are listed in the Glossary at the start of this report.

Figure 3-48 **Pliocene Baxter Formation Shoreline Sub Class, Red Bluff at Jam Jerrup**

Figure 3-49 provides an overview of the delineation of the extent of the soft rock, high cliff shoreline class in Western Port.



Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

Report_Fig_WPB_ShorelineClass_soft_rock.mxd
19/08/2013

Figure 3-49 **Delineation of Soft Rock, High Cliff Shoreline Class in Western Port**

3.6.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this conceptual shoreline type are displayed in Figure 3-50 and are discussed in more detail below:

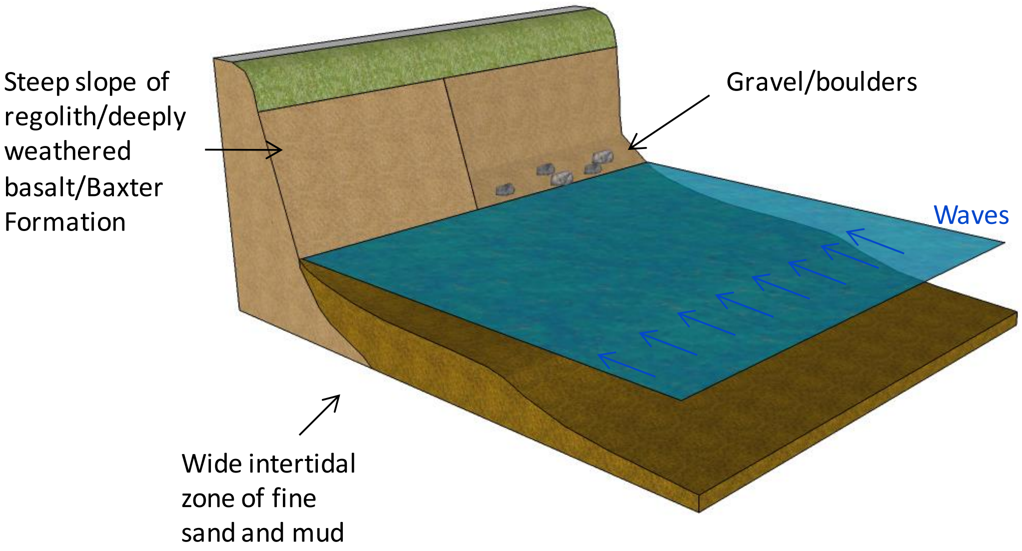


Figure 3-50 Soft Rock, High Cliff Conceptual Shoreline Type

Geomorphic Components

The key physical components of this shoreline type comprise the following:

- A wide intertidal zone of mud or fine sand;
- a narrow sand, gravel/boulder platform; and
- a high, steep slope/cliff of weakly consolidated sediments

Key Processes

A range of sub-aerial processes contribute to erosion of the high soft rock cliffs including groundwater pore pressure and seepage, shrink-swell detachment, and chemical interactions with the soil material which contribute to slope failure through block or slumping type movements.

Surface runoff and rain impact can affect the stability of the cliff face through mechanisms such as sheet flow across the surfaces or concentrated runoff that produce rills and drainage gullies which indent the cliff surface.

Wave action is also a significant process for change on these shorelines. Intermittent wave action at the toe of the cliff can create notches in the cliff face which undermine upper layers of the cliff face which subsequently topple onto the platform beach at the base of the cliff (Figure 3-51).

Figure 3-51 Erosion of Soft Rock Cliffed Shoreline Instability at Red Bluff (Photo: Neville Rosengren)

Rates of historical erosion of the Baxter Formation cliffs at Red Bluff (Lang Lang) were estimated by Parsons Brinkerhoff (2009) from analysis of aerial photography. The historical rates of recession estimated from this analysis are provided in Table 3-12. A conservative, upper annual erosion rate of 0.5m/year had been adopted for this study.

Table 3-12 **Historic Rates of Erosion in Baxter Formation Cliffs (Parsons Brinckerhoff, 2009)**

Location	Total Recession	Average Recession per year for the period shown (m)
North of Red Bluff	9 m (1947-2006)	0.15
Red Bluff	8 m (1973-1990)	0.47
South of Red Bluff	7 m (1947-1984)	0.19

3.6.3 Key Drivers and Rates of Change

Future rates of cliff erosion could be expected to vary as a function of changes to the amount of wave energy delivered to the toe of the cliff, although sub-aerial processes will still significantly influence future rates of cliff erosion on these shorelines.

To provide a provisional estimate of potential future erosion rates on these shorelines, the historical erosion rates determined for Red Bluff have been scaled by the predicted percentage change in wave energy on these shorelines to due to sea level rise. This is similar to the approaches adopted by authors such as Ashton et al (2011), Trenhaile (2009, 2010, and 2011).

Table 3-13 summarises the relative change in wave energy predicted by the spectral wave model for the different sea level rise scenarios as well as the subsequent estimate of the associated potential increase in average erosion rates within this shoreline class.

The average predicted recession rates for each sea level rise scenario have been linearly interpolated across the associated timeframes to provide a potential coastal hazard distance along this shoreline class.

Table 3-13 Summary of Predicted Future Rates of Shoreline Recession on Soft Rock, Low Cliffed Shorelines

Parameter	Sea Level Rise Scenario			
	Existing	+0.2 m (2040)	+0.5 m (2070)	+0.8 m (2100)
Percentage Change in Wave Energy Relative to Existing Sea Level (%)	-	135	190	240
Annual Shoreline Recession Rate (m/year)	0.5	0.68	0.95	1.2
Cumulative Recession (m)	-	15	45	75

As for the other cliffed shoreline classes, an additional factor that may impact erosion of these shorelines into the future was identified in the review of impacts on groundwater as a result of sea level rise (Report 4). The review found that increases in groundwater levels may alter shoreline erosional processes for cliffed shorelines around Western Port, increasing the rate of erosion. Insufficient information is available on either current or potential future groundwater conditions on these shorelines and therefore the potential impact of groundwater on erosion hazards has not been assessed further.

3.7 Sandy Spit Shorelines

3.7.1 Class Overview

The spatial extent of unconstrained sandy shorelines in Western Port is relatively limited. This is both a function of the geologic setting of Western Port which (apart from the northern shorelines) results in relatively bold coastal relief, and the lithology of the cliffed shorelines which yields little beach material when eroded.

Unconstrained sandy shorelines therefore exist essentially only as the major spit landforms of Sandy Point, Observatory Point, Stockyard Point and Spit Point within Western Port. Theses landforms comprise the terminal sediment sinks resulting from the longshore drifting of sediment along the shorelines of Western Port (described in Section 2.4.3). These landforms are therefore young, having only come into existence following the Holocene marine transgression approximately 10,000 years ago. They are also exceptionally dynamic and their geomorphology reveals evidence of rapid changes associated with variations in sea level and sediment supply (Marsden, Mallett and Donaldson, 1979).

Figure 3-52 Example of Sandy Spit Shoreline, Sandy Point (Photo: Neville Rosengren)

Figure 3-53 provides an overview of the delineation of the extent of the sandy spit shoreline class in Western Port.

Data sources : DEPI Vicmap, Western Port Coastal Hazard Assessment Project
Imagery : December 2009

Report_Fig_WPB_ShorelineClass_sandy.mxd
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Figure 3-53 Delineation of Sandy Spit Shoreline Class in Western Port

3.7.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this conceptual shoreline type are displayed in Figure 3-54 and are discussed in more detail below:

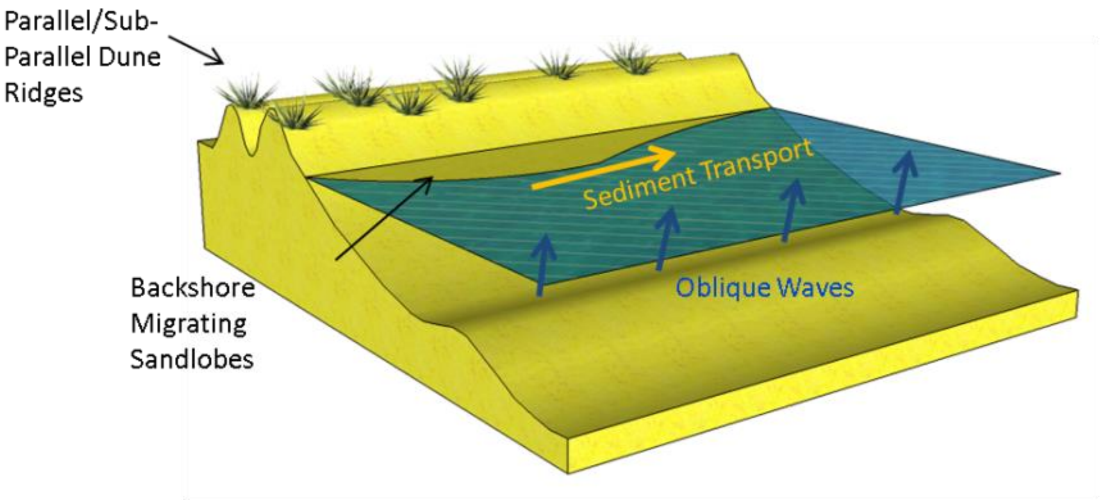

Figure 3-54 Sandy Spit Conceptual Shoreline Type

Geomorphic Components

The key physical components of this shoreline type comprise the following:

- Offshore sandy bed;
- Backshore migrating sandlobes;
- A series of parallel/sub-parallel dune ridge sequences which have formed successively as foredunes behind a prograding sandy beach

Waves

Waves arrive obliquely along these shorelines, generating longshore currents that drive the sediment transport processes towards the heads of the spits.

At Sandy Point and Observation Point, the wave climates are influenced by minor, residual ocean swells that have propagated into Western Port through the western entrance.

Sediment Transport

Longshore sediment transport processes play a critical role in shoreline position and variability along these shoreline types in Western Port. A longshore drift of sediment towards the spit heads is generated by obliquely incident waves. Longshore sediment transport along these shorelines is also possibly reinforced by residual tidal currents as well as aeolian transport driven by predominate westerly winds. The main source of sediment for these areas is from offshore, through the Western Entrance, as described in Section 2.4.3.

A pronounced feature of the sediment transport processes of these shoreline types in Western Port is the migration of backshore sand lobes. An example of a migrating sand lobe in the vicinity of the Silverleaves Estate along Observation Point is displayed in Figure 3-55. These lobes of sand are gradually transported in the downdrift direction by the action of waves and as these lobes of sand migrate along the shoreline they cause alternating patterns of accretion and erosion.

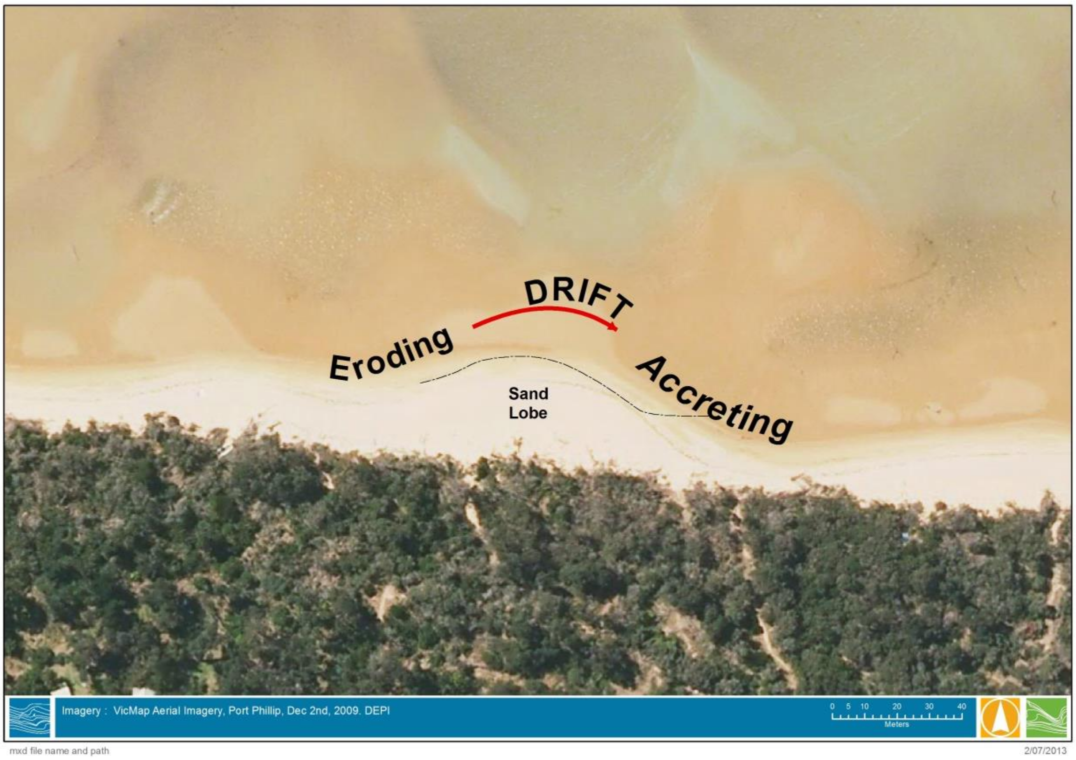

Figure 3-55 Migrating Backshore Sand Lobe along Observatory Point

Aspects of the genesis and processes that transport sediment as large longshore migrating sand lobes along these shorelines are considered poorly understood. Their significance to the formation of these landforms and contemporary processes and variability that is observed on the present shorelines cannot however be understated.

Bird (1993) mapped and described the evolution of the sequences of dune ridges that comprise the Sandy Point landform. The sequences of dune ridges at Sandy Point are captured with very high levels of detail by the LiDAR survey and are displayed in Figure 3-56. From Figure 3-56 the scale of the variability in the shoreline position of this landform over the Holocene can be interpreted from the relative alignments of the different sequences of dune ridges.

Failure to appreciate the scale of underlying variability of these shorelines due to backshore sand lobe migration has historically led to development being inappropriately located within the active width of these shorelines. This development has subsequently been threatened by erosion as the sand lobes have migrated past these developments over time. Specific examples include the yacht club at Somers and residential development along Cowes East and Silverleaves.

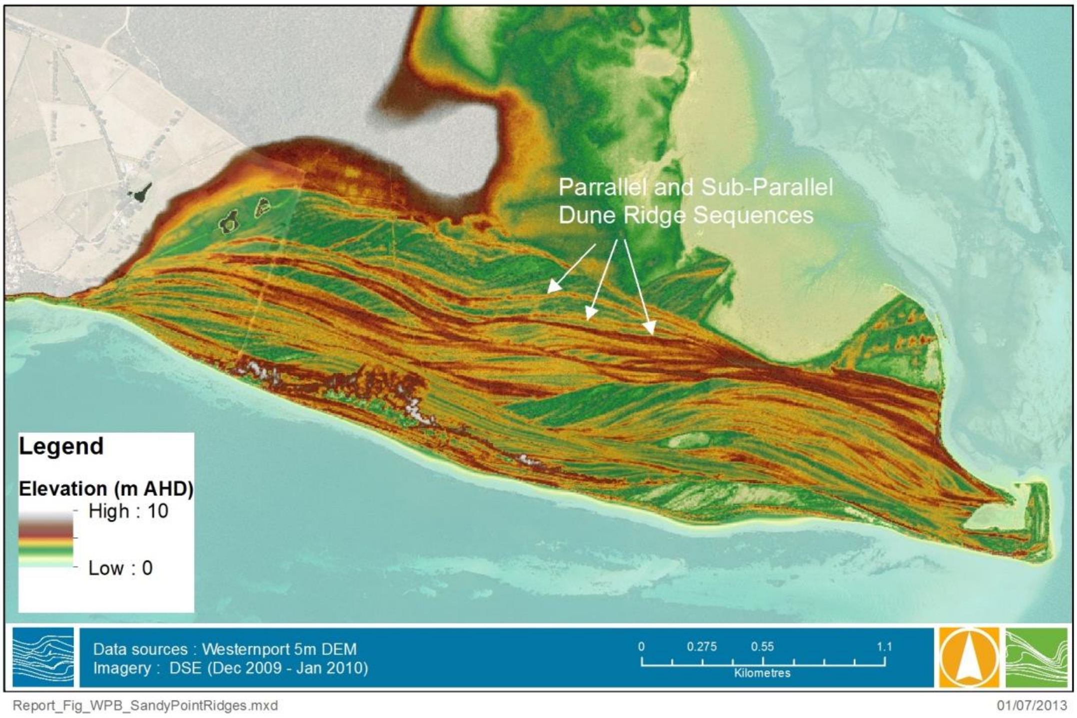

Figure 3-56 Sequences of Parallel/Sub-Parallel Dune Ridges at Sandy Point

3.7.3 Key Drivers and Rates of Change

The key drivers and potential rates of change on these shorelines due to sea level rise or underlying process variability is displayed conceptually for this shoreline type in Figure 3-57.

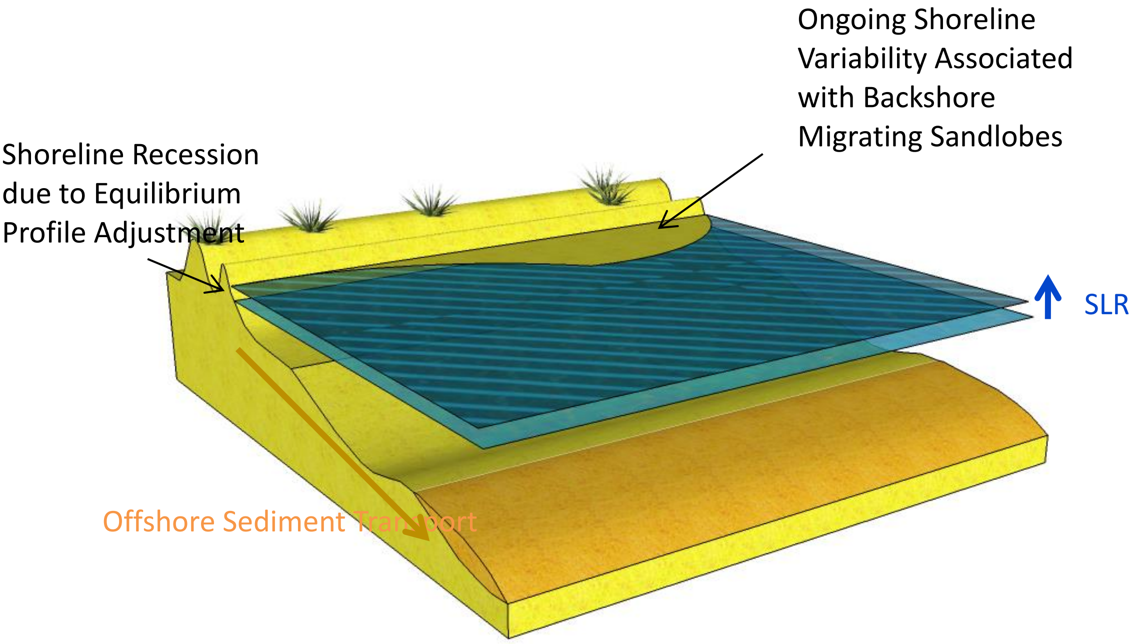

Figure 3-57 Sandy Spit Shoreline Sea Level Rise Response Mechanisms

Equilibrium Profile Recession

The Bruun (1962) model is one of the most widely used conceptual models for predicting sandy shoreline profile response to rising sea levels due to its ease of application, and lack of accepted alternatives for long-term shoreline profile response. The Bruun model is based on the concept that for a shoreline profile at, or close to equilibrium with present sea levels, and that is neither gaining nor losing significant volumes of sediment; a rise in relative sea level will lead to erosion as wave action erodes the beach face, transporting sediment offshore. Over time this process translates the shoreline profile shoreward and upward in response to the relative 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. A conceptual model of this process is shown in Figure 3-58.

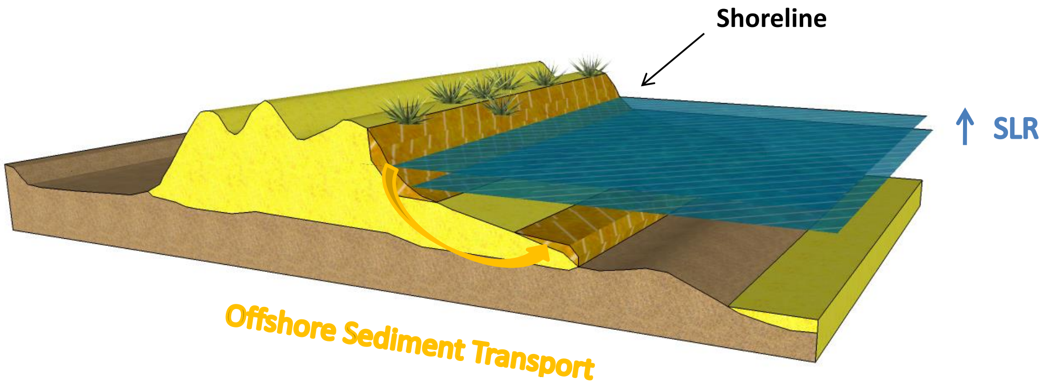

Figure 3-58 **Conceptual Model of Equilibrium Profile Recession along a Sandy Shoreline as a Result of Sea Level Rise**

The application of the Bruun model for estimating shoreline profile response to sea level along these sandy spit landforms in Western Port is however considered problematic. Figure 3-59 displays cross sections of the Sandy Point and Observation Point shorelines extracted from the LiDAR survey. From Figure 3-59 it can be seen that the depth of closure (describing the seaward extent of potential profile change due to sea level rise) is not readily definable for these shorelines as they are generally fronted by a wide, shallow and/or intertidal sandy bar systems. Sediment across these bars can be mobilised by wave and/or tidal current action and the sediment transport processes between the offshore bar systems and the shoreline are likely to be very complex.

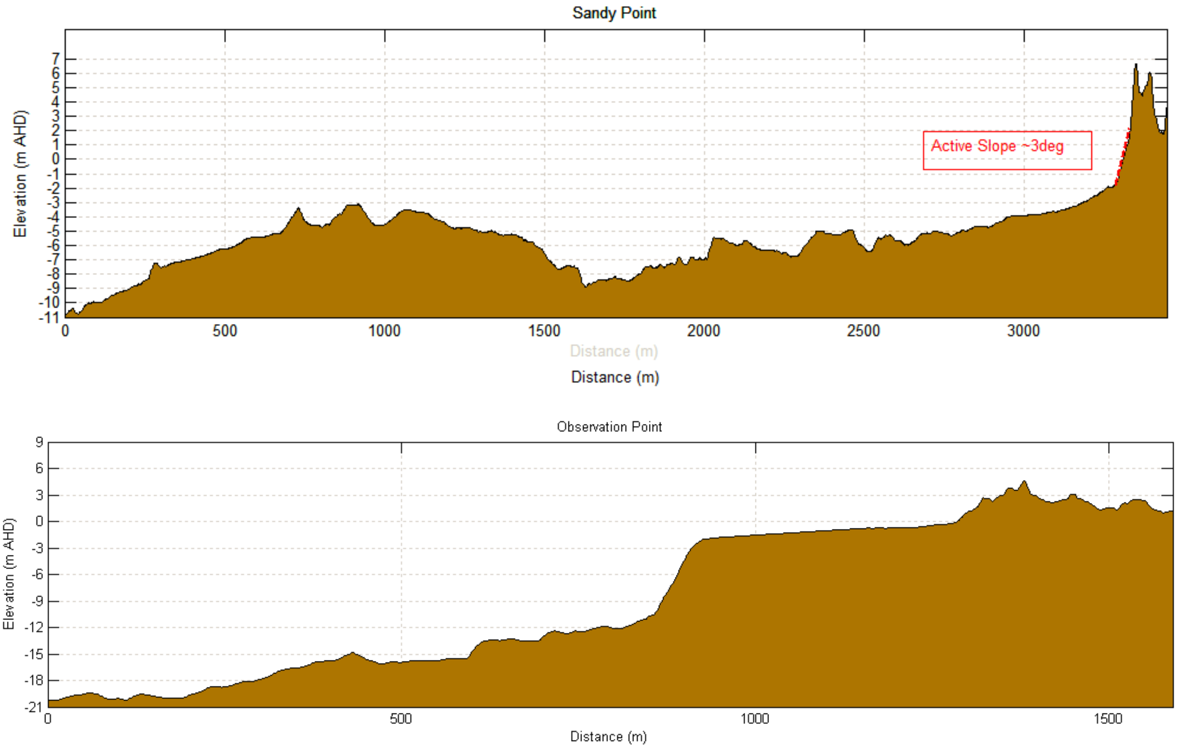

Figure 3-59 Cross Sectional Profiles through Sandy Spit Shorelines at Sandy Point and Observation Point

Due to the particular characteristics of the sandy spit shoreline class in Western Port, it is difficult to identify an active slope for application of the Bruun model for estimating the extent of equilibrium profile adjustment due to sea level rise on these shorelines. The active slope is simply defined as the ratio of the horizontal distance from the shoreline to the depth of closure divided by the closure depth plus the berm/dune crest height. This active slope yields the 'Bruun Factor' which describes the amount of horizontal profile adjustment (recession) per increment of sea level rise.

It is possible that sea level rise may predominately only impact the beach face and dunes on these shorelines (DEHP, 2013). Consideration of the upper beachface slopes for estimating the extent of the shoreline profile adjustment using this modified approach would however result in relatively small active slopes (Bruun Factor of approximately 12) and shoreline recession estimates. Given the complex offshore geometry and the dynamic sediment transport processes that are observed on these shorelines, it is however considered prudent to adopt a conservative Bruun Factor of 100 for the study are wide assessment. This factor reflects the limited understanding of the potential extent of the sea level rise response of this shoreline class. Table 3-14 summarises the recession distances for the sand spit shoreline class due to equilibrium profile adjustment with an adopted Bruun Factor of 100.

Table 3-14 Bruun Model Recession Distances for Sandy Spits Shorelines

Bruun Factor	Sea Level Rise Scenario		
	0.2m	0.5m	0.8m
100	20m	50m	80m

Backshore Sand Lobe Migration/Longshore Sediment Transport

A major component of the shoreline variability and subsequent extent of potential coastal hazard impacts on these shoreline types will continue to be associated with the migration of backshore sand lobes along these shorelines. This underlying shoreline variability will continue irrespective of presence or otherwise of sea level rise. As noted in Section 2.4.3, sand in these areas is derived from Bass Strait and is transported into Western Port via the Western Entrance

In order to provide an estimate of the potential extents of coastal hazards associated with these processes in the future, the scale and extent of these features observed from available historical aerial photography has been reviewed for landforms in Western Port that correspond to this conceptual shoreline type.

Contemporary mapping of the migration of a large backshore sand lobe at Cormorant Point, (located along the Sandy Point landform) from historical aerial photography (Bird & Jones, 1988) showed shoreline position fluctuated by 100-200 metres over a length of shoreline of approximately one kilometre between 1939 and 1984. More recent photography available from this study since the original analysis was undertaken by Bird has been used to track the ongoing evolution of this large backshore sand lobe at Cormorant Point and is displayed in Figure 3-60. Figure 3-60 shows the envelope of shoreline change between the earliest (1957) and latest (2011) available photos. The eastward migration of the lobate foreland can be clearly observed over the photographic sequence in Figure 3-60. Maximum variation in shoreline position is estimate at approximately 223 m between 1957 and 2011.

Available historical aerial photography of the sandy spit landform that terminates at Observatory Point to the East of Cowes as also been reviewed in Figure 3-61. Figure 3-61 displays a similarly high level of temporal variability in shoreline position as is observed along Sandy Point, although the magnitude of the changes are smaller.

The eastward migration of a backshore sand lobe is clearly observed, with the shoreline in the west of the frame receding and the shoreline to the east prograding by a similar amount (approximately 50 m) over the course of the photographic sequence along this landform. Shoreline changes on this landform have also been signficantly influenced by the construction of shore protection works including revetment and groynes which have resulted in down drift,terminal erosion impacts to the shorelines. The shoreline is not therefore considered to be in an equilibiurm state.

The review of available historical photography for the sandy spit shoreline class in Western Port has highlighted the extent of the underlying shoreline variability that can be attributed to the migration of backshore sand lobes along these landforms. Estimating the future location and extent of shoreline changes and associated coastal hazard impacts along these landforms due to these processes is not possible with any acceptable level of precision or confidence. However, detailed dating of the sediments comprising the dune ridges on these landforms would enable the evolution of these landforms and the temporal and spatial scales of the shoreline variability to be better understood which would assist in refining appropriate hazard extents.

Provisional hazard extents have been developed by adopting the maximum shoreline changes attributed to backshore sand lobe varaibility from the analysis of the historical photography and including a factor of safety of two to account for the longer time frames and level of uncertainty that exists in relation to these processes.

Table 3-15 Provisional Hazard Extents due to Backshore Sand Lobe Migration

Sandy Spit Landform	Backshore Sand Lobe Hazard Extents	
	Variability Based on ~50 years of Historical Photography (m)	Provisional Hazard Extent x2 Factor of Safety (m)
Sandy Point	~250	500
Observation Point	~50	100
Other Sandy Spit Landforms	50	100

Summary

Table 3-16 summarises the total combined coastal hazard extents incorporating equilibrium profile response due to sea level rise and the underlying shoreline variability due to backshore sand lobe migration, plus a factor of two due to uncertainties associated with this process over long timeframes. These coastal hazard extents have been mapped for each of the relevant sandy spit landforms

Table 3-16 Provisional Total Coastal Hazard Extents for the Sandy Spit Shoreline Class

Sandy Spit Landform	Sea Level Rise Scenario		
	0.2m (2040)	0.5m (2070)	0.8m (2100)
Sandy Point	270m	300m	580m
Observation Point	70m	100m	280m
Other Sand Spit Landforms	70m	100m	280m

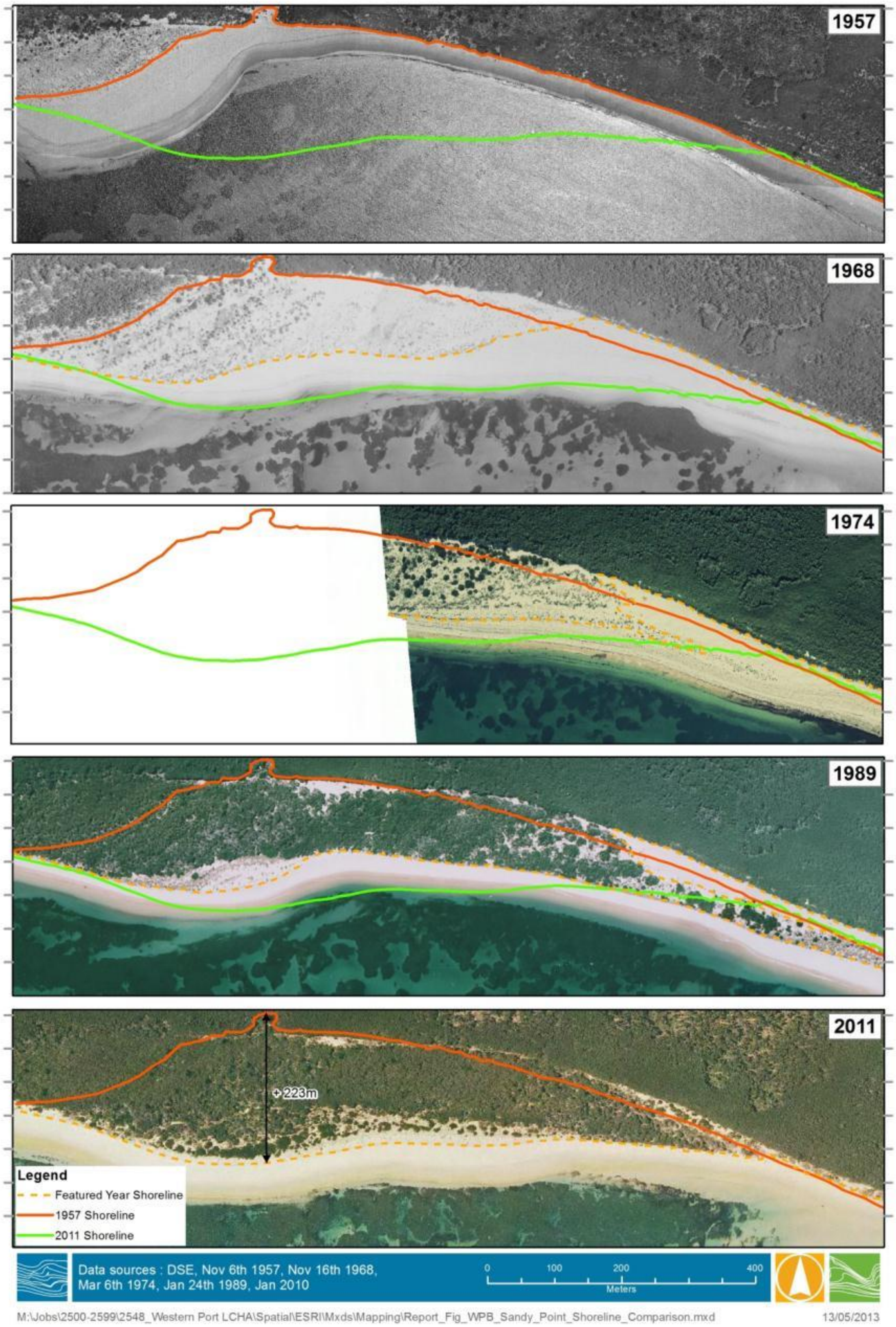

Figure 3-60 Eastward Migration of the Lobate Foreland at Cormorant Point (Sandy Point) (1957-2011)

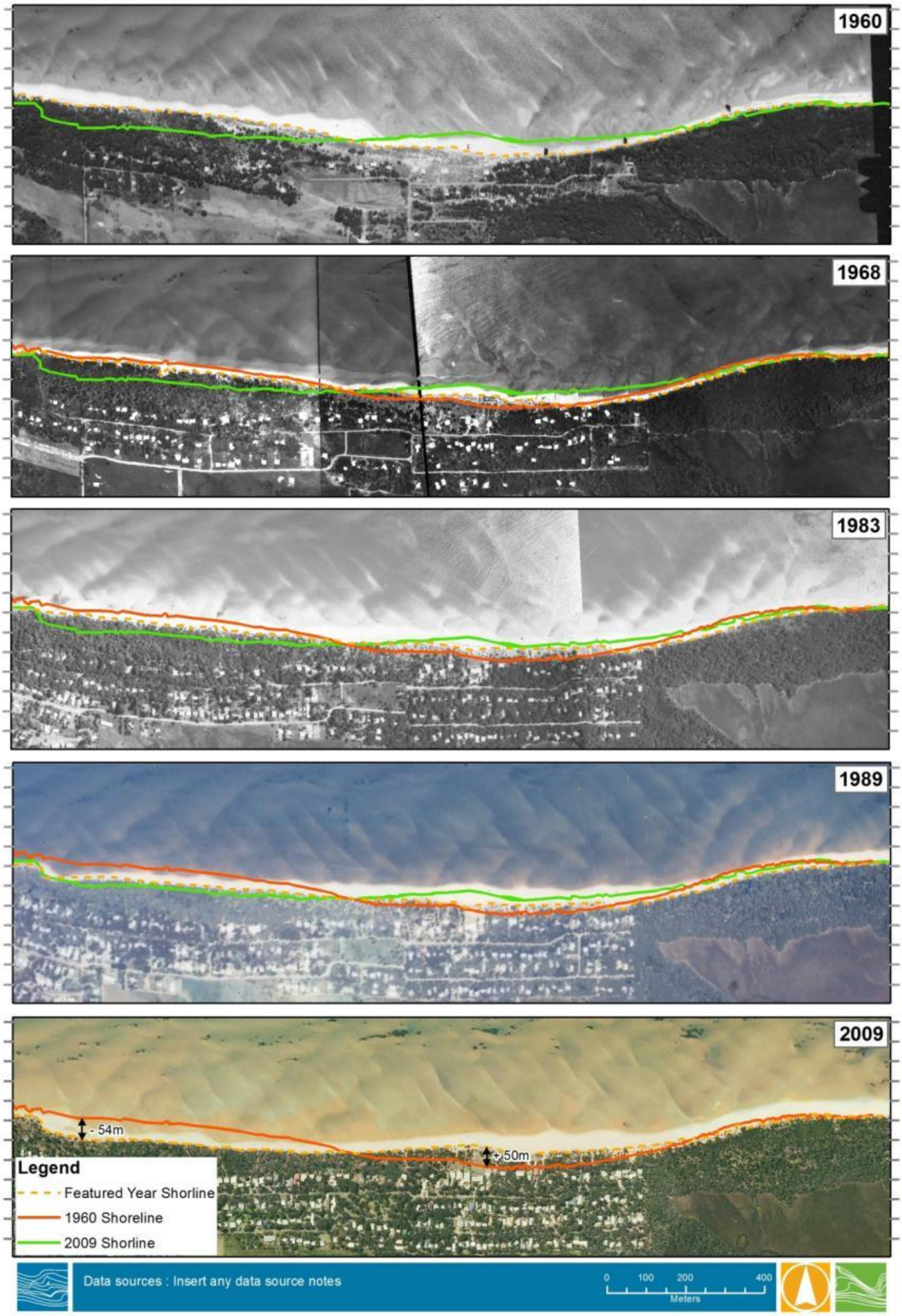

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Figure 3-61 Sandy Spit Landform, Observation Point to the East of Cowes (1960-2009)

3.8 Estuarine and Tidal Channels

3.8.1 Class Overview

This geomorphic conceptual shoreline type represents a wide grouping of shore perpendicular geomorphic features principally associated with tidal creeks and estuaries that occur within Western Port. While considerable differences in origin, evolution and contemporary processes can occur among individual examples of this unit, for the purposes of this study they have been grouped together, as they are relevant to the consideration of the potential extents of coastal hazard impacts in Western Port.

The critical component of this class relevant to the assessment of coastal hazard impacts in Western Port is the presence of a tidal or estuarine channel perpendicular to the shoreline. These channels can enable coastal influences to extend considerable distances landward of the main shoreline. Where the elevation of the backshore areas is such that sea level rise may result in tidal variations through these channels causing large areas to become tidally inundated, new shorelines could be expected to develop.

Report_Fig_EstuarineShorelineExample 2/7/2013

Figure 3-62 **Example of an Estuarine Shoreline Type**

Other classes of estuaries such as ‘intermittently closed and open lake or lagoon’ (ICOLL) systems (e.g. Merricks Creek), respond differently to sea level rise and have been assessed individually as required.

3.8.2 Key Processes and Dynamics

The key geomorphic components and processes operating on this conceptual shoreline type are displayed in Figure 3-63 and are discussed in more detail below:

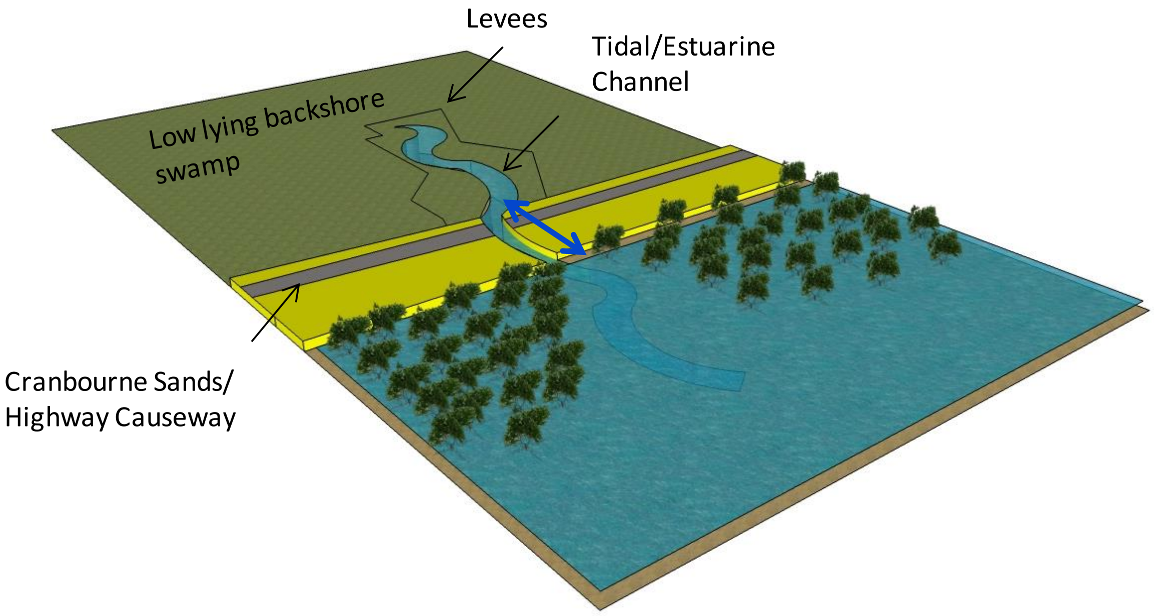

Figure 3-63 **Estuarine and Tidal Channel Conceptual Landform**

Geomorphic Components

The key physical components of this geomorphic shoreline type comprise the following:

- Tidal or estuarine channel that cuts perpendicular across the main shoreline.
- An elevated region of Cranbourne sands/mid-Holocene beach ridges and/or Highway causeway and embankments that separates the existing Western Port shoreline from low lying backshore swamp zones.
- A low elevation backshore swamp zone, frequently leveed

Tidal Inundation

The propagation of the tide along the tidal and estuarine channels is principally governed by the geometry of the channel and the relative elevation of low lying swampy areas that are adjacent to the tidal channels. In many instances, drains and associated embankments and levees have been constructed to limit the extent of tidal inundation in low lying swampy areas adjacent to tidal and estuarine channels.

Where the tidal channel is crossed by a road or highway, culverts are often present that can throttle the propagation of the tide further along the channel and into low backshore swamp zones. Culverts with one-way tidal flaps under the South Gippsland Highway at Tooradin significantly attenuate the propagation of the tide further in Sawtells Inlet at this location.

Refer to the Inundation Report (R04) of this study for further discussion.

3.8.3 Key Drivers and Rates of Change

The key drivers and potential rates of change on these geomorphic landforms due to sea level rise or underlying process variability is discussed below and displayed conceptually for this shoreline type in Figure 3-64.

Tidal Inundation of Low Lying Backshore Areas

As sea levels increase, the relative tidal plane elevations and subsequent extents of inundation could be expected to expand into low lying swampy areas adjacent to existing tidal and estuarine channels.

Low lying swampy areas that experience frequent tidal inundation due to sea level rise could be expected to evolve into muddy intertidal areas that may be fringed by proto shorelines of saltmarsh and mangroves.

The lateral extent of the increases in tidal inundation associated with sea level rise in these low swampy areas will however be significantly influenced by the degree to which the numerous levee and embankments systems that often exist in these areas are maintained and/or upgraded to adapt to rising sea levels.

Given the informal construction and management status of the majority of these levee and embankment systems and the likelihood that sea level rise will result in water logging and possible salinisation of these areas, it is considered prudent to assess the extent of future coastal hazards assuming they will not be maintained or upgraded to mitigate future impacts associated with sea level rise in the long term.

The potential extents of future shoreline expansion due to frequent inundation by tidal water level variations were estimated by considering the extents generated by the intersection of the modelled MHWS tidal plane extents predicted by the hydrodynamic model and the DTM in these areas. For further information refer to Report 4.

Changes to the hydrodynamics of the system as a result of the formation of new shorelines and erosion of the new shoreline materials has not been assessed within the hydrodynamic model as there is a knowledge gap as to how such systems would develop as a result of sea level rise, and also the time scale associated with such changes. Erosion responses in such areas will occur once the inundation processes are initiated.

Tidal Channel Expansion/Meandering

As the lateral extents of tidal inundation expand in low swampy areas due to sea level rise, the volume of water that must flow along the tidal channels each tide will increase. The increase in the tidal prism will increase velocities in these channels and subsequently the potential rates of sediment transport. Depending on the sediments comprising the tidal channel and the magnitude of the increase in the tidal prism in the channel with sea level rise, it is possible that the tidal channels may expand laterally and vertically to accommodate the increased tidal flows.

Lowering of stream gradients along the lower reaches of drains and estuaries in Western Port due to sea level rise may also result in variations in the channel alignments due to the development of more frequent and larger amplitude meanders. The significance of changes to stream gradients on the morphology of estuarine channels in Western Port due to variations in sea level can be readily observed in the estuarine reach of the Bass River following the mid-Holocene fall in sea level as discussed in Section 2.

The increase in tidal channel width and extent of meander development is location specific and has not been explicitly incorporated into this broad scale assessment.

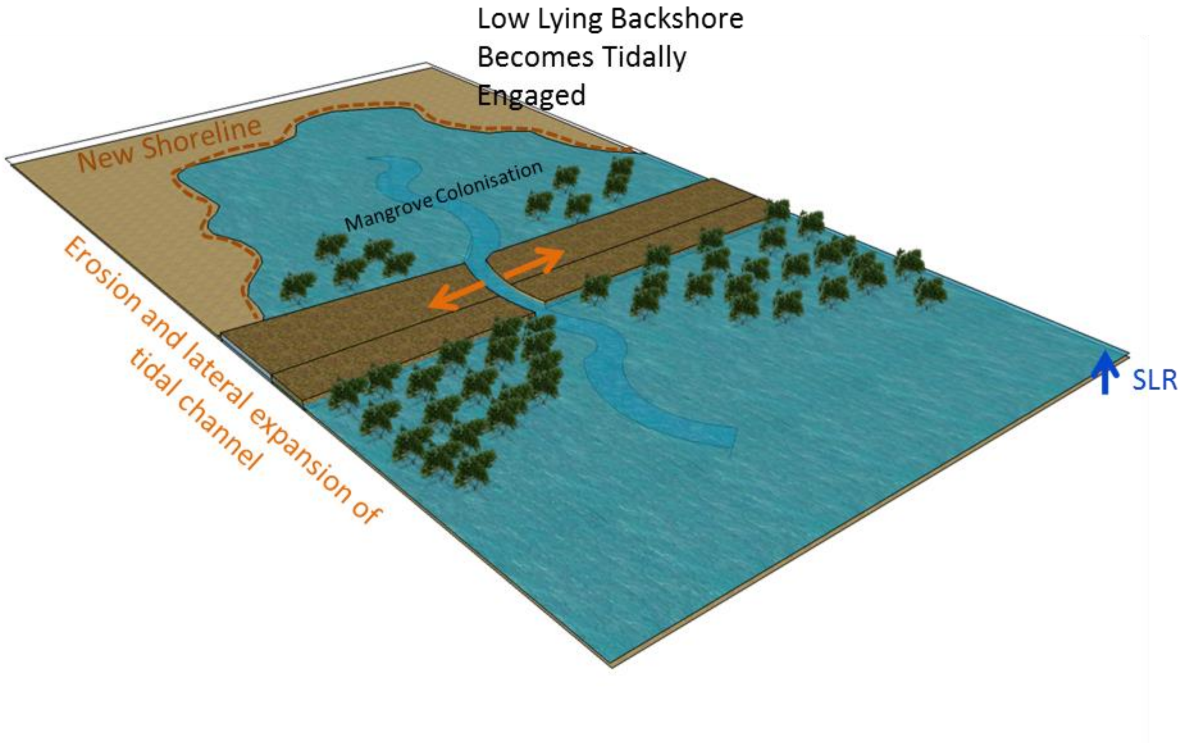

Figure 3-64 Response of Estuarine and Tidal Channel Geomorphic Landform to Sea Level Rise

4. COASTAL HAZARD MAPPING

4.1 Overview

The models of future shoreline change/hazards developed in the previous sections for each of the seven major shoreline classes identified for Western Port have been applied to develop a broad scale Western Port wide assessment and mapping of potential erosion hazards extents for each sea level rise scenario.

4.2 Mapping Methodology

The erosion hazard mapping of Western Port is based on a study specific shoreline that has been developed by mapping the modelled elevation and extent of the MHWS tidal plane in Western Port. For a number of the shoreline classes, the MHWS tidal plane strongly influences the existing shoreline positions and changes to the MHWS tidal plane due to sea level rise will significantly control future shoreline change.

Figure 4-1 displays the MHWS shoreline for Western Port and the delineation of the seven major shoreline classes.

For each major shoreline class, a set of rules/method was established to enable the processes and rates of change predicted due to sea level rise for each shorelines class to be translated to a mapped extent in a GIS.

The erosion hazard extents have therefore been mapped in a GIS using site specific information relating to the predicted changes in tidal inundation extents and elevations/slope of backshore regions within each shoreline class to provide hazard extents that are consistent with the local physical form and environment at all locations within Western Port.

There are a number of engineered sections of shoreline in Western Port as displayed in Figure 4-2. Depending on their standard of construction, maintenance and the ownership arrangements associated with these structures they are likely to result in localised changes to the potential rates of shoreline change predicted for each shoreline class. For major engineered shorelines associated with port and harbours facilities in Western Port it was assumed these engineered shorelines would be upgraded/adapted to future sea level rise and the hazard extents were locally altered to reflect this likely response. For other engineered shorelines it was considered prudent to assess the potential extent of coastal hazards assuming these structures would not be adapted for future sea levels.

Figure 4-1 **Overview of Shoreline Class Delineation for Western Port**

Data sources : DEPI (WP Coastal Protection Structures, 2012)
Imagery : December 2009

Report_Fig_WPB_structures.mxd
19/08/2013

Figure 4-2 Overview of Engineered Shorelines in Western Port

Table 4-1 summarises the mapping method and/or rates of change that were mapped in the GIS based on the conceptual models of shoreline change to develop a Western Port wide coastal hazard mapping extent.

Table 4-1 Summary of Hazard Mapping Method for Different Shoreline Classes

Shoreline Class	Mapping Method/Rate of Change
Coastal wetland	Hazard zone was determined by intersection of predicted MHWS tidal plane extent including sea level rise scenarios with the DTM to provide estimate of landward extent of mangrove fringe. Where the predicted MHWS tidal plane intersected steeper backshore terrain landward of the saltmarsh-mangrove depositional terrace, the hazard extent was truncated along this interface. The interface between the saltmarsh-mangrove depositional terrace and backshore landforms was delineated from analysis of the LiDAR survey, aerial photography and geological mapping data.
Low Earth Cliffed	Hazard extent buffered from existing shoreline based on the recession estimates provided in Table 3-5 for each sea level rise scenario. Where the predicted extent of the MHWS tidal limit without levees extended across low backshore plains along these shorelines, the hazard extent was extended around the tidal inundation extents predicted by the model for each sea level rise scenario.
Hard Rock Cliff and Shore Platform	Shorelines within Western Port the landward hazard extent mapped as a function of the height of the top of the cliff / tan(11^0). (Landward hazard distance effectively 5 times the cliff height) Shorelines along Bass Strait the landward hazard extent mapped as a function of the height of the top of the cliff/ tan(18^0). (Landward hazard distance effectively 3 times the cliff height). The hazard zone is constant for all sea level rise scenarios.
Platform Beach and Bluff	Initial coastal hazard extent estimate based on platform beach narrowing across shore platform. Hazard extent buffered based on estimates developed in Table 3-9. Where the translation of the platform beach intersected steeper backshore terrain associated with the bluff, the hazard extent was truncated along this interface. The interface between the platform beach and base of the bluff was approximated by the 3.0m AHD contour. Where the hazard extent intersected the base of the bluff, the hazard extent was buffered landward as a function of the height of the top of the bluff/ tan(11^0) as a provision for slope failures. (Landward hazard distance effectively 5 times the cliff/bluff height). The slope failure hazard zone is constant for all sea level rise scenarios.
Soft Rock High Cliffed	Hazard extent buffered from existing shoreline based on the estimates provided in Table 3-12 for each sea level rise scenario.
Sandy and Sandy Spit	Site specific hazard extents were specified for the Sandy Point and Observation Point based on provisional estimates provided in Table 3-16. All other sandy spit landforms were based on Observation Point estimates.
Tidal Channel and Estuary	Hazard extent mapped from changes to the MHWS tidal limit of inundation predicted by the hydrodynamic model for each sea level rise scenario.

4.3 Erosion Hazard Mapping

4.3.1 Overview

An overview of the coastal hazard extents mapped for each shoreline class in Western Port is displayed in Figure 4-3, Figure 4-4, and Figure 4-5. The scale of Western Port is such that the details of the mapped hazard zones are difficult to show clearly at a broad scale. However, as described below, the mapped hazard extents are provided as part of the project GIS and can be interrogated in detail within a GIS environment.

Mapping Note

The MHWS tidal plane required local interpretation in some locations due to localised differences in the DEM and the modelled outputs due to the different scales of the data.

4.3.2 Outputs

In addition to the detailed project reports, a project GIS dataset is provided as an output from the project. In addition to the inundation extent outputs described in Report 04, this contains:

- Erosion hazard extent polygons for each of the modelled scenarios.

The rules associated with defining the erosion hazard extent for each shoreline type are detailed in Table 4-1. The rules applied produced a set of hazard extent lines and buffers for different SLR levels. These have been converted to hazard areas by incorporating the shoreline as the seaward edge of the area.

By applying the rules in Table 4-1, different extents are generated for neighbouring shoreline types. Therefore to produce the final erosion hazard extent, edge matching has been undertaken to create a continuous hazard extent for each SLR scenario. The extent was generalised and smoothed to remove the sharp edges between the neighbouring extent lines for cartographic / presentation purposes.

A separate GIS layer has been created to represent the erosion hazard extent for the + 0.2 m, +0.5 m and +0.8 m SLR scenarios. The scale of usage and mapping should not be greater than 1: 20,000.

The hazard extent polygons are considered representative to a “group of properties” scale rather than at the scale of individual properties, similar to that produced the inundation modelling flood extents (R04).

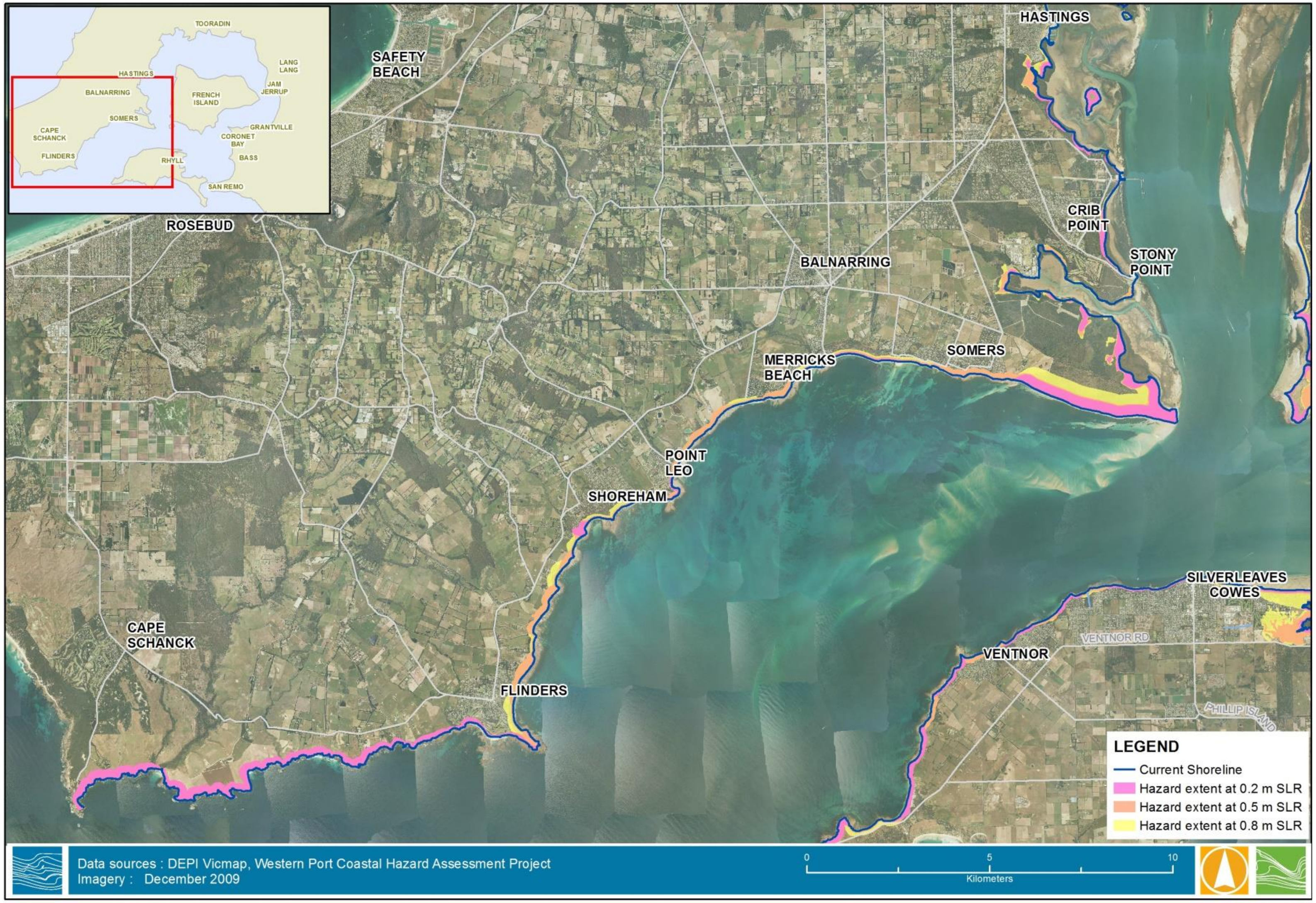

Figure 4-3 Overview of Coastal Erosion Hazard Extents for Western Region of Western Port – Map 1

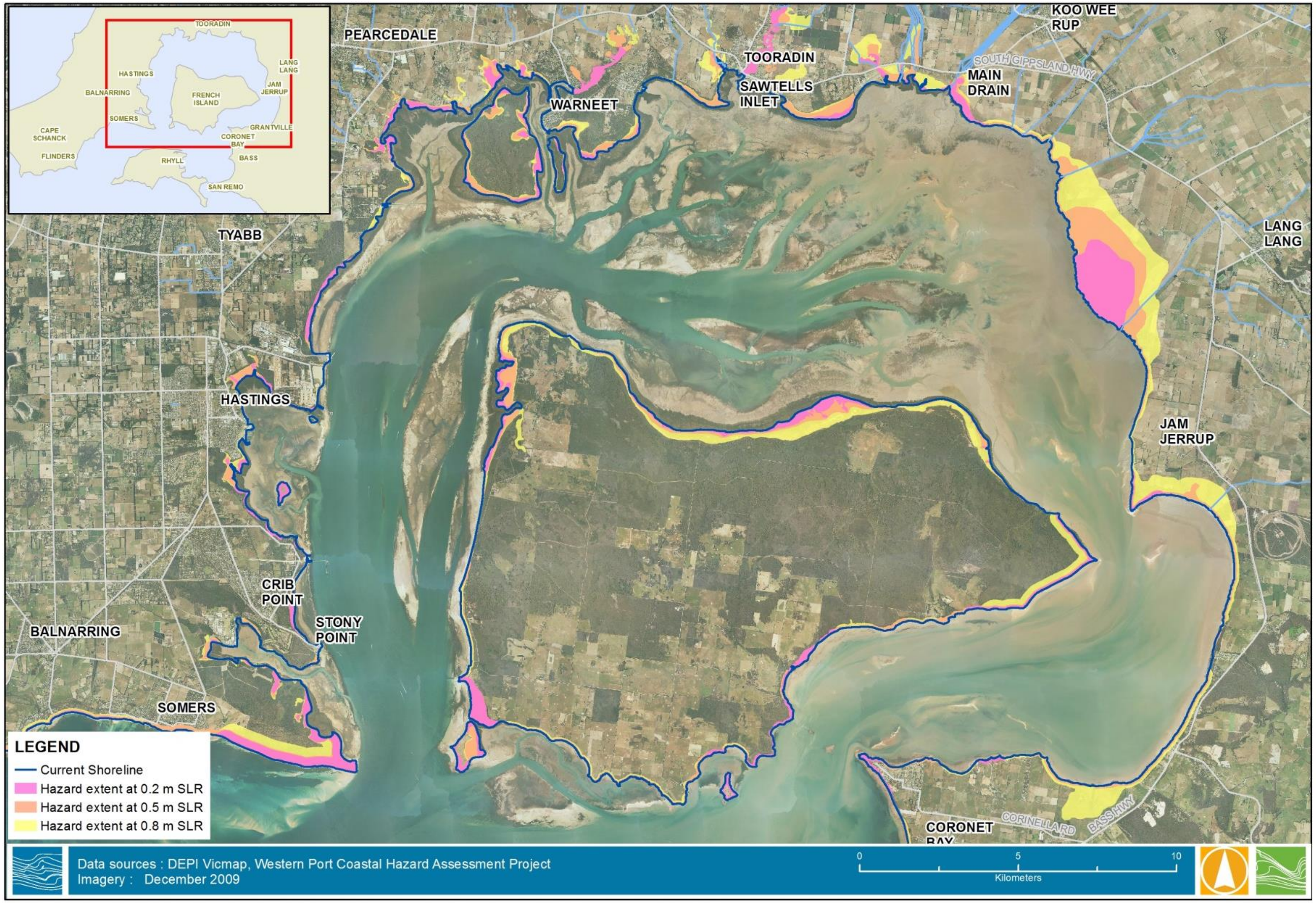

Figure 4-4 Overview of Coastal Erosion Hazard Extents for Northern Region of Western Port – Map 2

Figure 4-5 Overview of Coastal Erosion Hazard Extents for Eastern Region of Western Port – Map 3

5. SUMMARY AND RECOMMENDATIONS

5.1 Overview

This report has detailed the erosion component of the broad scale Part A local coastal hazard assessment for Western Port.

Western Port contains an unusually high diversity of coastal and backshore environments due to the complicated interaction of a wide range of processes including:

- Exposure of a large variety of different lithology;
- Long history of accumulation of alluvial (river transported) and aeolian (wind transported) sediments;
- Extensive development of coastal wetland plant communities;
- Meso scale tidal range;
- Exposure to different wave climate regimes; and
- Human induced changes.

Evidence of early, mid-Holocene emerged shorelines can be identified at many locations within Western Port. Review of the location and characteristics of these landforms is considered to provide important context and understanding to the assessment of the potential processes and rates of change that could be expected on the current shorelines of Western Port due to projected 21st century sea level rise.

In order to provide an assessment of the potential extent of the shoreline response that may occur due to sea level rise and/or climate change and associated coastal hazard impacts around such a diverse variety of shorelines, the shorelines of Western Port were characterised into seven major geomorphic shoreline classes.

Conceptual shoreline models have been developed for each shoreline and coastal landform class identified for Western Port. The conceptual shoreline models have been developed to provide an understanding of the geology, physical processes and dynamics that characterise each shoreline type. This approach provided the basis for understanding the key response mechanisms of the shorelines to sea level rise and/or climate change and the relationship between these response mechanisms and potential rates of shoreline change and associated coastal hazard impacts at a Western Port wide scale.

The following sections summarise the underlying sensitivity of the major shoreline classes in Western Port to sea level rise and the likely rates of shoreline change and level of uncertainty that exists in assessing coastal hazard impacts on these shorelines at a Western Port wide scale.

5.1.1 Coastal Wetland Fringed Shorelines

Coastal wetlands, largely comprising coastal saltmarsh and mangroves, represent one of the most extensive shoreline classes in Western Port.

These shorelines are particularly sensitive to sea level rise as mangroves and saltmarsh can only survive in a relatively narrow range of inundation regimes and the saltmarsh-mangrove depositional terrace generally has a very low gradient, such that relatively small absolute changes in mean sea levels results in large relative changes to the frequency and extent of inundation across the terrace.

Mapping of the changes in the modelled MHWS tidal plane due to sea level rise resulted in significant landward translation of the tidal inundation regime that currently defines the seaward and landward extent of mangroves in Western Port.

For sea level rise scenarios of approximately 0.5 m or greater, the MHWS tidal plane would extend across the majority of the existing saltmarsh-mangrove depositional terraces and intersect steeper backshore landforms in Western Port. In many locations in Western Port, the backshore landforms are associated with earlier, mid-Holocene sandy beach ridges.

Under these conditions, the shorelines are unlikely to provide appropriate inundation regimes to support extensive areas of coastal saltmarsh and the extent of mangroves would also be expected to be compromised by predicted significant increases in wave energy along the seaward mangrove fringe and subsequent increase in sediment transport dynamics.

Broad coastal hazard areas could therefore be expected to develop at the interface of the saltmarsh-mangrove terrace and backshore landforms including sandy beach ridges and bluffs, as frequent tidal inundation and increased wave action impact these previously isolated backshore landforms.

The predicted rates of change and responses of coastal wetland fringed shorelines may however be mitigated by the following:

- The ability of these vegetation communities to increase surface/sediment elevations via sediment deposition ; and
- Below ground organic production and possibly due to increases in mangrove productivity due to a warming climate and reduced incidence and severity of frosts.

5.1.2 Low Earth Cliffed Shorelines

Low earth cliffed shorelines occur relatively extensively on the eastern shorelines of Western Port and are highly susceptible to future shoreline change and are generally undergoing active, shoreline erosion and recession under existing sea level conditions.

Current rates of shoreline recession could be expected to increase significantly with sea level rise as the duration and depth of tidal inundation across the broad intertidal mud flats fronting these shorelines will enable very significant increases in the amount of wave energy expended to occur. Significant increases in the rates of future shoreline recession are projected for these shorelines.

Where sea level rise results in frequent, tidal backshore inundation, the persistent flood and ebb tide flows through failed levees and/or natural depressions in the backshore landscape could be expected to result in relatively rapid dissection of the shoreline as tidal channels develop and expand in response to the extent of backshore inundation generated by tidal water level variations along these shorelines.

The potential for this rapid response to sea level rise to occur on these shorelines is however currently controlled by the presence of extensive networks of raised embankments and levees (informal and formal) that have been constructed adjacent to these shorelines to prevent ingress of saline coastal waters during large storm tide events. The future maintenance and adaptation of these levees will largely control the rates and types of response that occurs due to sea level rise along these shorelines.

5.1.3 Hard Rock Cliff and Shore Platform Shorelines

Active, hard rock cliff and shore platform shorelines occur extensively in the southern sections of Western Port. The most extensive, highest and steepest slopes are in Palaeogene volcanic basalts along the Bass Strait coastline from Cape Shank to Flinders.

The local morphology of these shorelines is related to the resistance of the material and the relative exposure to wave energy. In many locations, the underlying hard rock lithology is capped by deeply weathered regolith. These slopes are particularly susceptible to deep-seated mass movements that may be precipitated by a combination of sub aerial processes and/or due to marine influences at the base of the cliff.

Sea level rise over the timeframes considered in this study are not considered to significantly influence the extent of potential hazards associated with slope failures/mass movements on these shorelines however, sea level rise may possibly increase the likelihood and/or frequency of these hazards along these shorelines.

Slope failures are considered a potential significant source of hazard along these shorelines in Western Port as they can result in major impacts landward of the cliff edge and can occur with little to no warning.

Detailed, site specific knowledge of the geology, geomorphology, hydrogeology and the soil and rock mechanics is however required to assess the site specific soil and rock slope stability and potential failure mechanisms along these shorelines. For these reasons, a conservative assessment of the potential extent of hazards resulting from slope failures and mass movements along these shorelines in Western Port has been adopted for this study.

5.1.4 Platform Beach and Bluff

This complex shoreline type occurs extensively along the western shorelines of Western Port and Phillip Island as well as the some southern sections of French Island.

These shorelines are comprised of bluffs of deeply weathered regolith that have been isolated from direct marine influence by the accumulation of sand and gravel breach ridges and plains. Many of these bluffs in Western Port likely existed as active marine cliffs during the mid-Holocene higher sea level still stand.

These shorelines generally have a high degree of spatial heterogeneity and complexity associated with the underlying structure of the geologic formations and associated shore platforms as well as the width of the sandy platform beach and plain.

The potential response of the platform beaches to sea level rise is likely to be complex and site specific; however the platform beaches are expected to be translated landward at a rate that is a function of the slope of the underlying shore platform. This will essentially result in the recession of the sandy shoreline and narrowing of the sandy plain in front of the bluffs with sea level rise.

Depending on the sea level rise scenario and the initial width of the sandy plain in front of the bluffs, it is likely that platform beach and plain will be narrowed to such an extent that marine influences may begin to impact the material comprising the base of the bluffs along sections of these shorelines.

A potential non-linear hazard response along these shorelines is a possible consequence of the loss of the sandy beach platforms, as the deeply weather regolith comprising the bluffs may be vulnerable to mass movements once the base of the bluff is destabilised by wave action. For this reason, a conservative assessment of the potential extent of hazards resulting from slope failures and mass movements along these reactivated bluffs in Western Port has been adopted for this study.

5.1.5 Soft Rock, High Cliffed Shorelines

Limited exposure of high cliffs in deeply weathered and/or weakly consolidated sediments occurs in Western Port. They are differentiated from other steep sloped shorelines in Western Port as their lithology generally results in different erosion processes and rates of change.

A range of sub-aerial processes contribute to erosion of these shorelines and intermittent wave action at the base of the cliff can undermine the cliff face resulting in block detachment/toppling of the cliff material onto the shore platform.

Increased rates of cliff erosion could be expected on these shorelines due to the increased amount of wave energy that would be expended on the cliff face due to sea level rise; however the processes and rates of change are likely to continue to vary linearly.

5.1.6 Sandy Spit Shorelines

The extent of unconstrained, sandy shorelines in Western Port is limited to a few discrete landforms. This is a function of the generally bold coastal relief and lithology of the cliffed shorelines which yields little beach material when eroded.

These landforms are particularly young, with the majority of these shorelines only forming following the Holocene marine transgression into Western Port approximately 10,000 years ago. The combination of their young age, unconsolidated geology and major influence of sediment transport processes associated with wave and tides is such that the shorelines are exceptionally dynamic geomorphologic environments.

A particular feature of the sediment transport processes along these shorelines that results in large underlying shoreline variability and subsequent coastal hazard impacts is associated with the migration of backshore sand lobes. Review of the detailed LiDAR survey and historical aerial photography of these landforms reveals the scale of shoreline variability that can be attributed to this process.

The assessment of the potential future rates of change and coastal hazard impacts along these shorelines due to underlying variability associated with the migration of backshore sand lobes and the impacts of sea level rise is particularly uncertain.

Aspects of the genesis and processes that transport sediment as large longshore migrating sand lobes along these shorelines are considered poorly understood and the mechanisms by which these shorelines may respond to sea level rise may possibly be not well described by conventional equilibrium profile models.

For these reasons, conservative extents of potential coastal hazards have been adopted for the Western Port scale assessment of these shorelines.

5.1.7 Estuarine and Tidal Channels

This conceptual shoreline type represents a wide grouping of shore perpendicular geomorphic features principally associated with tidal creek/drains and estuaries that occur within Western Port. For the purposes of this study they have been grouped, as they are relevant to the consideration of the potential full extent of coastal hazard impacts in Western Port due to sea level rise.

The critical component of this shoreline class relevant to the assessment of coastal hazard impacts in Western Port is the presence of a tidal or estuarine channel that cuts perpendicular across the shorelines of Western Port. These channels can enable coastal influences to extend considerable distances landward of the main shoreline. Where the elevation of the backshore areas is such that sea level rise may result in tidal variations through these channels causing large areas to become tidally inundated, new shorelines could be expected to develop at the advancing tidal limit in these areas.

Modelling of changes to the tidal limits in Western Port due to sea level rise identified a number of locations in the Koo Wee Rup area that may potentially become tidally engaged and could possibly develop proto shorelines around the tidal limit in these areas.

Lowering of stream gradients along the lower reaches of drains and estuaries in Western Port due to sea level rise may also result in variations in the channel alignments due to the development of more frequent and larger amplitude meanders.

For specific estuarine forms such as ‘intermittently closed and open lakes or lagoons’ (ICOLLs), which occur at locations such as Merricks Creek, the likely response to sea level rise will be an increase in the average berm height. As sea level rise occurs there will be a landward and upward movement of the shoreline at the estuary entrance. The increase in the entrance berm height will result in water levels in the lagoon reaching a higher level before a natural break out can occur across the entrance. This could result in an expansion of semi-permanently inundated areas. This is discussed in Report 6.

5.2 Erosion Trajectories

The current status of these shoreline types and their predicted erosion trajectory is summarised in Table 5-1. This table provides an indication of the general responses to sea level rise that could be expected for each shoreline. The actual responses will be site specific and are discussed in detail for the different shorelines present within the representative locations in Report 6.

Table 5-1 Summary of Shoreline Type Erosion Trajectory

Shoreline Type	Trajectory – Present Mean Sea Level to +0.8 m Sea Level Rise (2100)	
Coastal Wetland Fringed Shorelines	Present	Particularly sensitive to sea level rise as mangroves and saltmarsh can only survive in a relatively narrow range of inundation regimes and the saltmarsh-mangrove depositional terrace generally has a very low gradient, such that relatively small absolute changes in mean sea level results in large relative changes to the frequency and extent of inundation across the terrace.
	+0.2m (2040)	Changes are initiated in the extent of coastal saltmarsh and mangroves, with some shoreward movement of mangroves encroaching on existing saltmarsh extents. Shoreward movement of saltmarsh is generally limited by existing development along the shorelines.
	+0.5m (2070) to +0.8m (2100)	For sea level rise scenarios of approximately +0.5 m or greater, the tide would extend across the majority of the existing saltmarsh-mangrove depositional terraces and intersect with steeper backshore landforms. In many locations the backshore landforms are associated with earlier, mid-Holocene sandy beach ridges. The shorelines are unlikely to provide appropriate inundation regimes to support extensive areas of coastal saltmarsh and the extent of mangroves would also be expected to be compromised by predicted significant increases in wave energy along the seaward mangrove fringe and subsequent increase in sediment transport dynamics.
Low Earth Cliffed Shorelines	Present	Historically and presently undergoing active shoreline recession.
	+0.2m (2040) to +0.8 (2100)	These shorelines are highly susceptible to future sea level rise impacts. Current rates of shoreline recession could be expected to increase significantly with sea level rise as the duration and depth of tidal inundation across the broad intertidal mud flats fronting these shorelines will enable very significant increases in the amount of wave energy expended on these low cliffed shorelines to occur. Significant increases in the rates of future shoreline recession are projected for these shorelines. Where sea level rise results in frequent, tidal backshore inundation, the persistent flood and ebb tide flows through failed levees and/or natural depressions in the backshore landscape could be expected to result in relatively rapid dissection of the shoreline as tidal channels develop and expand in response to the extent of backshore inundation generated by tidal water level variations along these shorelines.

Shoreline Type	**Trajectory – Present Mean Sea Level to +0.8 m Sea Level Rise (2100)**	
Hard Rock Cliff and Shore Platform Shorelines	Present	The local morphology of these shorelines is related to the resistance of the material and the relative exposure to wave energy. In many locations along these shorelines the underlying hard rock lithology is capped by deeply weathered regolith. These hard rock cliff slopes are particularly susceptible to deep-seated mass movements that may be initiated by a combination of surface processes and/or due to marine influences at the base of the cliff.
	+0.2m (2040) to +0.8 (2100)	Sea level rise over the timeframes considered in this study (to 2100) are not considered to significantly influence the extent of potential hazards associated with slope failures/mass movements on these shorelines; however, sea level rise may possibly increase the likelihood and/or frequency of these hazards along these shorelines. Slope failures are considered a potential significant source of hazard along these shorelines in Western Port as they can result in major impacts landward of the cliff edge and can occur with little to no warning.
Platform Beach and Bluff	Present	These shorelines are comprised of bluffs of deeply weathered regolith that have been isolated from direct marine influence by the accumulation of sand and gravel beach ridges and plains. Many of the existing bluffs in Western Port likely existed as active marine cliffs during the mid-Holocene higher sea level still stand. Due to their isolation from the marine influences they are currently not experiencing active coastal erosion. These shorelines generally have a high degree of local variability and complexity associated with the underlying structure of the geologic formations and associated shore platforms as well as the width of the sandy platform beach and plain.
	+0.2m (2040) to +0.8 (2100)	The potential response of the platform beaches to sea level rise is likely to be complex and site specific; however the platform beaches are expected to migrate landward at a rate that is a related to the slope of the underlying shore platform. This will essentially result in the recession of the sandy shoreline and narrowing of the sandy plain in front of the bluffs with sea level rise. Depending on the sea level rise scenario and the initial width of the sandy plain in front of the bluffs, it is likely that platform beaches and plains will be narrowed to such an extent that marine influences may begin to impact the material comprising the base of the bluffs along sections of these shorelines. Failure of the cliffs could then be initiated.

Shoreline Type	**Trajectory – Present Mean Sea Level to +0.8 m Sea Level Rise (2100)**	
Soft Rock, High Cliffed Shorelines	Present	A range of surface processes contribute to erosion of these shorelines and intermittent wave action at the base of the cliff can undermine the cliff face resulting in block detachment/toppling of the cliff material onto the shore platform. Erosion under present mean sea level conditions is site specific.
	+0.2m (2040) to +0.8 (2100)	Increased rates of cliff erosion could be expected on these shorelines due to the increased amount of wave energy that would be expended on the cliff face due to sea level rise; however the processes and rates of change are likely to continue to vary linearly.
Sandy Spit Shorelines	Present	These landforms are particularly young, with the majority of these shorelines only forming following the Holocene marine transgression into Western Port approximately 10,000 years ago. The combination of their young age, unconsolidated geology and sediment transport associated with waves and tides is such that these shorelines are exceptionally dynamic geomorphologic environments. A particular feature of the sediment transport processes along these shorelines that results in large underlying shoreline variability and subsequent coastal hazard impacts is the migration of backshore sand lobes. Review of the detailed LiDAR survey and historical aerial photography of these landforms reveals the scale of shoreline variability (both erosion and accretion) that can be attributed to this process.
	+0.2m (2040) to +0.8 (2100)	Potential future rates of change and coastal hazard impacts along these shorelines due to the underlying variability associated with the migration of backshore sand lobes[5] and equilibrium shoreline recession[6] as a response to sea level rise is uncertain. These processes are described in detail in Reports 5 and 6. Aspects of the genesis and processes that transport sediment as large longshore migrating sand lobes along these shorelines are considered poorly understood. Consequently, the mechanisms by which these shorelines may respond to sea level rise may possibly not be well described by conventional sandy shore response models (referred to as 'equilibrium shoreline recession models').

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[5] In Western Port these sandy shorelines experience dynamic and intermittent longshore sediment movement which takes the form of large scale lobes of sand that migrate along the shoreline.

[6] Equilibrium shoreline recession describes the adjustment of the beach and shallow offshore areas to a rise in sea level through upward and landward movement. A key assumption is that the beach profile is in equilibrium with the present mean sea level.

Shoreline Type	**Trajectory – Present Mean Sea Level to +0.8 m Sea Level Rise (2100)**	
Estuarine and Tidal Channels	Present	Estuarine and tidal channels around Western Port occur in many different forms. The critical component of this shoreline class relevant to the assessment of coastal hazard impacts in Western Port is the presence of a tidal or estuarine channel(s) that cuts perpendicular across the shoreline. These types of channel link the coastal systems to backshore areas and can extend considerable distances landward of the main shoreline. Present conditions with relation to erosion of these systems are site specific.
	+0.2m (2040) to +0.8 (2100)	Where the elevation of the backshore areas is such that sea level rise may result in tidal variations through the estuarine or tidal channels this may result in large backshore areas becoming tidally inundated. With increasing frequency of inundation in these backshore areas new shorelines could be expected to develop at the advancing tidal limit. Lowering of stream gradients along the lower reaches of drains and estuaries in Western Port due to sea level rise may also result in variations in the channel alignments due to the development of more frequent and larger amplitude meanders. For specific estuarine forms such as 'intermittently closed and open lakes or lagoons' (ICOLLs), which occur at locations such as Merricks Creek, the likely response to sea level rise will be an increase in the average berm height. As sea level rise occurs there will be a landward and upward movement of the shoreline at the estuary entrance. The increase in the entrance berm height will result in water levels in the lagoon reaching a higher level before a natural break out can occur across the entrance. This could result in an expansion of semi-permanently inundated areas.

5.3 Uncertainty

The uncertainty related to both the existing knowledge and assessment methods used to underpin this erosion hazard assessment are briefly outlined in the following table.

Table 5-2 Summary of Key Erosion Hazard Uncertainties

Shoreline Type	Key Uncertainties
Coastal Wetland Fringed Shorelines	The level of uncertainty is low to moderate; the adaptive capabilities of vegetation communities may limit the impact of modest amounts of sea level rise but relatively major loss of coastal wetlands could be expected by the end of the century. An upper limit on the probable extent of erosion hazards can be reasonably defined.
Low Earth Cliffed Shorelines	Ongoing high rates of cliff recession are virtually certain. The uncertainty relating to the trajectory and probable rates of change is considered low.
Hard Rock Cliff and Shore Platform Shorelines	Detailed site specific knowledge of the geology, geomorphology, hydrogeology and the soil and rock mechanics is necessary to assess the local soil and rock slope stability and potential failure mechanisms along these shorelines. A moderate level of uncertainty exists in understanding the key processes influencing erosion of these shorelines due to the site specific nature of the local underlying geology. Site specific data and specialist geotechnical assessments are required to improve confidence at the lot/parcel scale.
Platform Beach and Bluff	Erosion hazards at these shorelines will occur as a possible consequence of the loss of the sandy beach platforms currently situated shoreward of deeply weathered bluffs. These bluffs may be vulnerable to mass movements once the base of the bluff is destabilised by wave action. A moderate level of uncertainty exists in understanding this process due to limited information or understanding of the underlying geology and potential hazard processes. Site specific data and specialist geotechnical assessments are required to improve confidence at the lot/parcel scale.
Sandy & Sandy Spit Shorelines	Erosion hazards along these shorelines are generally due to two main mechanisms; backshore migrating sand lobes, and equilibrium profile recession. Where backshore migrating sand lobes are present, a high level of uncertainty exists in understanding the likely response of these shoreline types to sea level rise. This is because the sediment transport processes are highly dynamic, can be intermittent, and vary both spatially and in time. Decision making in response to this hazard is only considered appropriate at the landform/settlement scale. Estimating equilibrium profile recession is considered to have a moderate level of uncertainty due to limitations of available assessment methods.
Estuarine & Tidal channels	Significant backshore tidal inundation is increasingly likely towards the end of the century within some areas such as the Koo Wee Rup Swamp. The level of uncertainty is considered low to moderate as the impact of this hazard on erosion processes can be predicted relatively confidently based on existing conditions. However future adaptive responses to levees or embankments

Shoreline Type	Key Uncertainties
	and the South Gippsland Highway will likely influence the hazard extent towards the end of the century.

5.4 Recommendations

The following recommendations are drawn from the results and findings of this Part A broad scale Erosion Hazard Assessment. Part B of the project detailed in Report R06, builds upon this work and provides a detailed local scale assessment of coastal hazards at four critical locations.

5.4.1 Critical Locations (for Part B Assessment)

In general, the results of the Western Port wide erosion hazard assessment have indicated the following:

- The “low” shoreline classes of coastal wetland fringed shorelines and low earth cliffed shorelines are likely to see the most rapid and largest responses to sea level rise;
- The low earth cliffed shorelines are perhaps more susceptible to major change than the coastal wetlands as in a number of locations they are backed by extensive low elevation plains which would become vulnerable to extensive tidal inundation;
- The “environmental values” of the coastal wetland fringed shorelines would be significantly impacted, particularly coastal saltmarsh as there are limited backshore areas for these vegetation communities to migrate into as sea level rises.
- Sandy spit shorelines are also particularly susceptible to rapid and significant change as they are highly variable geomorphic environments and the shoreline position is strongly influenced by sediment supply and transport processes. It is therefore difficult to predict future changes; however the geomorphic evidence suggests that these shorelines have shown major variability to changes in sea level and sediment supply.
- Although the platform beach and bluffs shorelines currently appear less susceptible to erosion, compared to other shoreline classes in Western Port, it is important to note that they are susceptible as the potential for major slope failures to occur on the bluffs as a result of rising sea levels and destabilisation of the base of the bluffs is possible.

Therefore it is recommended that the Part B assessment locations are chosen to be representative of a range of shoreline types, particularly those most susceptible to shoreline erosion due to sea level rise.

5.4.2 Future Data Collection & Knowledge Requirements

Further data, information or knowledge as outlined in the follow table would allow improved understanding of erosion hazard drivers and processes in Western Port and would allow the erosion hazard extent to be refined further.

Table 5-3 Recommended Data Collection, Monitoring and Future Assessments to Improve Certainty in the Erosion Hazard Estimation

Knowledge Gap or Uncertainty	Recommended Data Collection, Monitoring or Future Assessments
Response of Vegetation to Sea Level Rise	Data collection through long term monitoring programs: • To assess the ability of mangrove and salt marsh communities to increase surface/sediment elevations via sediment deposition. • To determine the impact of other climate change related factors such as increased atmospheric CO_2 and the reduction in the frequency of frost events on mangrove productivity. The monitoring program should be designed to also consider the effects of inundation frequency on mangrove response rates to sea level rise.
Condition Assessment of Existing Coastal Levees	The coastal levees and embankments (formal and informal) around Western Port in many instances control inundation extents, particularly on the low earth cliffed shorelines. The ownership and condition of these levees along with future maintenance and adaptation will impact upon the rates and types of responses that occur due to sea level rise along these shorelines. While acknowledging that many of the existing structures are in private ownership and/or on private land it is recommended consideration be given to undertaking an audit and condition assessment of these structures along with more detailed assessment of their potential to impact inundation of both private and public assets.
Sediment transport processes associated with backshore migrating sand lobes	Dating of the sediments and individual dune ridge sequences of the Sandy Spit landforms would enable the evolutionary trajectory and underlying variability of these landforms to be understood with much greater confidence and may provide the ability to refine hazard extents on these landforms. Improved understanding of the drivers and processes involved in genesis and transport of these sand lobes could be gained through additional study of the morphological dynamics of Middle Bank (in the western entrance of Western Port). However, such a study would require a significant field monitoring program and may not result in further refinement of the predicted erosion hazards along the sandy shorelines. Collation of further local information, such as oblique photographs, community history and recollections could inform an understanding of how these sand lobes have varied.
How backshore tidal channels develop into new shorelines	Further modelling of locations in the Koo Wee Rup Swamp that may potentially become tidally engaged and could possibly develop proto shorelines around the tidal limit in these areas would aid in understanding the potential risks to these areas and the time scale over which these processes may occur. This could include simulation of wave and tidal conditions for different levels of shoreline erosion, explicitly included within the model bathymetry.

Knowledge Gap or Uncertainty	Recommended Data Collection, Monitoring or Future Assessments
	A field monitoring program of sites where these types of changes are or are likely to occur could inform an understanding of the possible responses to these shorelines to sea level rise and be used to refine any future analysis of backshore inundation or channel development.
How lowering of stream gradients, along the lower reaches of drains and estuaries due to sea level rise may alter channel meander patterns	Lowering of stream gradients along the lower reaches of drains and estuaries in Western Port due to sea level rise may result in variations in the channel alignments due to the development of more frequent and larger amplitude meanders. This could be investigated further through additional geomorphic analysis, potentially utilising process based sediment transport modelling tools.
Slope Stability	Detailed, site specific knowledge of the geology, geomorphology, hydrogeology and the soil and rock mechanics through a geotechnical assessment is recommended in order to further understand the stability and potential failure mechanisms along the Hard Rock Cliff and Shore Platform shorelines
Underlying erosion processes and rates of change	Collection of repeat survey data sets of key landforms would enable the underlying processes and rates of change to be quantified more precisely and assist in refining estimates of future rates of change due to sea level rise. Emerging survey data capture technologies such as unmanned aerial vehicles (UAV's) are considered to provide the opportunity to cost effectively and accurately survey large lengths of coastline at high resolution and accuracy. The impact of specific "one-off" extreme events on erosion prone shorelines such as the low earth cliffs would extend the current understanding of the erosion processes i.e. for low earth cliffs, is the erosion predominantly driven by single large events or is it more progressive over time. The results of the current CSIRO study (CSIRO, 2013) of the low earth cliffs at Lang Lang may inform this. Continued acquisition and analysis of aerial imagery. Collection and analysis of wind and wave data, particularly for major storm events.
Impact of changes in groundwater on cliffed shorelines	Further studies are required to address the current lack of knowledge of both the processes associated with changes in groundwater levels on cliffed shorelines and the possible responses under present sea level and with sea level rise. It is recommended that any future site specific slope stability assessments for cliffed shorelines should consider the impact of raised groundwater levels on the maximum stable slope.

5.4.3 Assumptions

Coastal Structures

The analysis of local coastal hazards has adopted a precautionary approach with respect to the effect of existing coastal structures on erosion hazards. In locations where a coastal structure is present that is currently or has in the past provided some form of protection against local erosion the determination of the erosion hazard zone does not consider the presence of the structure in limiting potential future erosion, except for a small number of specific coastal infrastructure related structures detailed in Table 5-4. This is because many of the coastal structures in Western Port are informal and/or poorly designed and constructed and they are vulnerable to damage or failure due to extreme storm events or chronic exposure to wave action. Erosion hazards landward of these structures may develop quickly during future events if the structure is not maintained and upgraded to relevant engineering design standards. This approach is in keeping with the approach adopted for other coastal hazard assessments in Victoria and also in the recently released Queensland Coastal Hazard Technical Guidelines, EHP (2013).

In the locations detailed in Table 5-4 the erosion hazard zone extent has been reduced due the presence of coastal engineering structures at these locations. These locations and associated coastal structures are typically major marine infrastructure such as ports, harbours, or boat ramps, and may include sections of rock seawall or revetments as part of the infrastructure. It is considered that the coastal structures in these locations will be maintained and upgraded to an approved engineering design into the future and that any such repairs as are required would be promptly addressed.

Table 5-4 Coastal structures specifically included within coastal hazard layers

Location	Structure
Cowes	Jetty
Newhaven	Newhaven – Phillip Island Bridge
Tooradin	Rock wall adjacent to the tidal gates at Sawtells Inlet and rock revetment extending to the boat ramp.
Sommerville	Yaringa Boat harbour
Blind Bight	Boat Ramp
Hastings	Port of Hastings
Hastings	Hastings Marina
Crib Point	Jetty
Stony Point	Jetty
Cerberus	Defence Base

Changes below MHWS

Changes to the configuration or elevation of the coastal bathymetry below present mean sea level were not modelled or assessed in this study. It was assumed based on historical rates of change, sediment properties, and the detailed review of physical processes in Western Port that has been undertaken for this study, that elevation changes associated with increased deposition or erosion in these areas will not be sufficient to impact modelled water levels, inundation extents, or determination of wave energy.

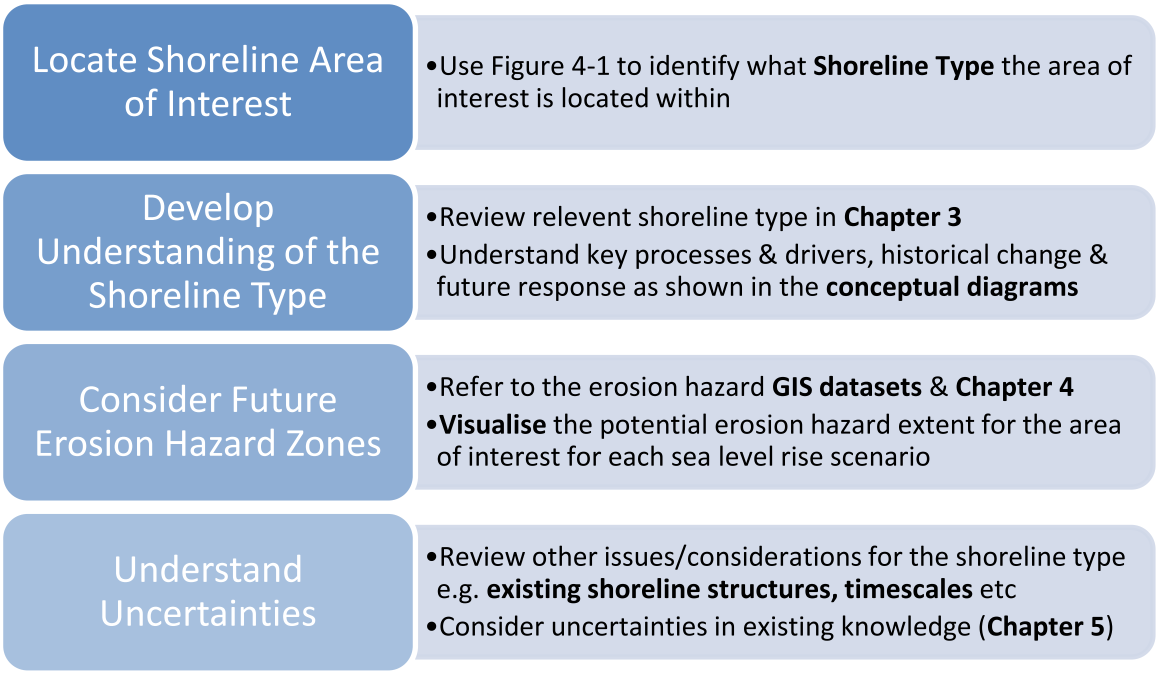
For instance, in areas, such as the eastern shoreline, significant erosion of the shoreline has occurred and is predicted to continue to occur over the time scale to 2100. As the banks erode the fine grained material eroded (typically mud) can be moved around Western Port with the tidal movements or deposited in the intertidal areas. Due to the fine nature of the material the rate of deposition is low and the subsequent rate of accretion of the intertidal flat is also low. Consolidation of this material can also occur which would reduce the rate of vertical accretion.

In low lying areas where significant erosion and backshore inundation could occur as a result of sea level rise, the effect of inundation on erosion rates or erosion on the extent of inundation have not been modelled. This approach was adopted as it is not possible to accurately quantify the spatial extent of erosion at a given location at a given time in the future due to the uncertainty around rates and progress of the erosion (episodic or gradual). There may be local effects related to wave energy on the shoreline due to changes in fetch and water depths as sea level rises and material is exposed which could change the rate of shoreline erosion, although without further information of sediment properties this cannot be quantified.

For areas where sand movement is important, such as Silverleaves on Phillip Island or the Somers-Balnarring shoreline, sea level rise may alter the flow movements within Western Port bay and change the dynamics of the sand movement which could influence shoreline recession and accretion. Due to the high level of uncertainty around the existing dynamics of large scale sand movement in this system, only qualitative predictions of future changes to these processes can be made.

5.5 How to Use the Study Outputs

The information contained in this report along with the erosion hazard GIS datasets can be used to provide a better understanding of erosion hazards in an area of interest, particularly the key process and drivers of change and how these may be impacted by sea level rise. Figure 5-1 outlines the typical process for applying the erosion hazard assessment outputs to assess potential risks for a particular section of the Western Port shoreline.



Locate Shoreline Area of Interest

- Use Figure 4-1 to identify what **Shoreline Type** the area of interest is located within

Develop Understanding of the Shoreline Type

- Review relevent shoreline type in **Chapter 3**
- Understand key processes & drivers, historical change & future response as shown in the **conceptual diagrams**

Consider Future Erosion Hazard Zones

- Refer to the erosion hazard **GIS datasets** & **Chapter 4**
- **Visualise** the potential erosion hazard extent for the area of interest for each sea level rise scenario

Understand Uncertainties

- Review other issues/considerations for the shoreline type e.g. **existing shoreline structures, timescales** etc
- Consider uncertainties in existing knowledge (**Chapter 5**)

Figure 5-1 How to Use the Erosion Hazard Assessment Outputs

The outputs from the erosion hazard assessment should also be considered in conjunction with the inundation hazard assessment detailed in Report 4. An overview of both the erosion and inundation hazard assessments is provided in the project Summary Report (R01).

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APPENDIX A PERIPHERAL VEGETATION

Western Port local coastal hazard assessment

Impacts of sea-level rise on peripheral vegetation

Mangroves fringing Western Port, Tooradin

Dr Paul I Boon

Dodo Environmental
15 Yawla Street
McKinnon VIC 3204

dodoenvironment@ozemail.com.au

(03) 9557 3342

Final report – 12 June 2013

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Types of peripheral vegetation

Tolerance to inundation and to salinity

Peripheral vegetation, succession and shoreline stability

Impacts of climate change – an overview of threats

Impacts of climate change – sea-level rise

Summary

This report provides a detailed overview of the peripheral water-dependent (wetland) vegetation of Western Port and is designed to help inform decision-making about coastal hazards along this part of the Victorian coast. It focuses on : i) the types and extents of peripheral vegetation around Western Port; ii) the tolerance/sensitivity of this vegetation to (tidal) inundation and to salinity; iii) the roles peripheral vegetation plays in shoreline stabilization; and iv) the likely impacts of sea-level rise on vegetation type and extent. As sea-level rise is only one manifestation of climate change, a brief overview of the likely impacts on plant performance of other important components, such as higher temperature and altered atmospheric CO_2 concentration, is included as well.

Western Port is fringed by many different types of water-dependent vegetation, including mangrove (*Avicennia marina*) shrublands, coastal saltmarsh (of various species), Sea Rush (*Juncus kraussii*) marshes, and Swamp Paperbark (*Melaleuca ericifolia*) swamps. At least eight other less well-known vegetation types (i.e. Ecological Vegetation Classes) may also occur in the region. The peripheral vegetation is critical in providing shelter, roosting sites, nesting sites, and food to large populations of migratory waders and other shorebirds.

Western Port accounts for a significant proportion of the total area of mangroves and of coastal saltmarsh in Victoria. There are over 1,700 ha of mangroves in Western Port, of which a substantial proportion (475 ha, or ~20%) occurs on the northern shore of French Island. Only the Corner Inlet-Nooramunga complex has larger total area of mangroves than does Western Port. The combined area of the different types of coastal saltmarsh in Western Port is 1,088 ha, with an additional 860 ha on French Island, 10 ha on the Lang Lang coast, and 49 ha in The Inlets. The only parts of the State with greater extents of coastal saltmarsh are in the Gippsland Lakes; substantial areas occur also in the Connewarre-Barwon River complex (1,605 ha) and around Port Phillip (1,378 ha), each with roughly the same area of saltmarsh as Western Port.

Two recent meta-analyses have shown convincingly that peripheral vegetation – mangroves and coastal saltmarsh – makes shorelines less susceptible to erosion and to damage by storm surges, and potentially even to small tsunamis.

The relationship between the level of the sea and the level of the sediments – and thus the extent of tidal inundation – is a crucial factor in the establishment, structure and function of coastal wetlands. Because of this relationship, a good understanding of the tolerance/sensitivity of different vegetation types to salinity and to inundation/desiccation is needed in order to infer the likely effects of sea-level rise on peripheral vegetation. The information base on hydrological and salinity regimes for plants in temperate mangroves and coastal saltmarshes is, however, extremely poor, and this deficiency presents a significant impediment to better understanding and prediction.

Coastal wetlands are dynamic environments. They change and evolve in concert with a suite of external pressures, orchestrated by complex synecological relationships and by random or stochastic events. Even so, plants in coastal wetlands are likely to be affected strongly by climate change and there is growing evidence that impacts are already being seen as, for example, described recently with Tasmanian coastal saltmarshes.

As sea-level rise is only one manifestation of climate change, ecological impacts are likely to occur as a consequence of the other physical and chemical components of the climate-change phenomenon, including: i) higher air temperatures and decreased incidence of frosts; ii) increased CO_2 concentrations in the atmosphere; iii) altered patterns of rainfall, freshwater run-off and river discharge; iv) increased evaporation rates; v) increased incidence of wild fires; and vi) effects of altered patterns of water circulation on plant dispersal.

The most obvious impact of rises in relative sea levels is that coastal wetlands and other types of peripheral vegetation may be inundated more frequently and more deeply with sea water. The simplest expectation is that saltmarshes would be replaced by mangroves, and mangroves by seagrasses. In more elevated positions along the coast, the frequency of inundation from storm surges will likely increase and this would be expected to have profound effects on the water and salinity regimes in fringing wetlands. Saltmarsh may invade into Swamp Paperbark woodlands, as has been observed to occur in the Gippsland Lakes. In turn, Sea Rush and Swamp Paperbark may also migrate into the hinterland, into currently terrestrial plant communities dominated by, for example, Manna Gum (*Eucalyptus viminalis*). Steep hills or dunes discourage the formation of extensive wetlands and, in a number of places along the Victoria coast (e.g. around Phillip Island), peripheral vegetation abuts steep terrain and thus has nowhere to retreat should sea levels rise. Moreover, the intensity of post-colonization development on coastal plains, often for housing but also for industrial facilities such as ports, has been such that there is little or no room left around much of the coast for a landward retreat of peripheral vegetation as sea levels rise.

Most of the early analyses (i.e. in the 1980s) of the likely impacts on rises in mean sea levels on coastal wetlands concluded that there would be a large-scale loss of wetland habitat. More recent studies have come to slightly different conclusions, as it has been recognized that the critical issue is not so much a simple rise in mean sea level *per se*, but instead that changes in *relative* sea level will be the fundamental determinant of ecological and geomorphological responses to climate change. In other words, if coastal wetlands can maintain their elevation by accumulating sediment and by laying down peat, they can keep up with – as opposed to catch up with – sea-level rise. There is a small information base on changes in surface elevation of sediments around Western Port, but observations ceased ~10 years ago and, as with the current poor understanding of the tolerance/sensitivity of peripheral vegetation to altered hydrological and salinity regimes, this is a significant knowledge gap. The associated problem is that estimates of the potential scale of vegetation loss as a result of sea-level rise will be in error unless changes in surface elevation are considered simultaneously.

Scope of this report

This report is one of a number of sub-consultants' contributions to the Western Port Local Coastal Hazard Assessment undertaken by Water Technology for Melbourne Water. It provides a detailed overview of the peripheral water-dependent vegetation[1] of Western Port and is designed to help inform decision-making about coastal hazards in this part of the Victorian coast. It focuses on : i) the types and extents of peripheral vegetation around Western Port; ii) the tolerance/sensitivity of this vegetation to (tidal) inundation and to salinity; iii) the roles peripheral vegetation plays in shoreline stabilization; and iv) the likely impacts of sea-level rise on vegetation type and extent. As sea-level rise is only one manifestation of climate change, a brief overview of the likely impacts on plant performance of other important components, such as higher temperature and altered atmospheric CO_2 concentration, is included as well.

Types of peripheral vegetation

Plant types and zonation

Western Port is fringed by many different types of water-dependent vegetation, including mangroves, coastal saltmarsh, Sea Rush (*Juncus kraussii*) marshes, and Swamp Paperbark (*Melaleuca ericifolia*) swamps. This fringing vegetation is critical in providing shelter, roosting sites, nesting sites, and food to large populations of migratory waders and other shorebirds. Western Port has been listed as a Ramsar site on the basis of, among other things, the extent and diversity of its coastal wetlands[2]. Large expanses of coastal wetland with such floristic and structural diversity are not common elsewhere in Victoria; mangroves line about 40% of the Western Port shoreline[3] and, second only to the stands of 'bonsai' mangroves at Corner Inlet, are the highest-latitude mangroves in the world[4]. Coastal saltmarshes are also extensive and, unlike the mono-specific mangroves that fringe Western Port, are floristically diverse[5]; they are also relatively undisturbed, unlike many other areas of coastal saltmarsh in south-eastern Australia[6].

Although 17 streams flow into Western Port, their discharge is small (~ 1,100 ML day^{-1}) in comparison with the volume of sea water encompassed within the 68,000 ha of the embayment[7]. What this means is that Western Port is overwhelmingly a mosaic of

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[1] Of course all vegetation is water-dependent to some extent. In the context of the present report, water-dependent means having a requirement for or being tolerant of periodic inundation. Thus the term includes, for example, mangroves and saltmarshes as well as other types of coastal wetlands.

[2] http://www.dse.vic.gov.au/__data/assets/pdf_file/0008/100151/Western_Port_Information_Sheet.pdf Viewed 11/04/2013. See also the most recent Ramsar site Ecological Character Description, by Kellog Brown & Root (2010)

[3] http://www.dse.vic.gov.au/__data/assets/pdf_file/0008/100151/Western_Port_Information_Sheet.pdf Viewed 11/04/2013

[4] Duke (2006); Morrisey *et al.* (2010)

[5] Boon *et al.* (2011)

[6] Laegdsgaard (2006); Laegdsgaard *et al.* (2009)

[7] http://www.dse.vic.gov.au/__data/assets/pdf_file/0008/100151/Western_Port_Information_Sheet.pdf Viewed 11/04/2013

marine – and mostly tidal – environments, and that truly estuarine habitats[8] are limited to small areas around the mouths of the debouching streams. Notwithstanding the overwhelming importance of tidal inundation to plant performance, fresh waters do play critical roles in structuring the peripheral vegetation, maintaining the condition of adult plants, and allowing episodic sexual recruitment to take place[9].

Because the vegetation is extensive, diverse and subject to regular tidal inundation, it is often sorted into clear zones with different plant communities, according to elevation and thus distance from the sea. Areas that are subject to the most frequent tidal inundation are either mud- and sand-flats devoid of vascular plants (but still vegetated with microscopic algae) or vegetated with seagrasses; slightly more elevated areas subject to regular (daily) tidal inundation support mangroves; higher areas subject to less-frequent inundation, coastal saltmarsh; and the highest areas, furthest from the shoreline and inundated only at exceptionally high tides, Sea Rush or Swamp Paperbark communities. Fully terrestrial vegetation lies behind these coastal wetlands, and in Western Port often has a canopy layer dominated by eucalypts such as Manna Gum (*Eucalyptus viminalis*)[10]. Figure 1 shows an example of the peripheral vegetation that fringes much of Western Port.

Figure 1: An example of the types of peripheral vegetation around Western Port, with ephemeral pools occupying the lowest-lying areas, chenopod saltmarsh the intermediate levels, and paperbark the very highest levels, in front of fully terrestrial vegetation dominated by eucalypts and other salt- and inundation-intolerant plant taxa.

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[8] Defined as per Tagliapietra *et al.* (2009)

[9] For example, see Boorman (2009)

[10] Patton (1942); Bird & Barson (1975); Bridgewater (1975); Barson & Calder (1981)

Figure 2 shows an idealized model of how the peripheral vegetation is zoned according to elevation, distance from the sea, and frequency/duration of tidal inundation.

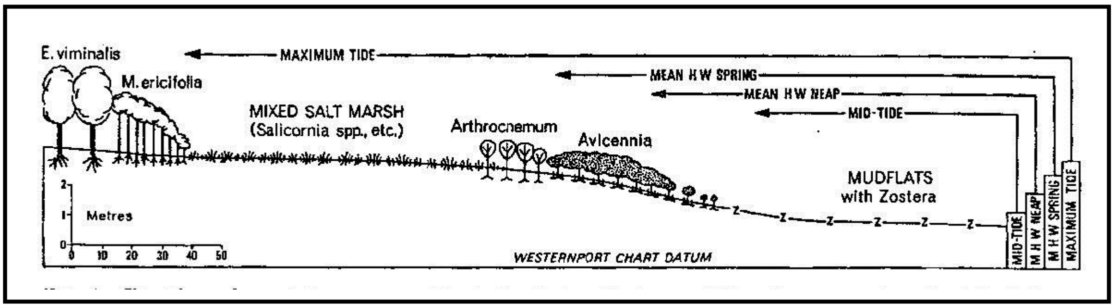
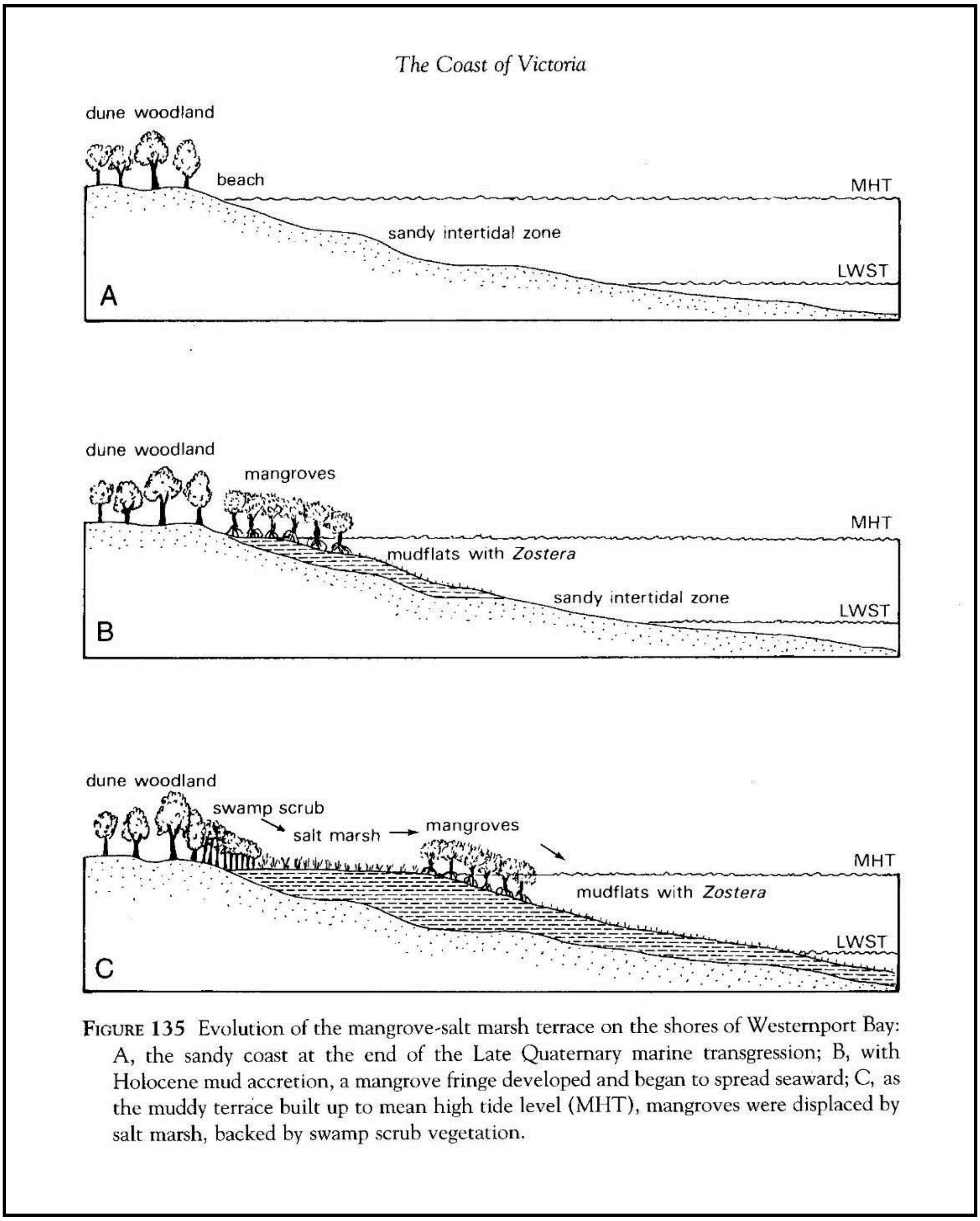


Figure 2: Model of the zonation of vegetation that fringes Western Port. Source: Bird & Barson (1975, Figure 3).

It is unusual for plant zonation to be defined as clearly along the Victorian coast as it is in Western Port. In part this is presumably because Western Port experiences a large tidal range (2.3−3.3 m: Harty 2011), especially in the northern part of the embayment, allied with the existence of a wide range of physical habitats on which different plant communities can develop. The strength of plant zonation was one of the reasons why a number of early studies, especially those by the eminent geomorphologist ECF Bird and co-workers, investigated the role played by tides in controlling vegetation patterns along this sector of the Victorian coast. Figure 3 shows the conceptual model devised by Bird (1993) to explain how peripheral vegetation developed in Western Port and how it was influenced by elevation and thus by tidal inundation.

The clear-cut patterning of different plant types shown in Figures 2 & 3 is, however, to some degree an idealized construction. In practice, the vegetation is not patterned as neatly as the models suggest, and this is because elevation is not related simply to distance from the sea. First, the models ignore the role that subtle microtopographic variation plays in structuring wetland vegetation (e.g. see Raulings *et al.* 2010, 2011). Second, a large number of channels cut across the wetlands that fringe Western Port, and they introduce much spatial complexity into the patterning of peripheral vegetation. The simple and regular plant zonation that occurs with distance from the sea is thus made messy by the additional patterning that occurs at much smaller scales with distance (and thus elevation) from these tidal channels (Figure 4).

Bird (2008) considered tidal channels to be a critical component of the saltmarshes of Western Port. Not only do they allow the penetration of mangrove stands deep into the landward marsh – thus confounding the simple zonation idealized in Figure 2 – but they affect patterns of sediment accretion across the entire band of intertidal vegetation. In the early stages of marsh development, the creeks are wide and shallow, but as vegetation develops on their banks, they become steeper and deeper. Eventually they become so steep that they slump and collapse.



The Coast of Victoria

Figure 135 Evolution of the mangrove-salt marsh terrace on the shores of Westernport Bay: A, the sandy coast at the end of the Late Quaternary marine transgression; B, with Holocene mud accretion, a mangrove fringe developed and began to spread seaward; C, as the muddy terrace built up to mean high tide level (MHT), mangroves were displaced by salt marsh, backed by swamp scrub vegetation.

Figure 3: Development of peripheral vegetation at Western Port, as explained by Bird (1993). Part C) shows the present-day plant zonation, with seagrass beds fronting a band of mangroves, which in turn fronts a saltmarsh community and behind it, a paperbark ('swamp scrub') community.

Figure 4: Tidal channels that cut into coastal wetlands complicate the simple zonation of vegetation types with distance from the sea. Photograph by Neville Rosengren, reproduced with permission.

Mangroves

Mangroves are trees, shrubs or palms, taller than 0.5 m, that grow above mean sea level in the intertidal zone of marine coastal environments and along the margins of estuaries[11]. Only one mangrove species, *Avicennia marina* var. *australasica*, is present in Victoria[12] and the vegetation community it forms is classified as Ecological Vegetation Class (EVC) 140 Mangrove Shrubland[13]. Mangroves occur mostly as a dense mono-specific shrubland, with individuals growing as shrubs or small trees up to ~4 m tall, although at their most southerly extent the plants can be isolated shrubs only ~0.3−0.5 m tall[14]. Frost and/or low winter temperatures are believed to be the environmental factor that limits the distribution, vigour and productivity of mangroves in southern Victoria[15].

The mangroves of Western Port have been subject to a large number of studies, including by Ashton (1971), Enright (1973), Bird & Barson (1975, 1982), Bridgewater (1975), Clough & Attiwill (1975), Shapiro (1975), Opie *et al.* (1984), Bird (1986), Vanderzee (1992), Ross (2000), Boon *et al.* (2010, 2011), Harty (2011), Kirkman & Boon (2012), and Sinclair & Boon (2012). Most of these studies have addressed issues related to plant distributions, and very significant gaps remain in our understanding of other aspects, especially the physiological ecology, of these plants.

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[11] Duke (2006); Woodroffe & Davies (2009)

[12] Duke (2006)

[13] Department of Sustainability and Environment (2012)

[14] Harty (1997); Duke (2006)

[15] Ashton (1971); Oliver (1982)

Coastal saltmarsh

Because of its much greater structural and floristic complexity, it is harder to define coastal saltmarsh[16] than it is mangrove shrubland. Boon *et al.* (2011) reviewed the wide range of definitions that had been proposed in the past, and recommended that coastal saltmarsh be described as 'land that experiences regular low-energy inundation by seawater and which is vegetated by low-growing vascular plants (<1.5 m height), such as succulent chenopods and salt-tolerant monocots'.

Coastal saltmarsh is found along many parts of the Victorian coast, but is best developed between Barwon Heads and Corner Inlet (Barson & Calder 1981). Extensive areas occur along the western coast of Port Phillip Bay, northern parts of Western Port, in the Corner Inlet-Nooramunga complex, and behind the sand dunes that line the Ninety Mile Beach in Gippsland, especially in Lake Reeve. To the west of Barwon Heads, patches occur at Breamlea, the mouth of the Anglesea River and Aireys Inlet, at Port Fairy, and in the estuary of the Glenelg River. To the east of Corner Inlet, saltmarsh fringes the shoreline of the Gippsland Lakes (and is particularly well developed in Lake Reeve) and extends as far east as the mouth of the Snowy River, Wingan Inlet, and Mallacoota. A later section of this report compares the areas of coastal saltmarsh in different sectors of the Victorian coast (see Table 2, below).

In response to the strong west-east gradient in rainfall along the coast (Bureau of Meteorology & Walsh 1993), saltmarsh in the western parts of Victoria differs from that in the east (Barson & Calder 1981). A 'dry' type is present in central-western regions, where low summer rainfall and high temperatures lead to intensely hypersaline conditions in elevated sites; vegetation in these areas is often dominated by *Tecticornia pergranulata* and *Tecticornia halocnemoides*. The 'wet' type is found east of Western Port and is often dominated by samphires such as *Sarcocornia* spp. and *Tecticornia arbuscula*.

In contrast to many Northern Hemisphere saltmarshes (which are often dominated by grasses such as *Spartina* spp. and *Puccinellia* spp.), Victorian coastal saltmarsh is floristically and structurally highly diverse[17]. One structural type consists of succulent shrubs such as *Tecticornia* spp; large tussocky monocots (e.g. *Austrostipa stipoides* and *Gahnia filum*) form another; low rhizomatous grasses (e.g. *Distichlis distichophylla* and *Sporobolus virginicus*) another; succulent herbs (e.g. *Sarcocornia* spp., *Hemichroa Pentandra* and *Disphyma clavellatum*) another; and prostrate shrubs (e.g. *Frankenia pauciflora* and *Wilsonia humilis*) another.

Despite this floristic and structural diversity, coastal saltmarsh is currently allocated to a single EVC (EVC 9 Coastal Saltmarsh Aggregate) in Victoria. The recent State-wide assessment of Victoria coastal wetlands proposed that the current EVC be divided into

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[16] The term 'coastal' is used to differentiate these maritime-influenced saltmarshes from inland saltmarshes, which are also saline or hypersaline and often have similar species and/or genera, but are not subject to maritime/oceanic influences.

[17] See Carr (2012) for a complete inventory of saltmarsh plant species in Victoria.

seven new EVCs that better reflected the floristic and structural diversity in the vegetation[18], and this recommendation has been endorsed as a tentative typology in the 2nd edition of the DSE (now DEPI) monograph on wetland EVCs[19].

Although almost if not all prior mapping of coastal saltmarsh mapped it as a single unit (see Spatial distributions section, below) the taxonomic and structural complexity in Victorian coastal saltmarsh has long been acknowledged. The *Sites of botanical significance in the Western Port region* report by Opie *et al.* (1984), for example, identified three types ('sub-communities') of *Salicornia quinqueflora* saltmarsh (Community 22), seven sub-communities of *Arthrocnemum arbusculum* (now *Tecticornia arbuscula*) saltmarsh (Community 23), and six sub-communities of Mixed Species saltmarsh (Community 23). In contrast, mangroves were all in one group, Community 24 Mangrove. Opie *et al.* (1984, page 241) argued that it was possible to assess the saltmarshes of Western Port as a single group despite this variation, on the dual grounds that it shared little or no overlap in plant species with other vegetation communities in the area (other than possibly for *Melaleuca ericifolia* scrub) and that it occupied a single ecological zone along the coast. In possibly the earliest scientific study of the coastal saltmarsh of Western Port, Patton (1942) had drawn much the same conclusions as to the floristic disjunction between the vegetation of saltmarshes and that of vegetation in the hinterland or even with other coastal vegetation types, such as that of sand dunes.

Mike Vanderzee's (1992) assessment of the vegetation of French Island similarly acknowledged the floristic and structural variety in coastal saltmarsh: he identified two sub-communities of Beaded Glasswort (*Salicornia quinqueflora*) saltmarsh, and six each of Shrubby Glasswort (*Tecticornia arbuscula*) saltmarsh and of Mixed Species saltmarsh. Vanderzee argued that the coastal saltmarsh that occurred along the north coast of French Island was '…one of the best examples of this range of communities and the only area in the Western Port Region and one of the few in Victoria where a substantial area of saltmarsh is reserved [in the French Island State Park]' (Vanderzee 1992, page 18−19).

Other types of peripheral vegetation

Although mangroves and saltmarsh are the most obvious types of coastal wetland around Western Port, both are commonly found nearby, or in mosaics with, a range of other estuarine wetlands that similarly experience a mixture of tidal and freshwater influences. These other types of coastal wetland are often vegetated by dense stands of rhizomatous perennial monocots, including Sea Rush (*Juncus kraussii*) and Common Reed (*Phragmites australis*) in the seaward reaches, and Salt Club-sedge (*Bolboschoenus caldwellii*) and Sharp Club-rush (*Schoenoplectus pungens*) in areas further from the influence of sea water (Sinclair & Sutter 2008). Some of the other types of coastal wetlands around Victoria and possibly also around Western Port include:

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[18] Boon *et al.* (2011)

[19] Department of Sustainability and Environment (2012)

- Estuarine Wetland (EVC 10), dominated by *Juncus kraussii*, occasionally with *Phragmites australis* or species of Cyperaceae.
- Brackish Sedgeland (EVC 13), dominated by *Gahnia trifida* (sometimes *Gahnia filum*) and *Baumea juncea*.
- Swamp Scrub (EVC 53), dominated by *Melaleuca ericifolia*, *Leptospermum lanigerum*, with aquatic or semi-aquatic spp. such as *Isolepis inundata*, *Triglochin procera*, *Villarsia* spp. and *Sphagnum* spp.
- Brackish Wetland (EVC 656), dominated by *Bolboschoenus caldwelli* and/or *Schoenoplectus pungens* and aquatic semi-aquatic species tolerant of at least moderate salinity.
- Tall Marsh (EVC 821), typically vegetated with *Phragmites australis*, *Typha* spp. and *Schoenoplectus tabernaemontani*.
- Estuarine Reedbed (EVC 952), dominated by *Phragmites australis*, with associated species variously including *Samolus repens*, *Juncus kraussii*, *Triglochin striatum*, *Bolboschoenus caldwellii* and *Suaeda australis*.
- Estuarine Scrub (EVC 953) *Melaleuca ericifolia* (in eastern Victoria), with other *Melaleuca* spp. (e.g. *Melaleuca lanceolata*, *Melaleuca gibbosa*) or *Leptospermum lanigerum* in marginal sites in western Victoria. Ground-layer includes *Samolus repens*, *Triglochin striatum* and *Selliera radicans*, variously with *Sarcocornia quinqueflora*, *Gahnia filum*, *Poa poiformis*, *Juncus kraussii*, *Disphyma crassifolium* and *Distichlis distichophylla*.

Table 1 provides a summary of these non-mangrove/non-saltmarsh types of coastal wetland.

As shown in Figure 2, *Melaleuca ericifolia* scrub or woodlands often form a landward fringe to coastal saltmarsh around Western Port. Because of this position in the landscape, paperbarks delimit the spatial extent of 'peripheral vegetation' in my assessment. Currently two distinct forms of *Melaleuca ericifolia*-dominated vegetation types are recognized along the Victorian coast: i) EVC 953 Estuarine Scrub, which posses a halophytic understory and occurs in salt-affected areas; and ii) EVC 53 Swamp Scrub, which also has *Melaleuca ericifolia* as the canopy layer but differs in having a glycophytic understorey. It thus is found in areas that share a roughly similar inundation regime to EVC 953 Estuarine Scrub but without the saline influence.

The different types of *Melaleuca ericifolia*-dominated woodlands occurring in the Western Port region were acknowledged by Opie *et al.* (1984), who recognized four different sub-communities according, in part, to whether they occurred in or around freshwater swamps in sand, clay or peats soils, or in more saline areas bordering costal saltmarsh. The type of most interest to us is the last one, Sub-community 12.1, which has a ground-layer typified by the saltmarsh taxa *Selliera radicans*, *Samolus repens*, and *Disphyma clavellatum* (see Opie *et al.* 1984, page 75). This differentiation was acknowledged also by Vanderzee (1992) in his assessment of the vegetation of French Island, where he recognized three *Melaleuca ericifolia*-dominated wetland-scrub communities.

Table 1: Examples of the range of coastal wetland types found in Victoria.
ECV = Ecological Vegetation Class. Source: Boon (2012)

EVC	EVC name	Characterization	Indicator species
9	Coastal Saltmarsh Aggregate	Low, variously shrubby, herbaceous, sedgy or grassy vegetation of salinised coastal soils, in or adjacent to tidally influenced wetland. Coastal Saltmarsh can include a number of zones of varying structure and floristics, reflecting the regimen of tidal inundation and substrate character	Variously *Tecticornia arbuscula*, *Sarcocornia quinqueflora*, *Suaeda australis* and *Samolus repens*, often in association with *Frankenia pauciflora*, *Atriplex paludosa*, *Puccinellia stricta*, *Juncus kraussii*, *Hemichroa pentandra*, *Selliera radicans* and *Triglochin striata*. *Gahnia filum*, *Austrostipa stipoides*, *Sporobolus virginicus*, *Schoenus nitens*, *Wilsonia backhousei*, *Disphyma crassifolium* and *Distichlis distichophylla* can variously be locally prominent in more peripheral habitats.
10	Estuarine Wetland	Rushland/sedgeland vegetation, variously with component of small halophytic herbs, occurring in coastal areas where freshwater flows augment otherwise saline environments.	*Juncus kraussii*, occasionally with *Phragmites australis* or species of Cyperaceae.
13	Brackish Sedgeland	Sedgeland dominated by salt-tolerant sedges in association with a low grassy/herbaceous ground-layer with a halophytic component.	*Gahnia trifida* (sometimes *Gahnia filum*), *Baumea juncea*, with a mixture of species as for Brackish Herbland and species which are not obligate halophytes.
14	Estuarine Flats Grassland	Tussock grassland or grassy sedgeland beyond zone of normal tidal inundation but sometimes subject to seasonal water-logging or rarely brief intermittent inundation.	*Poa poiformis* with *Ficinia nodosa*, and including non-halophytic species such as *Senecio* spp., *Clematis microphylla* and *Acaena novae-zelandiae*.
53	Swamp Scrub	Dense (and potentially tall shrubby vegetation of swampy flats), dominated by Myrtaceous shrubs (to small trees), ground-layer often sparse, aquatic species conspicuous, sphagnum and/or water-logging tolerant ferns sometimes present.	*Melaleuca ericifolia*, *Leptospermum lanigerum*, with aquatic / semi-aquatic spp. (e.g. *Isolepis inundata*, *Triglochin procera s.l.*, *Villarsia* spp., *Sphagnum* spp.).
842	Saline Aquatic Meadow	Submerged ephemeral or perennial herbland of slender monocots, occurring in brackish to saline water bodies subject or not to dry periods. The vegetation is characteristically extremely species-poor, consisting of one or more species of *Lepilaena* and/or *Ruppia*.	Variously *Ruppia megacarpa*, *Ruppia polycarpa*, *Lepilaena* spp. (e.g. *L. preissii*, *L. bilocularis*, *L. cylindrocarpa*).
140	Mangrove Shrubland	Extremely species-poor shrubland vegetation of inter-tidal zone, dominated by mangroves.	Characteristically occurs as mono-specific stands of *Avicennia marina*. In some stands, species from adjacent Coastal Saltmarsh or Seagrass Meadow also present.
196	Seasonally Inundated Subsaline Herbland	Very species-poor low herbland of seasonal saline wetland within relicts of former tidal lagoons, dominated by	*Wilsonia humilis* sometimes with *W. backhousei* and/or *W. rotundifolia*.

		Wilsonia spp.	
538	Brackish Herbland	Low herbland dominated by species tolerant of mildly saline conditions and rare intermittent inundation.	*Lobelia irrigua*, *Sebaea* spp., *Ranunculus* spp., *Apium annuum*, *Lachnagrostis* spp., *Isolepis cernua*, *Schoenus nitens*, *Wilsonia rotundifolia*; variously *Selliera radicans*, *Distichlis distichophylla* and/or *Samolus repens*.
656	Brackish Wetland	Collective label for the various zones of sedgy-herbaceous vegetation associated with sub-saline wetlands. Components variously include wetter versions of Brackish Sedgeland, Brackish Herbland and Saline Aquatic Meadow.	*Bolboschoenus caldwellii* and/or *Schoenoplectus pungens* and aquatic semi-aquatic species tolerant of at least moderate salinity.
821	Tall Marsh	Wetland dominated by tall emergent reeds, rushes or sedges, typically in dense, species-poor swards.	Typically *Phragmites australis*, *Typha* spp., *Schoenoplectus tabernaemontani.* Associated species are quite variable and can include *Calystegia sepium* and *Urtica incisa* and a range of aquatics.
845	Sea-grass Meadow	Sward-forming aquatic herbland of sheltered marine shallows, inter-tidal flats and lower estuarine habitats.	Dominated by *Zostera* and / or *Heterozostera* spp. (or localised variant also including *Lepilaena marina* and *Ruppia tuberosa*).
934	Brackish Grassland	Grassland on sub-saline heavy soils, including dominants of Plains Grassland (and a portion of associated herbaceous species) in association with herbaceous species indicative of saline soils.	*Poa labillardierei / Themeda triandra*, *Austrodanthonia* spp., *Distichlis distichophylla*, *Calocephalus lacteus*, *Selliera radicans*, *Sebaea* spp., *Wilsonia rotundifolia*, *Lobelia irrigua*; *Poa poiformis* in some coastal sites.
947	Brackish Lignum Swamp	Wetland dominated by *Muehlenbeckia florulenta* with a component or patches of salt-tolerant herbs (at least at low to moderate levels of salinity) and usually also with some species common to freshwater habitats. Can be very species-poor.	*Muehlenbeckia florulenta*, variously with *Samolus repens*, *Isolepis cernua*, *Triglochin striata*, *Chenopodium glaucum*, *Myriophyllum verrucosum*, *Selliera radicans*, *Mimulus repens*, *Distichlis distichophylla*, *Lobelia irrigua*, *Wilsonia rotundifolia*, *Lachnagrostis* spp. and/or *Gahnia filum.*
952	Estuarine Reedbed	Vegetation dominated by tall reeds (usually 2-3 m or more in height), in association with a sparse ground-layer of salt tolerant herbs. Distinguished from Estuarine Wetland by the vigour and total dominance of reeds, and from Tall Marsh by the presence of halophytes.	*Phragmites australis*, with associated species variously including *Samolus repens*, *Juncus kraussii*, *Triglochin striatum*, *Bolboschoenus caldwellii* and *Suaeda australis.*
953	Estuarine Scrub	Shrubland to scrub of Myrtaceous shrub species of sub-saline habitat, occurring in association with ground-layer including halophytic herbs.	*Melaleuca ericifolia* (in eastern Victoria), with other *Melaleuca* spp. (e.g. *Melaleuca lanceolata*, *Melaleuca gibbosa*) or *Leptospermum lanigerum* in marginal sites in western Victoria. Gound-layer includes *Samolus repens*, *Triglochin striata* and *Selliera radicans*, variously with *Sarcocornia quinqueflora*, *Gahnia filum*, *Poa poiformis*, *Juncus kraussii*, *Disphyma crassifolium*, *Distichlis distichophylla.*

Areal extents

Older estimates of the area of different types of coastal wetlands in Victoria were inconsistent and covered only a few vegetation types. Estimates of the total area of mangroves in the State, for example, varied from 12 km^2 (Galloway 1982) to 41 km^2 (Bucher & Saenger 1991, as cited by Harty 1997). Assessed in terms of the area of EVC 140 Mangrove Shrubland, mangroves cover ~66 km^2 in Victoria (Steve Sinclair, Arthur Rylah Institute, *pers. comm.*). Carr (1979) estimated the area of coastal saltmarsh in Victoria as <60 km^2, but the area of EVC 9 Coastal Saltmarsh is ~132 km^2 (Steve Sinclair, Arthur Rylah Institute, *pers. comm.*). Many of the uncertainties in existing values were resolved with the recently completed assessment of Victorian coastal wetlands[20]. Table 2 shows the areas of a number of different types of coastal wetland in Western Port in comparison with areas in some other sectors of the Victorian coast. Areas for all coastal sectors in the State are available in Boon *et al.* (2011).

It is apparent from the values in Table 2 that Western Port accounts for a significant proportion of the total area of mangroves and of coastal saltmarsh in Victoria. There are over 1,700 ha of mangroves in Western Port, of which a substantial proportion (475 ha, or ~20%) occurs on the northern shore of French Island. Only the Corner Inlet-Nooramunga complex has larger total area of mangroves than does Western Port. The combined area of the different types of coastal saltmarsh in Western Port is 1,088 ha, with an additional 860 ha on French Island, 10 ha on the Lang Lang coast, and 49 ha in The Inlets. The only parts of the State with larger areas of coastal saltmarsh are in the Gippsland Lakes; note, however, substantial areas occur also in the Connewarre-Barwon River complex (1,605 ha) and around Port Phillip (1,378 ha), each with roughly the same area of saltmarsh as Western Port.

Table 2 provides areas for two other classes of non-mangrove/non-saltmarsh coastal wetland: EVC 10 Estuarine Wetland, and EVC 196 Seasonally Inundated Subsaline Herbland. In comparison with the much larger extents in other parts of the State, there is only a relatively small area of EVC 10 (a plant community dominated by Sea Rush) in Western Port: the combined estimates for French Island, the Lang Lang coast, Western Port and The Inlets is about ~108 ha. It seems that Western Port does not support EVC 196 (a community dominated by *Wilsonia* spp.), although this type of coastal wetland is scattered along other parts of the Victorian coastline: large expanses of EVC 196 occur, for example, in Lake Reeve and in the Connewarre-Barwon River complex. The absence of saltmarshes dominated by *Wilsonia* spp. around Western Port is perhaps not surprising, given that this wetland type is often associated with sectors of the Victorian coastline that fall into rain shadows. Currently there are no reliable (i.e. recent and fully ground-truthed) estimates of area for the other types of coastal wetland identified in Table 1, although rough estimates could be obtained on the basis of distributions shown on the DSE (DEPI) interactive biodiversity mapsite.

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[20] Boon *et al.* (2011)

Table 2: The extent (hectares) of different types of coastal wetland in Western Port in comparison with areas in other sectors of the Victorian coast. Abbreviations are as follows: CS (Agg) Coastal Saltmarsh (aggregate); WSH (Wet Saltmarsh Herbland), WSS (Wet Saltmarsh Shrubland), CTS (Coastal Tussock Saltmarsh), CSG (Coastal Saline Grassland), SGS (Saltmarsh-grass Swamp), CDS (Coastal Dry Saltmarsh), CHS (Coastal Hypersaline Shrubland), BLS (Brackish Lignum Shrubland), EW (Estuarine Wetland), MS (Mangrove Shrubland), SISH (Seasonally-inundated Sub-saline Herbland). Saline Aquatic Meadow, Brackish Lignum Swamp and Brackish Herbland are not included in this tally, because we did not map all of these EVCs across the State, as described above. Note that due to the inclusion of the 'unresolved' aggregate unit which includes unknown areas of other saltmarsh EVCs, the areas given for WSH, WSS, CTS, SGS, CDS and CHS are minimum values. Source: modified from Boon et al. (2011; Table 5.5).

Coastal sector	**WSH**	**WSS**	**CTS**	**CDS**	**CHS**	**CSG**	**SGS**	**CS**	**All saltmarsh**	**EW**	**MS**	**SISH**
Western Port												
French Island	266	487	6	78	0	3	0	20	**860**	26	475	0
Lang Lang coast	8	0	<1	0	0	0	0	2	**10**	18	2	0
The Inlets	9	20	13	0	0	0	0	7	**49**	6	8	0
Western Port	182	761	39	8	0	0	0	98	**1088**	58	1230	0
Other Gippsland												
Anderson Inlet	58	26	72	<1	0	161	0	33	**349**	81	158	0
Corner Inlet	181	183	25	<1	0	1	0	48	**437**	13	846	0
Lake Reeve	676	0	513	485	115	12	0	393	**2194**	64	0	301
Lake Wellington	2123	0	52	140	12	36	0	36	**2399**	413	0	13
Lakes Victoria & King	1318	0	28	419	4	8	0	59	**1836**	622	0	79
Nooramunga coast	709	857	248	29	0	12	0	105	**1960**	121	994	0
Nooramunga islands	572	598	623	14	0	0	0	119	**1926**	34	1247	0
Shallow Inlet	79	71	18	<1	0	<1	0	3	**171**	8	0	0
Wilsons Promontory	81	40	2	<1	0	0	0	<1	**123**	5	54	0
Other Victoria												
Connewarre-Barwon	702	104	448	71	173	94	3	10	**1605**	133	49	84
Port Phillip	172	202	62	260	383	16	0	283	**1378**	12	6	<1
Victorian total	**8512**	**3801**	**2641**	**1583**	**763**	**383**	**3**	**1526**	**19212**	**3227**	**5177**	**647**

Spatial distributions

There have been many attempts to classify or to map the distribution of peripheral vegetation around Western Port. The early mapping studies, all undertaken in the 1970s, focussed on mangroves and coastal saltmarsh (as an aggregate, with no differentiation among the different types).

In one of the first studies, Bridgewater (1975) adopted a strongly phytosociological approach and on this basis identified ten vegetation complexes in the peripheral vegetation of Western Port. A suite of plant communities was identified within each vegetation complex: within the *Sarcocornia* (*Salicornia*) complex, for example, two communities were identified, a *Triglochin striata* community and a *Sarcocornia quinqueflora* community. The *Avicennia* complex and the *Spartina* complex were each represented by single plant communities, typified by *Avicennia marina* and **Spartina* x *townsendii*, respectively. Plant communities, however, were not mapped in this study.

The first State-wide mapping of coastal saltmarsh that I am aware of was undertaken by Geoff Carr (1979), as part of a study into the habitat requirements of Orange-bellied Parrot. Three types of saltmarsh were mapped at a scale of 1:100,000: *Sarcocornia* (*Salicornia*) *quinqueflora* with no *Arthrocnemum* (now *Tecticornia*) *arbuscula* present; *Tecticornia arbuscula* plus *Sarcocornia quinqueflora*; and *Tecticornia halocnemoides* ± *Sarcocornia quinqueflora* and *Tecticornia arbuscula*. As part of his assessment, Carr (1979) mapped the saltmarsh vegetation of Western Port, and his map is reproduced in Figure 5 below.

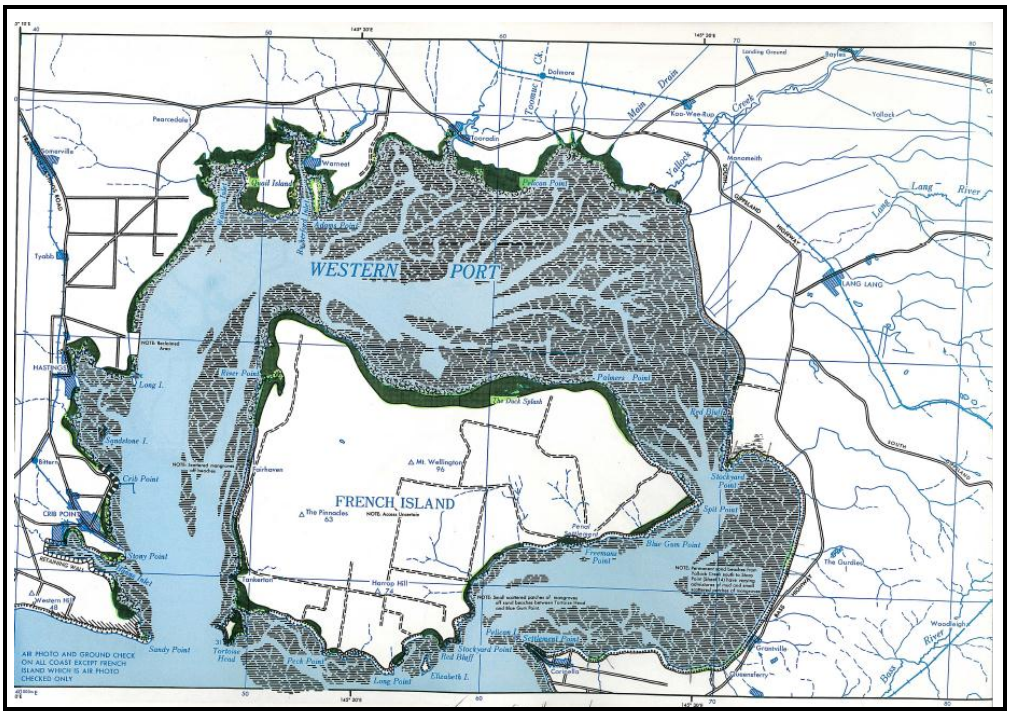

Figure 5: Distribution of saltmarsh (shown in green) around Western Port according to Carr (1979).

The first detailed mapping of the peripheral vegetation of Western Port was undertaken as part of the Western Port Environmental Study (Shapiro 1975). WB Calder mapped mangrove and saltmarsh vegetation and Figure 6 shows one of her maps, in this case of the western shoreline of Western Port.

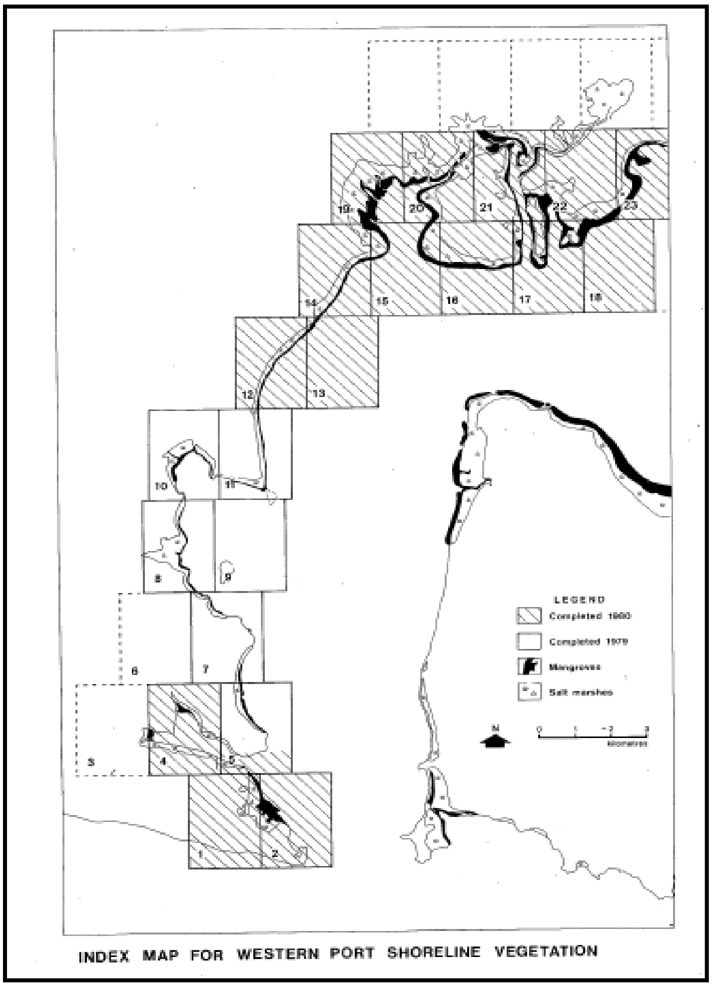

Figure 6: Distribution of mangroves and saltmarsh around the western shoreline of Western Port. Source: Calder (1980).

Around the same time, Bird & Barson (1974) devised a bay-wide map of mangrove and saltmarsh vegetation for Western Port. Their map is reproduced in Figure 7.

Detailed mapping of parts of Western Port have been undertaken in a number of other, but site-specific, investigations. The PhD thesis of Denis (1994), for example, provides detailed (1:3,000) maps of coastal vegetation along parts of the south-western shore of Western Port, from Jacks Beach to Hanns Inlet. More recently, Yugovic (2008) mapped in very fine detail the mangroves and coastal saltmarsh along the northern shore of Western Port, near The Inlets.

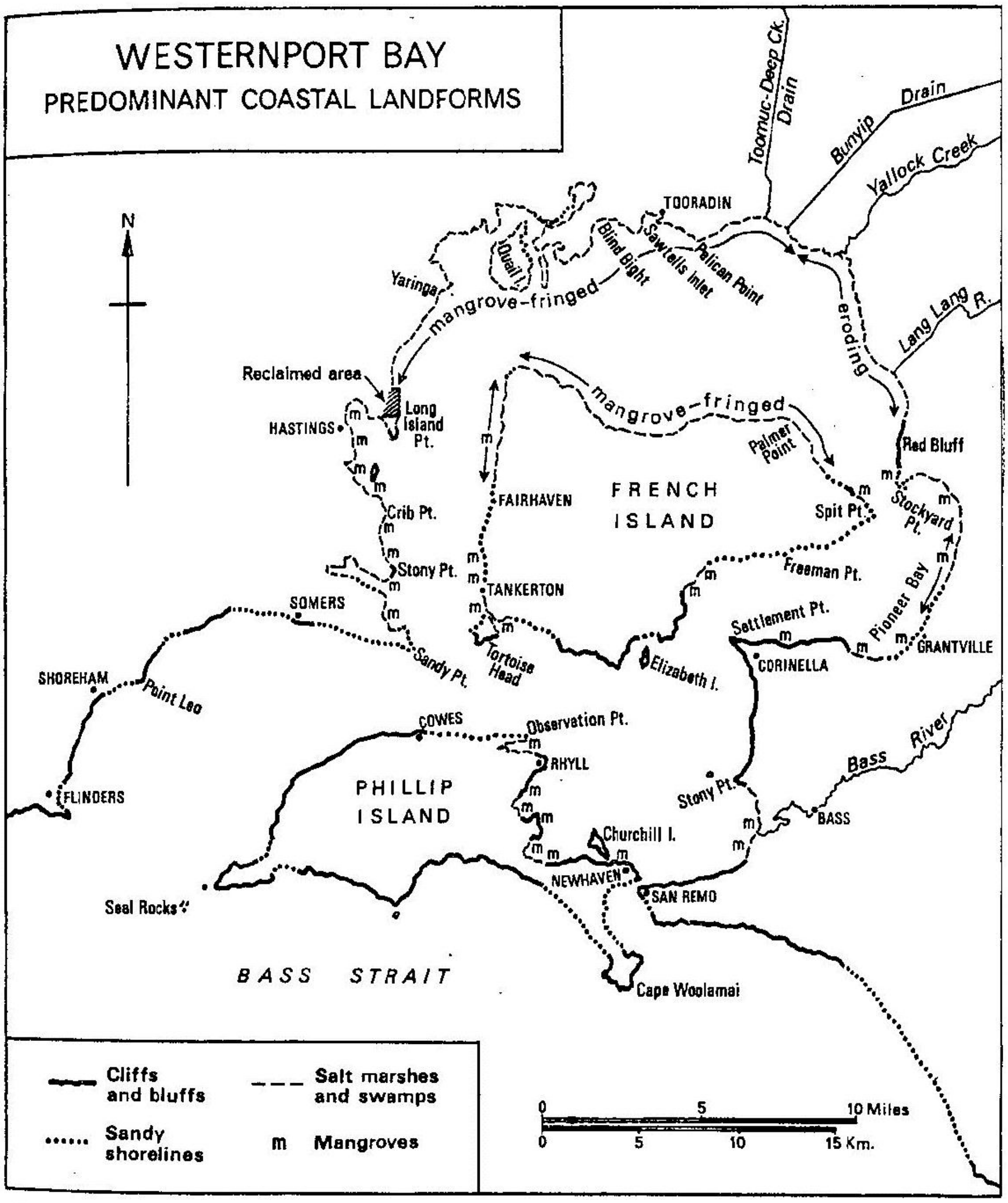

Figure 7: Shoreline features and distribution of mangrove and saltmarsh vegetation around Western Port as reported by Bird & Barson (1975, Figure 4).

The most recent and detailed mapping of coastal wetlands was undertaken by Boon *et al.* (2011). Coastal wetlands across the State were mapped at a scale of 1:10,000, using recently flown aerial photographs and extensive ground-truthing to confirm the aerial photographic interpretations. Vegetation was mapped according to the typology devised earlier to unravel the EVC 9 Coastal Saltmarsh Aggregate, meaning that all the different types of coastal saltmarsh, as well as other prominent vegetation types such as mangrove shrubland and estuarine wetland etc, were mapped explicitly, as well as mosaics where individual wetland types could not be differentiated at the scale of the mapping. This mapping exercise represents a marked advance over earlier studies, where coastal saltmarsh was mapped as an aggregate unit and not de-convolved into its constituent floristic and/or structural components. Figure 8 shows an example of this State-wide mapping, for the north-eastern shoreline of Western Port. GIS-formatted layers are available from the DEPI, and PDF versions available on-line for community use[21].

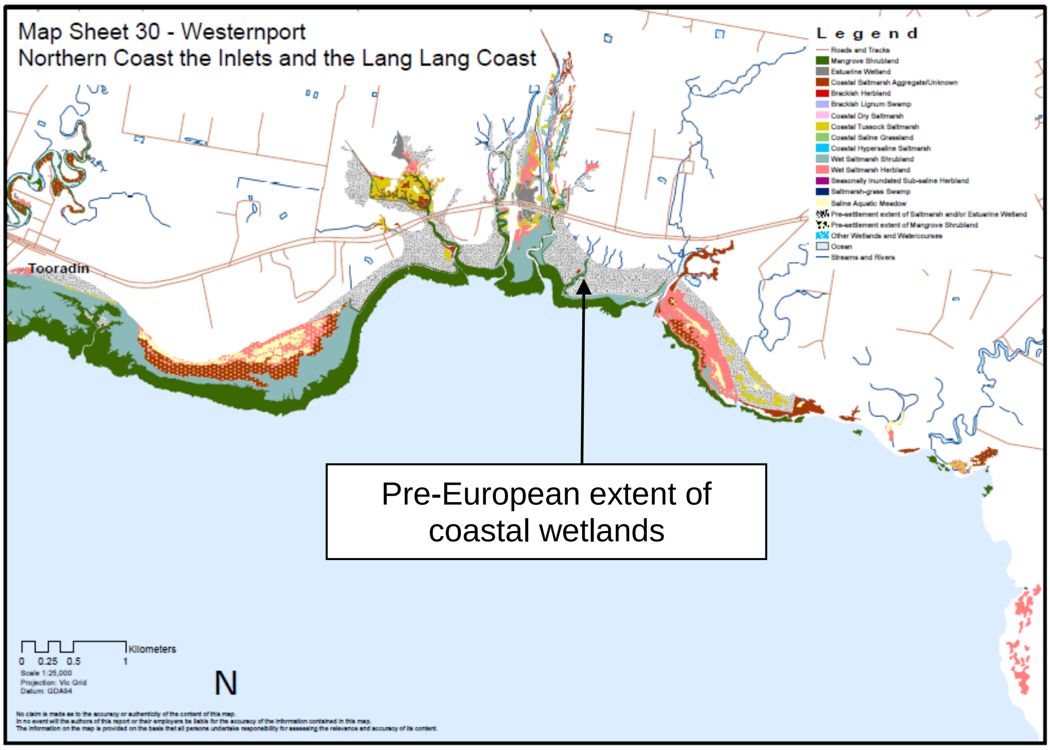

Figure 8: Current and post-European distributions of coastal wetlands along the north-eastern shoreline of Western Port. Source: Boon et al. (2011) and Sinclair & Boon (2012).

A number of attempts have been made to assess historical changes in peripheral vegetation around Western Port, much of which has appeared in unpublished student theses. Denis (1994), for example, described aspects of changes in the mangrove stands in south-western Western Port. In general terms, little change was detected over the period 1939−1985. In an unpublished BSc(Hons) thesis, Calderwood (1998) mapped changes in extent of *Avicennia marina* in Western Port from 1974 to 1994. The problem with this study is that different sectors of the coast were used for different time periods, so it is difficult to draw conclusions as to embayment-wide changes over the two-decade period.

In a review undertaken for the Department of Natural Resources & Environment, Ross (2000) summarised information on the historical mapping of shorelines, mangroves and saltmarsh in Western Port, commencing with the 1842 surveys of George Smythe. Harty (2011) transcribed the assessment undertaken by Ross (2000), and added to it with useful

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[21] http://www.vu.edu.au/institute-for-sustainability-and-innovation-isi/publications

updates for changes that had occurred along parts of the Western Port coastline in the intervening decade.

The most exhaustive study of historical changes was undertaken as part of the State-wide assessment of coastal wetlands[22], and was subsequently published a peer-reviewed paper by Sinclair & Boon (2012) in the journal of the National Botanic Gardens, Sydney. It quantified historical changes in the extent and distribution of coastal wetlands since the mid 19th century; Figure 7 shows an example of post-European changes in the area of coastal wetlands (indicated with the grey speckling) for the north-eastern shoreline of Western Port[23]. Comparable maps for all other sectors of the Victorian coast, including all of Western Port, are available in Boon *et al.* (2011). A summary of the investigation's findings is given in Appendix A.

Tolerance to inundation and to salinity

A later section of this report tries to predict the likely impacts of sea-level rise on peripheral vegetation of Western Port. The relationship between the level of the sea and the level of the sediments – and thus the tidal regime – is a crucial factor in the establishment, structure and function of coastal wetlands[24]. Because of this relationship, inferring the likely effects of sea-level rise requires a good understanding of the tolerance/sensitivity of different vegetation types to salinity and to inundation/desiccation.

Variations across wetland types

It is worth stressing at this point in the report that, despite their both occurring in intertidal parts of the coast, mangroves and saltmarshes are not the same type of coastal wetland: they differ greatly in floristics, structure, phenology, life histories, phylogeny and dispersal mechanisms[25]. A similar argument undoubtedly holds also for the other types of (non-mangrove and non-saltmarsh) wetland found around the Western Port shoreline (see Table 1). It has been reported, for example, that in northern Europe, *Phragmites*-dominated reed beds differ greatly from coastal brackish grasslands (mostly dominated by *Puccinellia* spp.) in the protection they offer the shoreline against erosion[26].

An added complication is that the effects on vascular plants of inundation and of salinity are not independent[27]. The inundation tolerance of mangroves, for example, is modified

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[22] Boon *et al.* (2011)

[23] Appendix A gives a summary of post-European changes in the area and distribution of coastal wetlands in different sectors around Western Port, taken from Sinclair & Boon (2012)

[24] Por (1984a, b); Woodroffe & Davies (2009)

[25] See the excellent comparison of the two wetland types by Friess *et al.* (2012)

[26] Moller *et al.* (2009)

[27] Kozlowski (1997); Barrett-Lennard (2003)

by salinity, as is the growth of young Swamp Paperbark seedlings[28]. Similar interactions presumably occur with saltmarsh and other halophytic plant taxa as well[29].

Mangroves

Ellison (2009) reviewed current knowledge of the tidal range colonized by different species of mangrove, mostly drawing from tropical studies. The problem with extrapolating from this overview to the peripheral vegetation of Western Port specifically is that *Avicennia marina* has the greatest geographical (including latitudinal) distribution and one of the broadest ecological niches of any mangrove species in Australia[30]. Given this complication, what information is there on how sensitive or tolerant *Avicenna marina* is to prolonged inundation or to prolonged desiccation, and what is the tidal regime under which it grows best?

Inundation and tidal regimes

Mangroves are obligately intertidal plant species and they die if not periodically inundated with the tides. Despite their extraordinary adaptations to episodic inundation[31], mangroves are killed if their roots are kept permanently submerged, no matter whether the water is fresh, brackish or oceanic. The entry on *Avicennia marina* by the Queensland Department of Agriculture, Fisheries & Forestry, for example, notes that this species is killed if it is inundated for longer than ~14 days[32]. An example of *Avicennia*'s sensitivity to permanent inundation is provided by Figure 1.46 of Boon *et al.* (2011), which shows the death of mangroves after they had been permanently flooded a result of sand movements along southern French Island. This figure is reproduced below, as Figure 9.

Roy E Lewis III, one of the leading specialists in the field of mangrove rehabilitation in North America, recommended that *Avicenna marina* be planted in zones that were inundated by all medium−high tides, which in his categorization is equivalent to elevations that receive 45−59 tidal inundations per month[33]. Given the world-wide distribution of *Avicenna marina*, it would be better if useful information could be extracted from studies of the species in temperate Australia; a search using, among other approaches, Web of Science® indicated relatively few sources of useful information[34]. What I found is summarized below.

First, in their review of the estuarine vegetation of south-eastern Australia, Sainty *et al.* (2012, page 147) noted that *Avicennia marina* 'thrives in high to low tidal areas, mostly below 1.6 m Lowest Astronomical Tide'.

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[28] Yang *et al.* (2013); Salter *et al.* (2007)

[29] For example, see Schile *et al.* (2011) and the review by Colmer & Flowers (2008)

[30] Duke (2006)

[31] Saenger (1982)

[32] http://www.daff.qld.gov.au/28_9226.htm Viewed 12/04/2013

[33] http://www.mangroverestoration.com/pdfs/mangrove_restoration.pdf Viewed 12/04/2013

[34] See also Smith (1987), but this study refers to *Avicenna marina* in tropical Australia

Figure 9: Death of mangroves after ponding created by sand movement, southern French Island. Source: Original photography by Dr Steve Sinclair and reproduced in Boon et al. (2011, Figure 1.46)

Second, *Avicennia marina* was reported by Clarke & Myerscough (1993) to be present at various sites along the New South Wales coast in the zone between mean sea level and 0.42 m above mean sea level (which was roughly equal to the normal high-water mark).

Third, when modelling climate-change impacts on Western Port's wetlands, Boon *et al.* (2010) argued, on the basis of the State-wide mapping project, that *Avicennia marina* typically occurred in the elevational range of about 0.3 m AHD to 1.2 m AHD around Western Port.

Fourth, a simple rule-of-thumb is that mangroves tend to grow best when inundated for 30% of less of the time by tidal waters[35]. This heuristic, however, does not take into account the large variation in inundation regimes experienced by different species in extensive mangrove swamps in the tropics, so can be considered only as a very approximate guide.

Finally, as part of his research into the relationships between tidal inundation and mangrove and saltmarsh vegetation, Denis (1994) took transects across the shoreline at a number of sites in south-western Western Port. These consistently showed mangroves to occur in the band between mean sea level and mean high water. Denis' observations

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[35] Lewis (2005)

match closely those of Clarke & Myerscough (1993) further up the coast, in temperate New South Wales.

Salinity regimes

Despite the large number of studies that have been undertaken on the species in Western Port and elsewhere across Australia, there is surprisingly little known about the salinity tolerance of *Avicennia marina*. In broad terms, the anatomical and physiological adaptations that allow it to grow in saline environments are well understood[36]. But in an exhaustive (100+ page) review of temperate mangroves, Morrisey *et al.* (2010) could cite only one publication[37] on the salinity requirements of *Avicennia marina* in southern Australia, and that study concerned seedlings not adult plants. A couple of other studies have been undertaken on tropical *Avicennia marina*[38], and what these few studies indicate is that, contrary to many expectations that *Avicennia marina* 'prefers' to grow in full seawater, the maximum growth rate of seedlings with tropical or with temperate origins is about 15−25 g L^{-1} and that growth rates decrease markedly at higher salinities (Figure 10). This finding is consistent with the more general observation that mangroves often grow best in salinities less than full seawater[39].

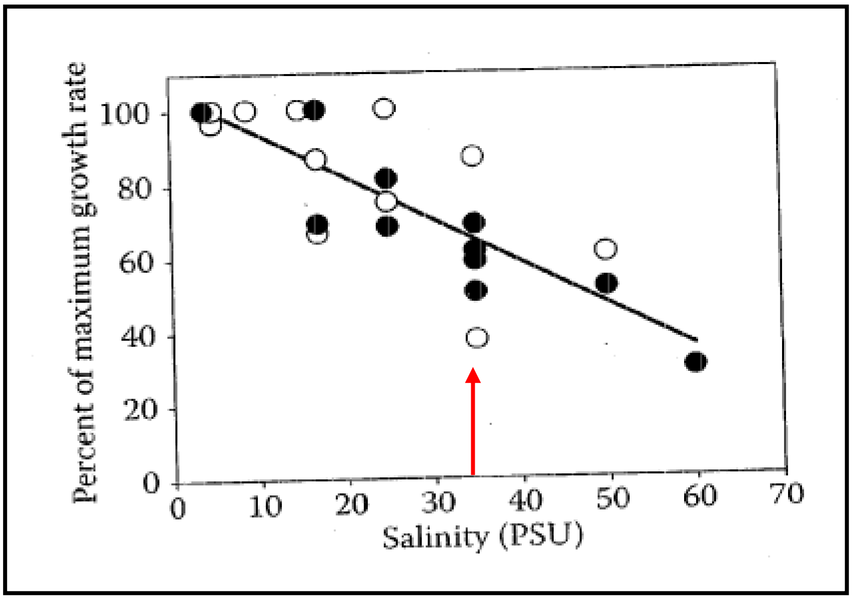

Figure 10: Effect of salinity on the growth rate of Avicenna marina seedlings. Individual with a tropical origin are indicated by the open circles: temperate-origin plants with the filled circles. Seawater salinity, ~35 PSU, is indicated with the red arrow. Source: modified from Morrisey et al. (2010, page 54). Note: the sloping orientation of the graph is unavoidable: it is how my copy of the article was received.

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[36] Saenger (1982); Clough *et al.* (1982); Boon & Allaway (1986)

[37] Ball (1998)

[38] For example, Clough (1984)

[39] Kathiresan (2013); see also Clough (1984) for tropical Australian *Avicenna marina*

Coastal saltmarsh and other types of peripheral vegetation

The quantitative information base on hydrological and salinity regimes for plants in saltmarshes and other types of non-mangrove coastal wetlands is relatively poor, even worse than that for mangroves. Unlike the voluminous information available on the way plants in inland wetlands respond to different water regimes[40] and to salinity[41], there is very little available on these topics for plants in coastal or estuarine environments, especially in temperate Australia[42].

My interrogation of literature databases uncovered only a couple of useful studies. The most relevant to Western Port is, again, the PhD thesis of Denis (1994). As described above in the section on mangroves, Denis took transects across the shoreline at a number of sites in south-western Western Port and then correlated plant distributions against tidal inundation and elevation. Figure 11 shows as an example one set of results, for Transect 3 at Hanns Inlet. The presence of mangroves only below the mean high water mark is evident, as is the intermixed presence of a large number of saltmarsh plant taxa at elevations around 3 m WCD[43]. Excepting mangroves at the lowest elevations, only *Stipa* sp., *Poa* spp. and *Melaleuca ericifolia* showed an unequivocal pattern of zonation, being confined in all cases to elevated positions where tidal inundation was exceptionally rare. Figure 12 shows another way to represent these data, which again indicates the substantial overlap in elevational distribution of the main saltmarsh plant taxa.

In one of the few other detailed field-based studies undertaken in south-eastern Australia, Hickey & Bruce (2010) correlated the distributions of mangrove and salt marsh communities at Towra Point (near Sydney, NSW) with frequency of tidal inundation. Not unexpectedly, the two mangrove species found in the Sydney region (*Aegiceras corniculatum* and *Avicennia marina*) were found at the lowest elevations (~0.55−0.7 m[44]) and at higher elevations there was a weak and strongly overlapping zonation from Beaded Glasswort (*Sarcocornia quinquenervia*) at the lowest levels, to Austral Seablite (*Sueda australis*), to Saltwater Couch (*Sporobolus virginicus*) and, at the most elevated sites (~ 1 m), Sea Rush (*Juncus kraussii*). The boundary between mangroves and saltmarsh occurred around the level of mean high water, meaning that the lower levels of the saltmarsh were inundated by mean high water spring tides and the upper levels, including the *Juncuss kraussii* communities, only by the very highest tides. The transition between the upper band of mangroves (here *Avicennia marina*) and the lowest level of the saltmarsh was ~10 cm, and from the mean position of *Avicennia marina* to the mean position of *Juncus kraussii* communities only ~ 25 cm; these very small differences in height reflect the extreme sensitivity of plants in coastal wetlands to subtle changes in elevation and thus in tidal inundation. Indeed, Hickey & Bruce (2010) concluded that variations of only ~2.5 cm in

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[40] Roberts & Marston (2011); Rogers (2011)

[41] Bailey *et al.* (2002); Hart *et al.* (2003); James *et al.* (2003); Nielsen *et al.* (2003)

[42] Boon (2012)

[43] Denis (1994, page 115) quantified elevation in terms of the Western Port Chart Datum (WCD), '…which is set at the height of the Lowest Astronomical Tide and is 1.600 m below the Australian Height Datum (AHD)'.

[44] Whether this is referenced to AHD or to MSL is not clear from the paper.

elevation could result in marked changes in species zonation in the middle parts of the saltmarshes of Towra Point.

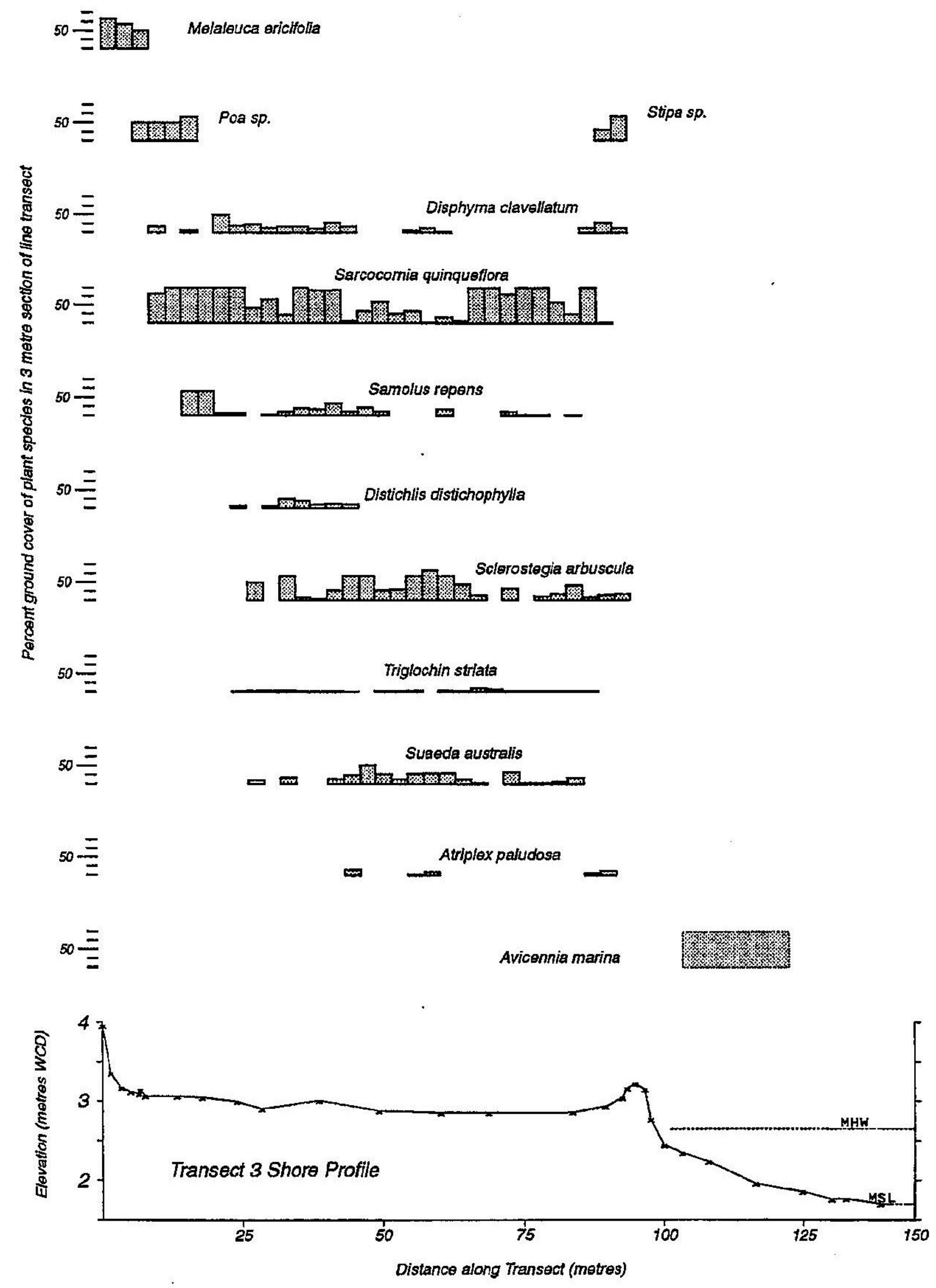

Figure 11: Relationship between plant presence/cover and elevation at Hanns Inlet, Western Port. Source: Denis (1994, Figure 3.3).

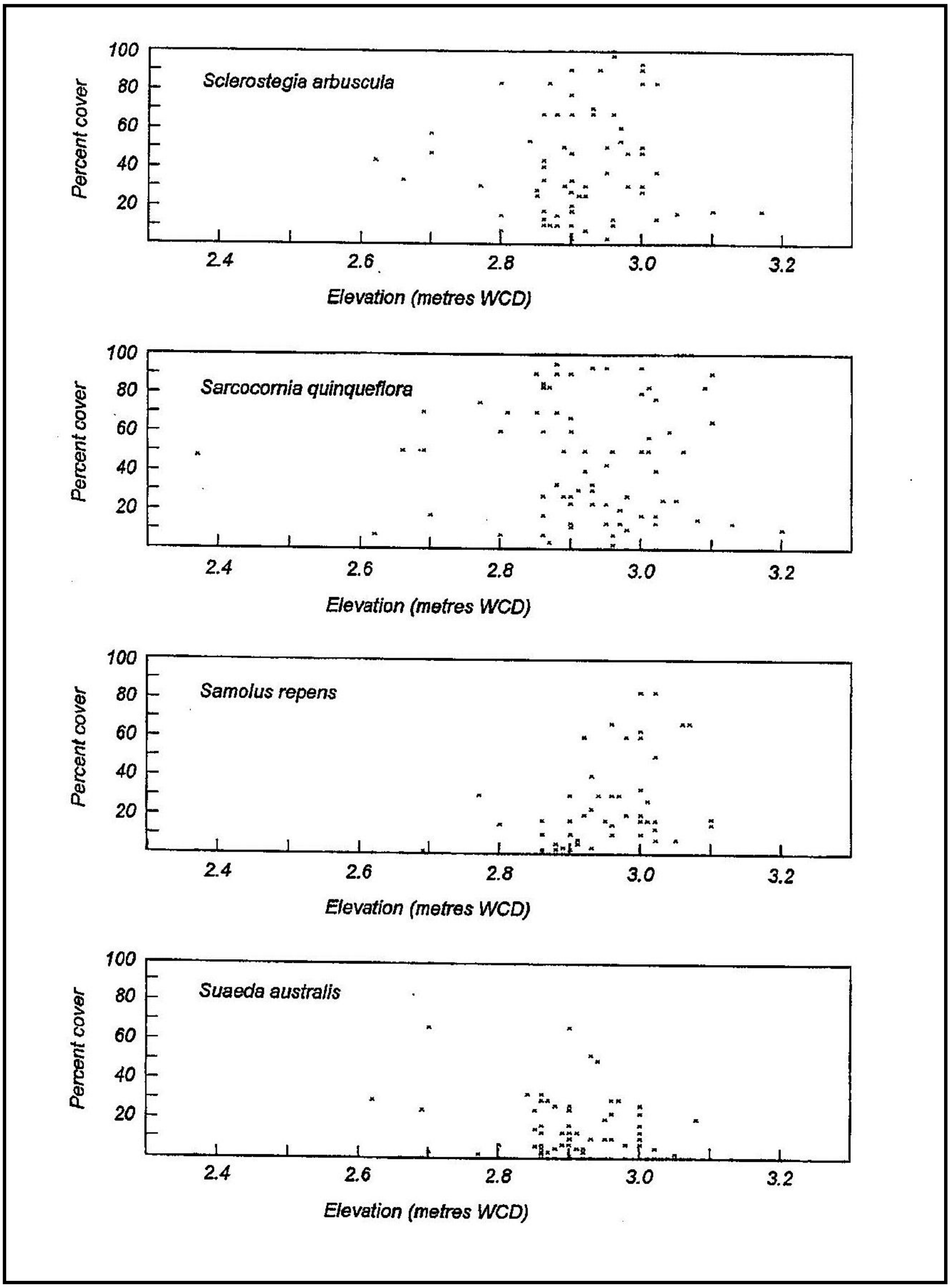

Figure 12: Relationship between cover and elevation for various species of saltmarsh taxa at Hanns Inlet, Western Port. Source: Denis (1994, Figure 3.8).

Table 3 shows a summary of the upper and lower elevational limits of different vegetation types from all the Western Port transects reported by Denis (1994). *Scleostegia arbusculum* (= *Tecticorna arbuscula*) had the narrowest elevational range of the saltmarsh plant taxa, in almost all cases extending only from 2.85−3.02 m for plants with a high percentage cover. Less dense stands, however, were present at elevations as high as 3.18 m and as low as 2.62 m. Limits could not be calculated for the various other species of saltmarsh taxa at Western Port because of the great overlap they showed in distributions: *Samolus repens*, for example, achieved maximum cover at elevations of 2.9 to 3.07 m, but could also be found in sites as elevated as 3.1 m and in other ones as low as 2.77 m. *Sarcocornia quinqueflora* was reported at a similarly wide range of within-saltmarsh elevations, from 2.84−3.10 m, but was found in one transect as low as 2.35 m and at another at 3.2 m.

Table 3: Elevation boundaries for different vegetation types at two locations in Western Port. Means ± standard deviations are shown, with n in brackets. Source: from Denis (1994, Table 4.1).

Vegetation type	**Elevation (m Western Port Chart Datum)**		
	Hanns Inlet	**Jacks Beach North**	**Jacks Beach South**
Melaleuca ericifolia Seaward limit	3.09 ± 0.06 (12)	3.24 ± 0.07 (11)	3.12 ± 0.05 (11)
Tecticornia arbuscula Landward limit	2.98 ± 0.05 (12)	3.02 ± 0.06 (12)	2.99 ± 0.05 (11)
Tecticornia arbuscula Seaward limit		2.85 ± 0.05 (10)	2.84 ± 0.01 (5)
Avicenna marina Landward limit	2.39 ± 0.06 (11)	2.60 ± 0.06 (10)	2.60 ± 0.08 (14)
Avicenna marina Seaward limit	1.68 ± 0.08 (20)	1.37−1.47(22)	1.43 ± 0.07 (10)

The results obtained by Denis (1994) and Hickey & Bruce (2010) both point to complicated overlaps that often occur in the elevational distributions of plant taxa in south-eastern Australian coastal saltmarshes. In a similar vein, Green *et al.* (2009) reported the high sensitivity that saltmarsh plants exhibit for very subtle variations (of the order of cm) in elevation and thus in inundation and salinity regimes.

Some complementary information on plant zonation can be gleaned from the botanical survey of Jervis Bay undertaken by Peter Clarke in the early 1990s[45]. Unlike the case with the studies summarized above, Clarke reported a strong and clear patterning of plant species with elevation in the saltmarshes that fringed this coastal embayment on the south coast of New South Wales, as shown in Figure 13.

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[45] Clarke (1993b)

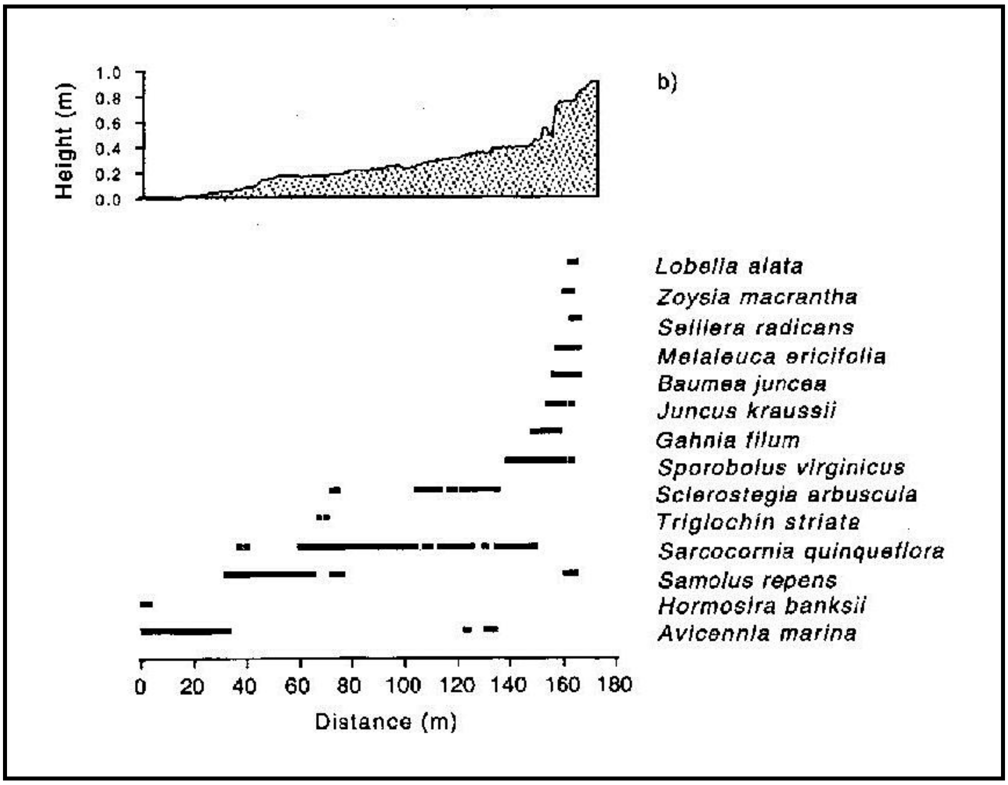

Figure 13: Zonation of plant species in saltmarshes fringing Jervis Bay, southern NSW, with distance from the sea and with elevation. Most of these plant species occur also in Western Port, with the possible exception of Lobelia alata. *Source: Clarke (1993b, Figure 4b)*

Studies such as those cited above provide information on species zonation that is highly site-specific. A supplementary, integrative approach is to attempt to synthesize what information there is on the salinity and inundation tolerance of the various plant taxa, in order to uncover any general patterns. One of the few studies that attempted to do this is Kirkpatrick & Harris (1999), who outlined the relative role of water-logging and salinity in controlling the distribution of plant taxa in Tasmanian saltmarshes (Figure 14).

Nothing similar seems to be available for the mainland of Australia, so I turned to the information on inundation and salinity tolerances outlined in Sainty *et al.* (2012) for common saltmarsh plant taxa in south-eastern Australia. Only those taxa indicated in Sainty's maps as having a distribution that potentially included Western Port were included in my summary, which is shown in Table 4. The limitation with this gross overview of the responses of saltmarsh and allied plant species to inundation and salinity regimes is that it is not quantitative in the way that similar information – albeit very limited – is available for *Avicenna marina*. The lack of useful information on the hydrological and salinity niches of non-mangrove plant taxa in coastal wetlands of south-eastern Australia is a critical knowledge gap at the present[46].

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[46] Boon (2012); see also Voice *et al.* (2006) for a similar complaint

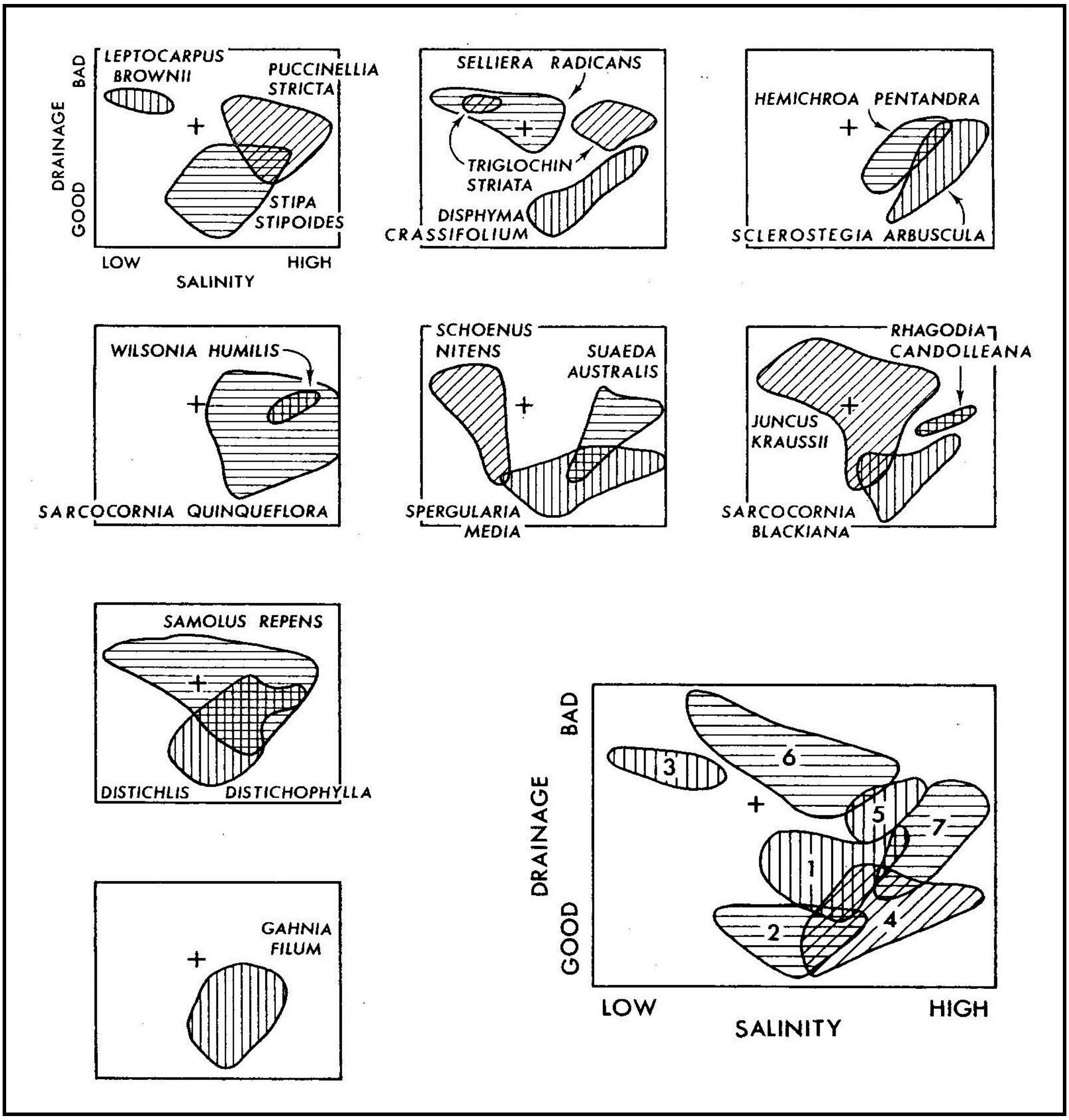

Figure 14: Distribution of various plant taxa in Tasmanian saltmarshes according to water-logging and salinity regimes. Source: Kirkpatrick & Harris (1999, Figure 14.9)

*Table 4: Inferred tolerance to water-logging and to salinity of non-mangrove plant species likely to occur in the peripheral vegetation of Western Port. Abbreviations are as follows: L = Low; LM = Medium-Low; M = Medium; MH = Medium High; H = High. Exotic species are indicated with *. Source: derived from Sainty et al. (2012).*

Scientific name	**Common name**	**Water-logging tolerance**	**Salinity tolerance**
Taxa of the low saltmarsh			
Atriplex paludosa subsp. *paludosa*	Marsh Saltbush	H	H
Cotula coronopifolia	Water Buttons (*?)	H	H
Hemichroa pentandra	Trailing Hemichroa	H	H
Samolus repens var. *repens*	Creeping Brookweed	H	H
Sarcocornia quinqueflora subsp. *quniqueflora*	Beaded Glasswort	H	H
Spartina spp.	Cord-grass or Spartina*	H	H
Sporobolus virginicus	Saltwater Couch	H	H
Sueada australis	Austral Seablite	H	H
Triglochin striata	Streaked Arrowgrass	H	H
Taxa of the high saltmarsh			
Apium prostratum subsp. p*rostratum*	Sea Celery	M	MH
Aster squamatus	Bushy Starwort*	M	M
Atriplex australisica	Native Orache	M	MH
Austrostipa stipoides	Prickly Spear-grass	M	MH
Baumea juncea	Bare Twig-sedge	LM	MH
Bolboschoenus caldwellii	Salt Club-sedge	MH	M
Chenopodium glaucum	Glaucous Goosefoot	M	MH
Cuscuta tasmanica	Tasmanian Dodder	LM	H
Cyclospermum leptophyllum	Slender Celery	M	MH
Cynodon dactylon var. *dactylon*	Couch	LM	M
Disphyma crassifolium subsp. *crassifolium*	Rounded Noon-flower	LM	H
Distichlis distichophylla	Australian Saltgrass	M	M
Ficinia nodosa	Knobby Club-sedge	M	MH
Frankenia pauciflora var. *gunnii*	Southern Sea-heath	M	MH
Gahnia filum	Chaffy Saw-sedge	M	MH
Gahnia trifida	Cutting Sedge	M	MH
Hordeum marinum	Sea Barley-grass*	M	MH
Hydrocotyle boniensis	Pennywort*	LM	MH

Isolepis cernua	Nodding Club-sedge	H	H
Juncus acutus	Spiny Rush*	MH	MH
Juncus bufonius	Toad Rush	MH	M
Juncus kraussii	Sea Rush	M	H
Lachnagrostis filiformis	Common Blown-grass	M	M
Lawrencia spicata	Salt Lawrencia	M	M
Leptinella longipes		M	M
Limonium ausytrale & Limonium hyblaeum	Native Sea Lavender & Sicilian sea Lavender*	M	MH
Melaleuca ericifolia	Swamp Paperbark	M	LM
Mimulus repens	Creeping Monkey-flower	M	M
Parapholis incurve	Coast Barb-grass*	H	H
Phragmites australis	Common Reed	H	MH
Plantago coronopus subsp. *Coronopus*	Buck's-horn Plaintain	L	M
Poa poiformis var. *poiformis*	Blue Tussock-grass	L	M
Polypogon monspeliensis	Annual Beard-grass*	H	H
Puccinellia stricta & *Puccinellia perlaxa*	Australian Saltmarsh-grass	M	H
Sarcocornia blackiana	Thick-head Glasswort	MH	H
Schoenus nitens	Shiny Bog-sedge	M	M
Selliera radicans	Shiny Swamp-mat	M	H
Senecio glomeratus susp. *longifructus*		LM	M
Sonchus hydrophilus	Native Sowthistle	MH	M
Spergulara marina	Salt Sand-spurrey	LM	H
Stenotaphrum secundatum	Buffalo Grass	M	MH
Tecticornia arbuscula	Shrubby Glasswort	LM	H
Tecticornia pergranulata subsp. *pergranulata*	Blackseed Glasswort	M	H
Tetragonia tetragonoides	New Zealand Spinach	LM	MH
Trifolium fragiferum var. *fragiferum*	Strawberry Clover*	LM	MH
Vulpia fasciculata	Sea Fescue	LM	M
Wilsonia backhousei	Narrow-leaf Wilsonia	M	H
Wilsonia humilis	Silky Wilsonia	M	MH
Wilsonia rotundifolia	Round-leaf Wilsonia	M	MH
Zoysia macrantha subsp. *macrantha*	Prickly Couch	M	H
Other brackish-water species			
Bolboschoenus fluviatilis	Marsh Club-sedge	H	M

Schoenoplectus tabernaemontani	River Club-sedge	H	M
Stuckenia pectinata	Sago Pondweed	H	M
Typha domingensis	Narrow-leaf Cumbungi	H	MH

Peripheral vegetation, succession and shoreline stability

Does peripheral vegetation protect shorelines?

Two recent meta-analyses have shown convincingly that peripheral vegetation – mangroves and coastal saltmarsh – makes shorelines less susceptible to erosion and to damage by storm surges, and potentially even to small tsunamis[47]. These overviews are consistent with a number of earlier assessments, for example by French (1997) and Doody (2008), that argued for the value of coastal wetlands in protecting against shoreline erosion in the United Kingdom. French (1997) argued that coastal saltmarsh provided a critical valuable ecosystem service by protecting land against erosion and that many of those benefits were lost when seawalls and other 'sea defence' structures were employed in the place of healthy and extensive swards of coastal wetland vegetation. The irony of 'protecting' the hinterland by building seawalls and alienating coastal saltmarsh was further explored by Doody (2008), who calculated that the retention of an 80-m wide strip of coastal saltmarsh could reduce by a factor of twelve the cost of sea defences in south-east England. Similarly, Tuyen & Hung (2010) reported that mangrove forests in Vietnam could reduce waves by up to 80%, depending on water levels[48]. To achieve significant protection against large waves, such as tsunamis, mangroves need to be at least 100 m wide[49].

Mangroves and land-building

Although peripheral vegetation almost certainly protects shorelines against erosion, particularly during storms, it is quite a different question as to whether it facilitates shoreline development; i.e. whether plants in coastal wetlands are 'land-builders'. The assumption that peripheral vegetation functions as land-builders is based on the following train of necessary events: i) the tidal waters that inundate coastal wetlands are commonly turbid; ii) wetland vegetation reduces flow velocity and turbulence; iii) those reductions allow suspended (inorganic) particles to settle out of the water column; iv) sediments therefore accumulate as a result of the settling of these particles; v) the slightly elevated mounds thus created around emergent plants facilitate further sediment

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[47] Gedan *et al.* (2008); Shepard *et al.* (2008)

[48] The specific effect of mangroves in attenuating waves, however, will be a complex one, dependant on the density, size and shape of the mangrove trunks and their aerial roots, the degree to which they have been colonized by algae, barnacles and other marine life, spectral characteristics of the waves, tidal stage, and slope of the shore: see Massell *et al.* (1999), Mazda *et al.* (2006) & Alongi (2008).

[49] Alongi (2009)

deposition; and vi) mangrove and saltmarsh plants therefore assist the sediment accretion and/or inhibit sediment erosion[50].

Mangroves are thought to be particularly important in land-builders, for two reasons. First, their position in the inter-tidal zone allows them to accumulate tidally-deposited sediments (*cf* saltmarshes, which are inundated far less frequently and thus cannot easily facilitate sediment deposition). Second, mangrove pneumatophores are believed to be critical in trapping and retaining sediment (Bird 1971, 1980, 1986). In Western Port pneumatophores can attain densities of ~300 per m^{-2} (Denis 1994; Bird 2008: see also Figure 15).

Figure 15: High density of pneumatophores achieved by mangroves in Western Port.

Spenceley (1997) presented evidence that was counter to a number of these assumptions. He showed that although mangrove pneumatophores may promote sedimentation under low-energy conditions, under medium to high-energy conditions they caused the development of eddy currents, which initiated localized scour and erosion in the sediments. Spenceley (1997) concluded that when considered in isolation, *Avicennia* pneumatophores did not promote sediment deposition, and that other factors were required to explain the stabilization of sediments that occurs in mangrove swamps with these types of aerial roots. The presence of fine rootlets in the upper layers of the sediment is probably a critical mechanism that makes mangrove sediments resistant to erosion. Bird & Barson (1982) similarly argued that the stabilising role of mangroves was limited to areas where the wave energy was low, and that under higher-energy situations (e.g. after protective sand spits had been removed) mangroves were soon eroded away.

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[50] For example, see Furukawa *et al.* (1997)

One of the reasons for confusion as to the roles played by mangroves in land-building is that it is often assumed the only geomorphological process involved is the settling onto the sediment surface of inorganic particles with incoming tides. In reality, the surface level of coastal sediments is controlled by two processes: i) sediment trapping and/or loss; and ii) the accumulation (or loss) of organic material built up by the roots and rhizomes of peripheral vegetation[51]. The latter process, often ignored or undervalued, is a result of the high rates of below-ground productivity of coastal plants, and can be due to accumulations either of dead plant remains (e.g. peat) or living plant roots and rhizomes. In turn, how the below-ground accumulation of dead organic matter behaves is controlled to a large degree by the degree of water-logging, and this is controlled by tidal inundation and by the behaviour of local ground waters (Figure 16).

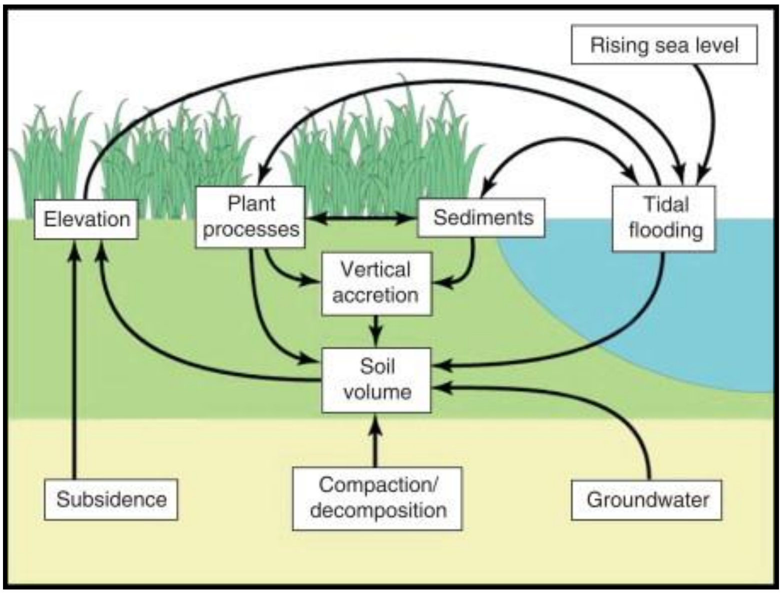

Figure 16: Interactions between above and below ground productivity, sediment deposition, peat accumulation, tidal inundation and groundwater behaviour in controlling sediment elevations in coastal wetlands. Source: Spencer & Möller (2011, Figure 13).

The two processes of deposition on the sediment surface versus the below-ground accumulation of peat and or living plant matter can be differentiated and net rate of changes in sediment elevation quantified using sediment elevation tables, or SETS. Figure 17 shows how this type of instrumentation can be deployed in coastal sediments to not only track changes in the elevation of surface sediments but also to discriminate between surface sediment deposition and below-ground processes such as peat accretion and increases in the biovolume of plant roots and rhizomes.

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[51] For example, see Rogers *et al.* (2006, 2012)

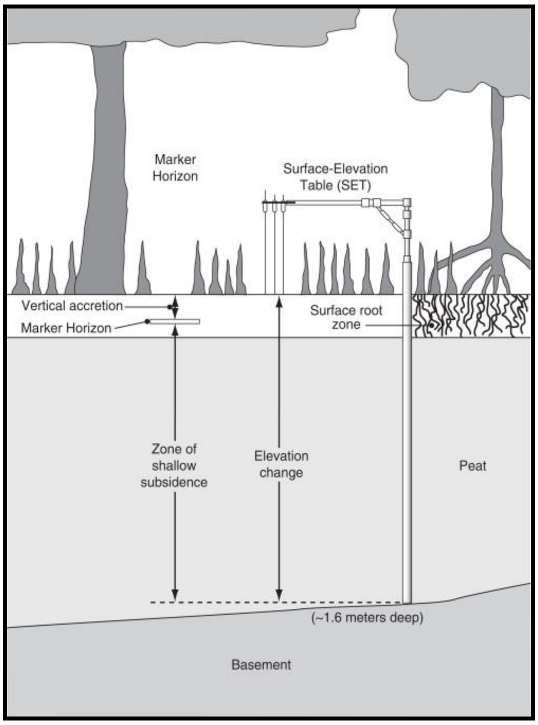

Figure 17: Sediment elevation tables to measure changes in sediment elevation. Source: Spencer & Möller (2011, Figure 12).

In summary, mangroves − and to a lesser extent other types of peripheral vegetation in less tidally inundated zones, such as coastal saltmarsh − can facilitate sediment deposition and stability in four ways:

- The fine mat of surface roots and deeper roots/rhizomes bind sediment and limits erosion.
- Emergent shoots and roots (e.g. pneumatophores in mangroves, shoots in rhizomatous taxa) decrease current velocities and encourage the deposition of fine particles, at least under low-energy conditions (but probably not under high-energy conditions).
- Plants add organic matter to sediments via below-ground productivity (i.e. roots, buried leaves etc), thus building up the sediment surface. If material is accumulated for long enough in a stable environment, peat deposits can form.
- Plant roots and rhizomes form a dense, sometimes impenetrable mat, which as well as protecting the sediment from physical erosion (dot point 1 above) deters burrowing invertebrates that would otherwise rework the sediments.

Given the operation of these four processes, mangroves should slowly increase sediment elevations in coastal wetlands. The simplest evidence for such a process taking place is where individual mangrove trees occur on locally raised mounds (Figure 18), or where coastal areas vegetated with mangroves are steeper than nearby unvegetated areas (Woodroffe 1992). Note that the first example is, of course, not necessarily causal.

Figure 18: Example of a mangrove tree on a locally raised 'mound', near Grantville, Western Port.

There are few reports of changes in surface elevation in Australian intertidal systems, but the study by Rogers *et al.* (2006) indicated rates of about –2 to +5 mm year^{-1} in various sites across south-eastern Australia[52]. Rates for saltmarshes and mangroves at four sites around Western Port are shown in Table 5[53]. Relevant also is the recent finding by Stokes *et al.* (2010) that the rate of sedimentation (not necessarily the same thing as change in surface elevation) in New Zealand *Avicennia marina* woodlands ranged from 0 to +21 mm year^{-1}, whereas on adjacent mudflats they ranged from –16 to +15 mm year^{-1}.

The values reported by Rogers *et al.* (2005b, 2006) reinforce the controversy about whether mangroves are land-builders or not: in some parts of Western Port (e.g. on French Island) mangrove sediments are sinking at a rate of ~2 mm year^{-1}, whereas in others (e.g. near Rhyll) they are increasing by about 1 mm year^{-1}. Given the current/looming impacts of sea-level rise on peripheral vegetation around Western Port, it is unfortunate that studies to quantify changes in sediment elevation around the embayment have ceased (due to lack of funds) and more recent and/or spatially more finely resolved information is not available[54].

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[52] Rogers *et al.* (2005b) presents additional information for Western Port. Note also that SETs as shown in Figure 16 were used to make these measurements.

[53] Ellison (2009) provides a world-wide summary of accretion rates for mangrove sediments.

[54] Note that this is not the case for many wetlands in other parts of the world, where detailed studies are being undertaken to determine rates of sediment elevation and the susceptibility of coastal wetlands to sea-level rise. See, for example, van Wijinen & Bakker (2001) and D'Alpaos (2011) in Europe, and Day *et al.* (2011) and Cahoon *et al.* (2011) for the USA. The recent report on these processes for the Hunter River estuary in NSW by Rogers *et al.* (2012) is noteworthy.

Table 5: Mean (± standard errors) rates of change in surface elevation at four sites around Western Port. Source: Rogers et al. (2006, Table 3).

Site	**Vegetation type**	**Change in surface elevation (mm year^{-1})**
French Island	Mangrove	−2.13 ± 1.66
	Saltmarsh	5.27 ± 0.96
Kooweerup	Mangrove	−0.03 ± 2.23
	Saltmarsh	−0.16 ± 0.94
Quail Island	Mangrove	−2.60 ± 2.07
	Saltmarsh	−0.68 ± 1.18
Rhyll	Mangrove	0.92 ± 1.87
	Saltmarsh	0.64 ± 0.75

Although the topic of land-building has long engendered discussion (e.g. see Bird 1971, 1980, 2008; Bird & Barson 1975, 1982; Ellison 1998, 2009; Woodroffe 1992), coastal geomorphologists and mangrove ecologists now generally not believe that mangroves function in this way. The following extracts from recent papers show why. Smith (1992, page 106, citing Egler 1950) called land-building by mangroves '…part of arm-chair musings of air-crammed minds'. More recently, Hogarth (2007, page 60) concluded that 'The idea that mangroves create land is now discredited'. Hogarth, however, went onto to argue that 'Mangroves undoubtedly trap sediment … [and] … in so doing, they may accelerate accretion, or retard erosion, of a shoreline'. He concluded that a more accurate interpretation of the role played by mangroves in coastal stability was that 'mangroves opportunistically follow a shoreline that is accreting for physical reasons, or retreat as a shore erodes than that they make the running'.

A similar conclusion had been reached by Blasco and co-workers a decade before[55], when they concluded that mangroves were reactive opportunists; when mangroves colonized newly deposited sediment they then helped to consolidate that sediment and promote further sedimentation. Woodroffe (1992, page 8) reached similar conclusions: 'The view is increasingly accepted that mangroves follow areas of mud accumulation but that their establishment leads to more rapid accretion'.

In his most recent monograph, Bird (2008, page 290-291) concludes similarly, that 'Mangroves colonise mudflats that are slowly accreting, but once established they promote accelerated accretion within the network of stems and pneumatophores that diminishes current flow and wave action'. Such a process has been reported recently for mangroves (*Avicennia marina*) in Gulf St Vincent in South Australia, where sediments have aggraded by about 0.5 m as a consequence of mangroves quickly colonizing formerly bare mudflats (but not sand flats, as the authors reported mangroves as being incapable of colonizing sandy substrata)[56].

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[55] Blasco *et al.* (1996)

[56] Cann *et al.* (2009)

Seral succession from mangroves to paperbarks

Related to the argument about mangrove land-building is the question of whether or not the zonation of coastal vegetation can be interpreted in terms of seral succession. Seral succession is the notion that vegetation communities change in time according to a process whereby pioneer communities modify the physical environment such that they can no longer grow there, and make way for later stages that are better adapted to the new conditions. Each sequence of communities is referred to as a 'sere', and the entire process as 'seral succession'. The end-point of a seral succession is posited to be a 'climax community' or 'biome'. In the case of Western Port, mangroves (perhaps even seagrasses) would generally be viewed as the pioneer sere, and mature eucalyptus forest as the climax community.

Strong zonations of peripheral vegetation have sometimes – but controversially – been interpreted as evidence of seral succession. In the case of coastal vegetation, the succession is conventionally proposed to commence with pioneer mangroves colonizing bare mudflats. As the mangroves accumulate sediment, the sediment surface becomes elevated and less frequently inundated, which in turn creates conditions suitable for invasion by less flood-tolerant species such as saltmarshes, brackish-water taxa and, eventually, terrestrial plants. With increasing sediment elevation, the original pioneer species are able to colonize towards the sea and thus make land available for subsequent colonization by saltmarshes and, again eventually, by more terrestrial taxa such as paperbarks and eucalypts.

The strongest proponent for a seral succession in mangrove-saltmarsh-terrestrial vegetation was Chapman (1974), but the interpretation has a much longer history. It was proposed, for example by Pidgeon (1940), to occur in mangrove and saltmarsh communities along the central New South Wales coast. The successional model is hypothesised to commence with saline mud flats, which then progresses sequentially through mangroves, *Sarcocornia/Suaeda* saltmarsh, *Sporobolus virginicus* grassland, *Juncus kraussii* rush meadow, *Baumea juncea* sedge meadow, *Casuarina glauca* she-oak forest, *Eucalyptus robusta* mahogany forest and culminates in a mixed eucalypt forest.

Given current understanding of geomorphological processes in the coastal zone, the successionalist interpretations of saltmarsh now sound naïve. Adam (1994) strongly criticised the model, noting (among other objections) that it was difficult to see how seral succession could be driven by sediment accretion above the tidal limit. The more plausible and restricted case of whether vegetation within coastal saltmarsh exhibits a regular pattern of clear successional change is also controversial. Unfortunately, evidence from temporal and spatial changes in saltmarsh vegetation fails to provide strong arguments for or against succession or seral development in saltmarsh (Saintilan *et al.* 2009).

Shoreline stability and mangrove expansion

Bird & Barson (1982) argued that a mangrove system could be considered stable if it occupied the same area of intertidal land, and unstable if its boundaries advanced or retreated. In cases where there is a seaward advance, there is also often evidence of landward senescence, due to either the replacement of mangroves by *Melaleuca* swamps or even terrestrial *Eucalyptus* plant communities, or, under more salinized conditions, by saltmarshes or, under the most hypersaline conditions, by unvegetated mud- or sand-flats. Newly deposited sediments can be quickly colonized by mangroves, if prevailing hydrological and wave-exposure regimes permit. When coastal exposure is too great, for example around the Lang Lang coast of Western Port, mangroves are either absent or are very difficult to introduce as planted specimens[57]. In cases such as these, positive feedback processes may operate that enable mangroves to persist in otherwise unfavourable areas, but unable to recolonize such areas if adult plants are destroyed by, for example, freak storms or by pollution[58]. Colonization is likely to interact synergistically with reduced flows and increased sediment deposition, providing an additional feedback loop for the deposition of yet higher sediment loads and a greater opportunity for mangrove development and/or expansion within the tidal zone.

Many studies in eastern Australia have reported the progressive encroachment of mangroves into coastal saltmarsh, particularly since the turn of the 20th century[59]. In her review of Australian saltmarshes, Laegdsgaard (2006, page 389) referred to mangrove incursion as an 'imminent threat'. Laegdsgaard's review focussed strongly on New South Wales and southern Queensland and it has yet to be demonstrated empirically that the situation is as critical in Victoria as it is in these northern States. Rogers *et al.* (2005b) concluded that there was less mangrove encroachment into coastal saltmarsh in Western Port than has been reported for comparable sites along the New South Wales coast. Even so, it is not unusual to find mangrove seedlings establishing into areas of coastal saltmarsh in Victoria[60]. An expansion of mangroves into coastal saltmarsh has been reported elsewhere across the world, including for example in the Gulf of Mexico[61].

The topic of mangrove encroachment into the wetland vegetation that backs mangrove swamps was reviewed by Saintilan & Williams (1999), who concluded that the landward encroachment of mangroves into saltmarsh along the coast of south-eastern Australia was facilitated by local factors which contributed to the compaction of saltmarsh soils during drought periods. Data generated under the auspices of the first National Land and Water Resources Audit (NLWRA) provided circumstantial evidence for the importance of local factors on the encroachment into saltmarshes by mangroves. The

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[57] Sinclair & Boon (2012); Kirkman & Boon (2012)

[58] Huisman *et al.* (2009)

[59] For example, see Mitchell & Adam (1989a, b); Saintilan & Hashimoto (1999); Saintilan & Williams (1999, 2000); Saintilan & Wilton (2001); Wilton (2001); Haworth (2002); Rogers *et al.* (2005b); Saintilan *et al.* (2009)

[60] See Boon *et al.* (2011) for specific examples in Victoria

[61] Krauss *et al.* (2011); Comeaux *et al.* (2012)

OzCoasts (2008) information sheet[62], making use of NLWRA data, showed that the proportion of saltmarsh:mangrove area in tide-dominated deltas and tidal creeks progressively decreased in favour of mangroves as one moved from near-pristine, to largely unmodified, to modified, then severely modified systems. The progressive change was interpreted in terms of the effect of increased sediment load and consequential rapid infilling in modified estuaries. Saintilan & Wilton (2001) argued that sea-level rise could not explain the loss of saltmarsh in most of these cases, and proposed instead that altered patterns of freshwater and nutrient inputs were probably responsible. In contrast, however, studies of mangrove encroachment into brackish-water and freshwater wetlands in Florida, USA, have invoked rises in sea level (combined with reductions in freshwater discharge from the catchment) as the mechanisms responsible (e.g. see Krauss *et al.* 2011).

Impacts of climate change – an overview of threats

The first – and a critical – point to make is that coastal wetlands are dynamic environments. They change and evolve in concert with a suite of external pressures, orchestrated by complex synecological relationships[63] and by random or stochastic events[64]. Figure 19 shows a conceptualization of these various spatial and temporal scales and how different types of environmental and biotic processes interact to influence coastal wetlands. In this model, responses to (natural) sea-level rise is predicted to occur over temporal scales of centuries to millennia and over spatial scales of 10+ km. Such a prolonged temporal response is probably correct for non-anthropogenic seal-level rise, but given the pace of with which climate-change impacts are now becoming apparent, it is likely that plant responses are now likely to occur over much shorter time frames, as indicated by the red arrow in the diagram.

Notwithstanding the importance of stochastic events and the complexity of the biotic inter-relationships between and among different species, plants in coastal wetlands are likely to be affected strongly by climate change[65]. Indeed, there is growing evidence that impacts are already being seen as, for example, outlined with Tasmanian coastal

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[62] OzCoasts (2008)

[63] Synecological relationships are ecological interactions among suites of organisms.

[64] Stochastic events are non-deterministic, often random. Erfanzadeh *et al.* (2010) explains the critical role they play in coastal wetlands.

[65] Analyses of likely climate-change impacts on other wetlands the reader can refer to Meith (1991) for Mediterranean wetlands; Simas *et al.* (2001) for Portuguese saltmarshes; Scavia *et al.* (2002) for coastal and marine systems of the USA; Morris *et al.* (2002) for *Spartina*-dominated wetlands in the USA; Chmura *et al.* (1992) for saltmarshes along the Louisiana coast; Walsh (2004) on saltmarshes and mangroves; the series of reports published by the Australian Greenhouse Office (including Voice *et al.* 2006; Hobday *et al.* 2006) for Australian coastal systems; Gilman *et al.* (2007, 2008) for global mangroves; Sjerp (2007) for the Gippsland Lakes; FitzGerald *et al.* (2008) for global salt marshes; and reports contained in the workshop notes on wetland adaptations to climate change (Sydney Olympic Park 2008). The most comprehensive analysis of likely climate-change impacts on Australian mangroves and coastal saltmarsh is found in Steffen *et al.* (2009a, b); their reviews, however, addressed impacts on an Australia-wide scale and thus little space could be allocated to mangroves and saltmarsh specifically. Saintilan & Rogers (2013) examine the topic as part of their review of Australian coastal saltmarshes. See also Traill *et al.* (2011) & Rogers *et al.* (2012).

saltmarshes by Prahalad *et al.* (2011). Most often the effects of climate change are envisaged only within the perspective of the effects of higher mean sea levels. Certainly there is some validity in this focus, as the sensitivity of peripheral vegetation to climate change is largely a function of their coastal location and hence of their great susceptibility to the altered hydrological and salinity regimes that will accompany sea-level rise; saltmarsh vegetation, for example, is particularly sensitive to subtle changes in water-logging and in salinity regimes, and both variables will be affected by rises in mean and extreme sea levels[66].

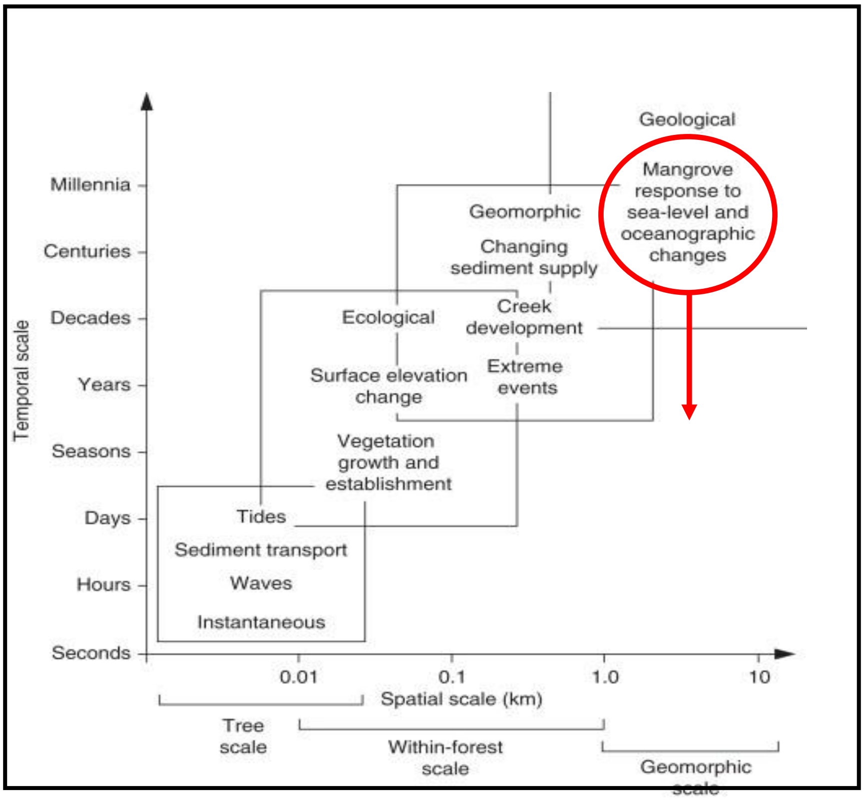

Figure 19: Interactions among environmental and biota factors that influence coastal wetlands at a range of spatial and temporal scales. Source: modified from Spencer & Möller (2011, Figure 4).

Rises in mean eustatic sea level, however, are not the only aspect of climate change that will affect coastal wetlands and other types of peripheral vegetation around Western Port. Sea-level rise is only one manifestation of climate change, and ecological impacts are likely to occur as a consequence of other physical and chemical components of the climate-change phenomenon, such as higher temperatures and altered atmospheric CO_2 concentrations. Moreover, impacts will probably occur as a result of societal responses to climate change, such as the creation of sea walls and other structures built to protect the hinterland[67].

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[66] Adam (1990)

[67] For example, see Burley *et al.* (2012)

Before the likely impacts of sea-level rise on peripheral vegetation is assessed, it is worth briefly discussing these other sorts of impact that are likely to occur in response to other environmental shifts associated with climate change:

- Ecological impacts arising directly from climate change, specifically
    - Higher air temperatures and decreased incidence of frosts
    - Increased CO_2 concentrations in the atmosphere
- Indirect ecological impacts arising from secondary effects, including
    - Altered patterns of freshwater run-off and river discharge
    - Increased evaporation rates
    - Increased incidence of wild fires
    - Effects on plant dispersal.

Higher air temperatures and decreased incidence of frosts

An increase in ambient temperature will have wide-ranging effects on individual organisms and on ecosystem structure and function[68]. Expected effects include phenological impacts (the timing of onset of different phases of a plant's development e.g. flowering, seed germination, and establishment of seedlings), changes to the allocation of resources to above- and below-ground components (e.g. leaves and shoots versus roots and rhizomes, with impacts on physical stability and sensitivity to herbivory), changes to the allocation of resources to reproductive versus maintenance activities (e.g. investment in seeds and the success of sexual recruitment; shifts to clonal spread), effects on life history and longevity (e.g. shortened life spans due to heat stress or drought), and effects on competitive and mutualist interactions among different species (e.g. on pollination of plants by animal vectors).

Most relevant to peripheral vegetation around Western Port is the projected increase in winter temperatures and decrease in the incidence of frosts. As noted earlier, low winter air temperatures and/or the episodic occurrence of frosts have been proposed as the primary factors that control the growth and distribution of *Avicennia marina* in Victoria. Relieved of their current limitation by cold and/or frost, mangroves could expand their distribution, and possibly also their productivity, across southern Victoria, including in Western Port. There is some palaeobotanical evidence for a similar shift having taken place with *Avicennia marina* in New Zealand, where mangrove pollen has been preserved in early Holocene sediments ~150 km to the south of the present-day limit of the species and coinciding with a period when the climate was warmer than today[69]. Episodic frosts have also been invoked as a factor that limits further sea-level induced expansion of mangroves into coastal wetlands in Florida, USA[70].

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[68] Bonan (2002)
[69] Morrisey *et al.* (2010)
[70] Krauss *et al.* (2011)

Increased temperatures may have consequences also for the spread of exotic plants in the coastal wetlands that fringe Western Port. Two species of **Spartina* are noxious weeds in parts of Western Port[71] and it is possible that higher temperatures and altered tidal inundation regimes could increase their invasiveness[72]. Coastal wetlands are susceptible also to invasion of weed from the hinterland as well as infestation by the highly inundation-tolerant **Spartina*. The exotic Saltwater Couch (**Paspalum vaginatum*) could expand under likely future climate-change conditions[73], and higher temperatures could facilitate a southwards spread of the exotic shrub **Baccharis halimifolia*, which is currently a major threat to saltmarsh vegetation in coastal saltmarsh in New South Wales and Queensland[74].

Increased CO_2 concentrations in the atmosphere

Changes in ambient CO_2 concentration will directly affect the growth of plants via fundamental effects on photosynthesis and water use. This effect will occur because different species of plant fix atmospheric CO_2 in different biochemical pathways, each of which has a competitive advantage in different environments:

- C_3 photosynthesis, the pathway used by most plants for photosynthesis
- C_4 photosynthesis, notably common in warm-season grasses and advantageous in warmer climates and under water stress
- CAM photosynthesis, which occurs in relatively few taxa but is strongly advantageous under extreme water stress, as occurs during drought.

Most Victorian saltmarsh plants, as well as *Avicennia marina*, possess the C_3 photosynthetic pathway[75]. Some, however, including native saltmarsh grasses such as *Distichlis distichophylla* and the exotic *Spartina* spp., possess the C_4 photosynthetic pathway. There are marked differences in the growth rates and water-use efficiencies of C_3 and C_4 plants: C_4 grasses, for example, show little photorespiration and at full sunlight can be twice as productive as C_3 plants. Because of their more efficient use of CO_2, C_4 plants use less water to achieve the same rate of primary production as C_3 plants. As the optimal temperature for C_4 plants is usually greater than that of C_3 plants, a warmer and drier climate thus might be expected to favour the former over the latter. The complication is that the C_3 plants require higher CO_2 concentrations than do C_4 plants. Thus we can expect complex and difficult-to-predict interactions among plant species and possibly even replacement of some taxa (and thus plant life forms) with others as concentrations of CO_2 in the atmosphere increase[76].

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[71] For example, in The Inlets and around the mouth of the Bass River: see Boon *et al.* (2011)

[72] For example, see Loebl *et al.* (2006) for a study on the effects of climate change on *Spartina* in the Northern Hemisphere

[73] Geoff Carr, Ecology Australia, pers. comm.

[74] Saintilan (2009a, b)

[75] Boon *et al.* (2011)

[76] Gray & Mogg (2001); Adam (2008); Mckee & Rooth (2008)

Altered patterns of rainfall, freshwater run-off and river discharge

Although the greatest and most obvious impacts of climate change on peripheral vegetation around Western Port is likely to be caused by rises in mean and extreme sea levels, a suite of subtle – but still important − effects can be expected to arise as a consequence of altered patterns of rainfall and of freshwater run-off[77]. In turn, the corresponding changes in river runoff will influence inundation and salinity regimes in coastal wetlands. The effects could be experienced either as decreased long-term local run-off into peripheral vegetation (e.g. from the immediate hinterland) or as altered base flows and patterns of over-bank flooding from rivers and streams during extreme events.

In Western Australia, Hobday *et al.* (2006) noted the sensitivity of mangrove ecosystems to even slight changes to hydrological regimes, induced by either shifts in tidal inundation or fluxes of freshwater from the hinterland and nearby rivers. More recently, Eslami-Andargoli *et al.* (2010) have reported on the effects of drought on the expansion and contraction of mangroves in south-eastern Queensland. Other than these investigations, few studies have been undertaken on these potential impacts in Australia.

In south-eastern USA, however, drought is thought to be one of the major causes of widespread die-off in coastal saltmarsh in the early parts of the 21st century[78]. The causal mechanism was that landscape-scale reductions in freshwater inflows led to the development of lethal hypersalinity in coastal environments; simultaneously, the dry periods allowed increased grazing pressure (by gastropods) to cause a cascade of ecological disruption that eventually resulted in large-scale losses of wetland vegetation. On shorter (annual) time scales, variations in precipitation have been shown to differentially affect the performance of different plant species in saltmarshes in Texas (USA), with variations of between 20−60% in plant cover of individual species occurring in response to wet versus dry periods[79].

As well as these direct effects on the plants, periods of exceptionally high or low rainfall will influence the surface level of sediments in coastal wetlands. As shown earlier (Figure 11), whether or not wetland peats remain water-logged is dependent in large part on the depth to groundwater, and thus is controlled strongly by climatic conditions. Rogers *et al.* (2005a), for example, reported that a recent and severe El Nino period in southern Australia lowered the watertable sufficiently to allow sub-surface peats to desiccate, thus causing sediment levels to drop in some New South Wales coastal saltmarshes.

Increased evaporation rates

Inundation and salinity regimes in coastal wetlands are controlled not only by the periodicity and extent of tidal flooding and by freshwater inflows, but also by the strength of evaporative conditions existing in coastal environments. Figure 20, taken

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[77] Boorman (2009)
[78] Silliman *et al.* (2005)
[79] Dunton *et al.* (2001)

from the pioneering work done on mangroves and saltmarshes in the Sydney district by Clarke & Hannon in the mid-late 1960s, shows the strength and complexity of these interactions. As noted in the earlier section on floristic and structural diversity in the peripheral vegetation that fringes Western Port, the geographic separation of 'dry' and 'wet' coastal saltmarsh along the Victorian coast from west to east is direct result of west-east gradients in rainfall and evaporative losses.

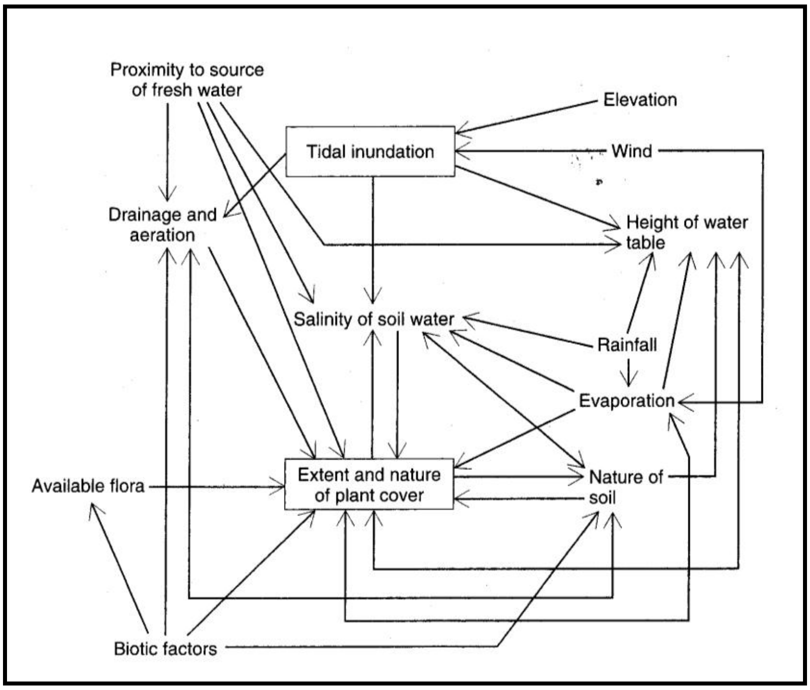

Figure 20: Interactions among tidal inundation and other environmental factors on plant performance in coastal wetlands. Source: Clarke & Hannon (1969)

Evaporative losses in wetlands are controlled interactively by irradiation, by wind speed, and by relative humidity. Climate-change projections for Western Port by Macadam *et al.* (2008) indicate increases of 0.3–5.3% in solar radiation by 2070 and a decrease in relative humidity by up to 3.2%. Projections for wind speed are highly variable, but mean wind speeds are more likely to increase than decrease across coastal Victoria and Bass Strait in summer, winter and spring[80]. The combined effect of increased insolation, lower relative humidity, higher wind speeds and an increase in the number of hot days is increased rates of evaporation, which in turn will lead to faster evaporative losses and a greater risk of the development of hypersalinity in coastal wetlands, particularly those that are not subject to daily tidal flushing.

Increased incidence of wild fires

Increases in the incidence and/or severity of wild fires could have a number of impacts on peripheral vegetation. First, the vegetation could be simply burnt. Initial thoughts

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[80] McInnes *et al.* (2005)

might suggest that coastal saltmarsh is resistant to fire because so many of the plants are succulent; this, however, is not the case and there are a number of reports of fires in coastal saltmarsh, including from Australia[81]. Second, wildfires in the catchment will result in a suite of indirect effects arising from the loss of terrestrial (forest) vegetation and related changes in run-off, which in turn will affect patterns of river discharge and sediment load and, ultimately, the supply of inorganic material to near-coastal environments.

Effects on plant dispersal

Plants need to disperse in order to colonize new areas and one case where climate change could have marked impacts is on the ways in which plant propogules can or cannot move to different parts of the coast. *Avicennia marina*, for example, is dispersed by large, living and buoyant seeds/seedlings that float on the water and are dispersed along the coast by waves and tides[82]. Altered patterns of coastal circulation and of tidal inundation could have substantial impacts on the spatial pattern and success of mangrove recruitment. Since *Avicennia marina* propagules can establish successfully only within 4–5 days of dropping from the parent tree, colonization of new areas may be limited by the ability of the seedlings to reach new areas.

Impacts of climate change – sea-level rise

A large number of studies, undertaken mostly on wetlands in the Northern Hemisphere, have concluded that changes in mean sea level will have drastic impacts on coastal wetlands[83]. Sea levels have, of course, varied greatly in the past. Before the extensive utilization of the coastal zone by humans, vegetation could respond to sea-level rise by retreating into the terrestrial hinterland, but only where it was not too steep[84]. Steep hills or dunes discourage the formation of extensive wetlands and, in a number of places along the Victoria coast (e.g. around Phillip Island), peripheral vegetation abuts steep terrain and thus has nowhere to retreat should sea levels rise. What this means is that the intensity of post-colonization development on coastal plains, often for housing but also for industrial facilities such as ports, has been such that there is little or no room left around much of the coast for a landward retreat of peripheral vegetation as sea levels rise.

Increases in mean sea level

In one of the first analyses of climate-change impacts on Victorian coastal vegetation, Vanderzee (1988) argued that the well-defined pattern of plants in Victorian saltmarshes reflected strongly the extent, timing and duration of inundation by seawater, and

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[81] Boon *et al.* (2011)

[82] Clarke (1993a); Clarke & Allaway (1993); Clarke & Myerscough (1993)

[83] For example, see Day *et al.* (2008); Gilman *et al.* (2007, 2008); Woodroffe & Davies (2009)

[84] Woodroffe & Davies (2009)

therefore that even small changes in tidal inundation would have large consequences for saltmarsh floristics and, probably, plant productivity. Vandezee's study was centred on changes in saltmarsh communities at Corner Inlet, and he argued that likely changes included the landward migration of plant species in response to tectonic submergence of the coastline. Such naturally occurring changes were proposed to be a good model for predicting possible impacts arising from climate-induced rises in sea levels. The model developed to explain the response by vegetation to changes in sea levels is shown in Figure 21.

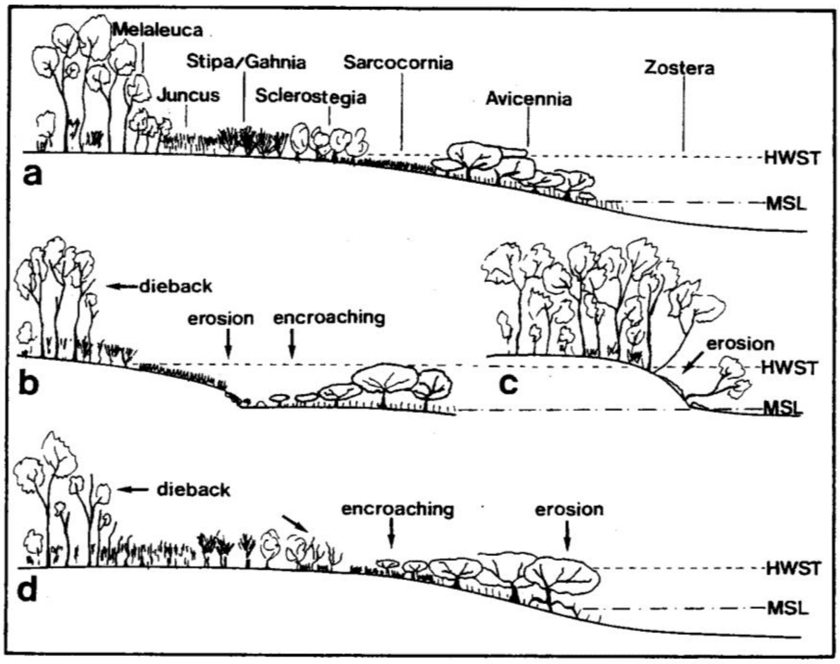

Figure 21: Impacts of sea-level rise on peripheral vegetation in Corner Inlet as explained by Vanderzee (1988). Part a) shows an idealized sequence with species characteristic of each zone; b) Avicennia marina encroaching into saltmarsh; c) erosion of saltmarsh back to the Melaleuca ericifolia zone; and d) a typical sequence in response to sea-level rise. Source: Vanderzee (1988, Figure 2).

Most of the early analyses (i.e. in the 1980s) of the likely impacts on rises in mean sea levels on coastal wetlands similarly concluded that there would be a large-scale loss of peripheral vegetation and of wetland habitat[85]. More recent studies have come to slightly different conclusions, as it has now been recognized that the issue is not so much a simple rise in mean sea level *per se*, but instead one of changes in the *relative* sea level that will be the fundamental determinant of ecological and geomorphological responses by fringing vegetation. In other words, if coastal wetlands can maintain their elevation *viz-a-viz* current sea levels by accumulating sediment and by laying down peat or by expanding

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[85] For example, see see Pratolongo *et al.* (2009) for a detailed review.

root/rhizome volumes, they can keep up with – as opposed to catch up with – future sea-level rise[86].

What this means is that if changes in the level of the sediment surface meets or exceeds average rates of sea-level rise, peripheral vegetation can maintain itself in the face of this aspect of climate change[87]. The few available data, summarized in Table 5, indicate that rates of sediment elevation around Western Port can be up to ~5 mm year^{-1} in some saltmarsh environments but, conversely, can be −2 mm year^{-1} in some mangrove areas. The prognosis for wetlands experiencing an on-going lowering of the sediment surface, for example due to sediment contraction or erosion, in the face of chronic sea-level rise is therefore not good. This topic is addressed later, where the possible impact of storm surges and wave set-up is discussed.

In contrast, for those coastal wetlands where the level of surface sediments is increasing fast enough, mangroves could expand either (or both) towards the sea or towards the land. In the case of the former type of expansion, the outer boundary of the mangrove zone will remain constant or expand, depending on the rate of elevational shift. Examples can be seen already along parts of Western Port where a seawards expansion of mangroves is occurring (e.g. see Harty 2011). In the latter case, a landwards expansion of mangroves, the expansion will occur into the present-day saltmarsh zone. Whether this represents an invasion at the expense of coastal saltmarsh will depend, in turn, on whether rates surface-sediment elevation in the saltmarshes can keep pace with those of the mangrove zone and with sea-level rise. As noted earlier, because of their near extra-tidal position in the landscape increased rates of sedimentation are unlikely to be responsible for increases in sediment levels in the saltmarsh zone, and the formation of peat and other similar below-ground processes are instead going to have to take place if saltmarshes are not to be lost via mangrove encroachment. In turn a landwards-expanding saltmarsh zone may or may not encroach into the other types of coastal wetland that lie behind saltmarshes (see Table 1). The fringe of Swamp Paperbark (*Melaleuca ericifolia*) would seem to be then at most risk. It is not clear whether it could withstand the altered physio-chemico conditions (e.g. via a shift in the understorey from glycophtic to halophytic taxa) or, in turn, would push back further into the hinterland.

Historical studies indicate that changing sea levels can result in changes such as those described immediately above and may cause the large-scale destruction, re-organisation or movement of coastal ecosystems[88]. Bryant (1990), for example, cited the work of Jones *et al.* (1979) which showed that mangroves at Bulli (Sydney) were able to colonise new sediments and keep pace with sea-level rises of approximately 15 mm year^{-1} over the recent Holocene. Such rates of sea-level rise are within the predicted range of increases under most climate-change scenarios to 2030 or 2050. In other cases, however, palaeobotanical studies have shown that sea-level rises have caused widespread changes

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[86] Pratolongo *et al.* (2009); see also Rogers *et al.* (2012) for the implications of sediment elevation when modelling wetland losses with simple 'bath-tub' models of sea-level rise.

[87] Morris *et al.* (2002)

[88] Soares (2009) and Morrisey *et al.* (2010) provide detailed critiques of these historical studies.

in coastal plant communities. Walker & Singh (1981), for example, showed that, at Wilsons Promontory, a marine incursion converted a formerly freshwater swamp to saltmarsh about 7,000 years ago which, after the accumulation of sand, changed into the current *Melaleuca ericifolia* scrub. As noted below, marine incursions (often mediated by tidal channels the penetrate into the landward wetlands) are likewise causing marked changes to coastal vegetation across northern Australia.

In order to survive anticipated rises in mean sea levels, increases in surface elevation of between 2−8 mm year^{-1} and up to ~10 mm year^{-1} by the end of the century will be required[89]. As noted by Morrisey *et al.* (2010), these rates are broadly similar to the slower-to-intermediate rates of sea-level rise that were observed during the Holocene. Given known rates of sediment elevation (e.g. as in Table 5), it can be predicted that some coastal wetlands will survive future sea-level rises and others will not.

On these grounds Morrisey *et al.* (2010) predicted that temperate mangrove swamps in sediment-rich infilled estuaries, especially in the drowned river valleys such as are common along the New South Wales but not the Victorian coast, were likely to survive and indeed could be quite resilient to rises in mean sea level. They also concluded that 'a 2- to 5-fold increase in estuary sedimentation rates would be required to keep pace with about a 10 mm yr^{-1} average rate of eustatic SLR [sea-level rise] or more if subsidence were occurring'. Whether such a rate of sedimentation can be achieved in Western Port when substantial efforts are being made to decrease sediment loads in order to rehabilitate seagrass beds presents an interesting conflict between management practices required to conserve seagrasses and those required to maintain other types of peripheral vegetation[90].

The effect of extreme events

Sea levels are controlled not only by the mean level of the sea (and its relationship with land levels in setting *relative* sea levels) but also by extreme events. Extreme events include rare storms or floods that temporarily increase further the height of the sea and, combined with increased wave action, result in greatly increased erosion and penetration of the ocean inland than would otherwise be the case[91]. Bryant (1990) outlined the range of factors that contribute to variations in extreme sea level, including king tides, storm surges, wave set-up, shelf waves, and seiching.

Water levels in coastal wetlands are likely to be affected also by large variations in river discharge that arise from changed precipitation, run-off, or storm frequency in the catchment. Marine intrusions into coastal wetlands can be exacerbated by such riverine floods, in which case increased river discharge can cause estuarine waters to 'back up' into the swollen rivers and inundate adjacent lands. Boon *et al.* (2007) provides an

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[89] Morrisey *et al.* (2010)

[90] Anderson *et al.* (2011) have reported a similar concern with 'sediment deficiencies' for coastal saltmarshes elsewhere in the world.

[91] Walsh (2004)

example of this process for the Gippsland Lakes, where saline water was forced into *Melaleuca*-dominated Swamp Scrub wetlands surrounding the western Lake Wellington as a result of increased riverine discharge in eastern parts of the lakes complex[92]. Because of the limited number and small size of streams that discharge into Western Port (see page 5), this type of secondary impact is likely to be less important here than along other parts of the Victorian coastline.

Storms and other extreme events will have a diverse range of geomorphological impacts on coastal wetlands[93]. Erosion will be most severe during extreme events, and it would seem that sandy coastlines are particularly susceptible to storm surges[94]. Mean sea-level rises of 0.17 m and 0.49 m are projected for Western Port by 2030 and 2070, respectively[95]. These are relatively small values when compared with the heightened sea levels expect to arise from extreme events. Storm tides at Cowes (on Phillip Island), for example, could reach 2.29 m by 2030 and 2.74 m by 2070. Not only will storm surges be higher than currently, but they will be more frequent. It was projected that storm surges with a current return interval of 1:100 years would have a new average return interval of only 1:40 or even 1:6 years by 2030, and 1:20 or 1:1 years by 2070. In other words, what is currently a severe storm that occurs only once a century could become an annual event by 2070. Linked with the increase in the severity and frequency of storm surges is a projected increase in extreme rainfall and extreme winds.

The impacts of extreme events on peripheral vegetation is most likely to be seen via two processes: i) the landward penetration of sea water, with resultant effects of inundation and soil salinity; and ii) altered processes of sediment deposition or erosion. Marine incursions into coastal wetlands have occurred across large parts of northern Australia, including in Kakadu National Park, with notable poor outcomes for nominally freshwater vegetation such as *Melaleuca* woodlands[96]. Often tidal creeks act as the medium for such marine incursions. Mangroves and coastal saltmarsh are susceptible also to excessive sedimentation and to erosion, and the effects can occur at both the establishment phase of young plants and on adult specimens. As a generalization, it is well known that young wetland plants are particularly susceptible to breakage by wind or by waves during their establishment. In a set of trials into the rehabilitation of *Melaleuca ericifolia* wetlands in the Gippsland Lakes, for example, we found that seedlings (up to ~30 cm tall) were often blown down by wind and, once in the water, suffered high mortality (Raulings *et al.* 2007; Morris *et al.* 2008). Similarly, wind- and wave-induced disturbance and toppling were identified as significant factors limiting the establishment of young mangrove plants along the eastern shore of Western Port by Kirkman & Boon (2012).

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[92] See also Bird (1966) and Boon *et al.* (2008) for lakes-wide impacts of secondary salinization.
[93] Cahoon (2006)
[94] Walsh (2004)
[95] Western Port Greenhouse Alliance (2008)
[96] Winn *et al.* (2006)

Despite their ability to build-up sediments and rapidly colonize areas that are actively sedimenting, *Avicennia marina* is susceptible to smothering by sediments and to erosion. There are examples of both processes at Western Port (Figure 22). Bird & Barson (1982) reported that erosion of sediments at Port Clinton (South Australia) had caused the death of mangroves (which would have been *Avicennia marina*), and that dead plants had not been replaced via natural recruitment. Conversely however, rates of sedimentation as high as 1.6 cm year^{-1} have been reported at mangroves at Yaringa in Western Port for the period 1966–1971 (Bird 1971; see also Bird & Barson 1982). It is not clear that the mangroves survived, but it is presumed that they did. Ellison (2009) reviewed some studies of Indonesian mangroves which showed excessive sedimentation causing the death of some species, especially *Avicennia* and *Sonneratia*, both of which are generally the species that grow in the most seaward edges of complex tropical mangrove swamps. Indeed, Affandi *et al.* (2010) have recently argued against using the related *Avicennia alba* in rehabilitation projects where rates of sedimentation are likely to be high.

Figure 22: Increased sedimentation (by sand) and potential smothering of mangrove pneumatophores (left-hand photograph) and severe erosion (right-hand photograph) of mangroves near Grantville, Western Port. Photographs: Paul Boon (February 2010).

Smothering is likely to exert an effect on mangroves by covering pneumatophores, thereby altering patterns of gas exchange and interfering with the essential aeration of belowground organs (Hogarth 2007). Ellison (1998) reported 26 cases where mangroves had been adversely affected by burial with sediments. In a later review (2009), she concluded that mangroves could generally deal well with accretion rates of <5 mm year^{-1}; but there would seem to be insufficient data to establish specific tolerance for different species (Ellison 1998). It is worth remembering, however, that mangroves are not merely passive recipients of environmental changes, but can readily adapt (e.g. via morphological change in pneumatophore height and density) to different rates of sedimentation (e.g. see Dahdouh-Guebas *et al.* 2007).

The studies cited above have been concerned with adult plants. Altered patterns of sedimentation and/or erosion arising from storms and other extreme events are likely also to affect the process of plant establishment. Sexual recruitment is a risky process for higher plants, and success depends on the often-rare alignment of a suite of appropriate physical (e.g. temperature, light, humidity), chemical (e.g. salinity, redox) and ecological (e.g. absence of herbivores) conditions[97]. In the case of mangroves, it is well known that successful recruitment requires good seed set, appropriate patterns of dispersal, calm conditions for seedlings to establish, appropriate salinity, inundation and light regimes, and an absence of competitive interactions with other biota, for example, weighing-down by attached barnacles or herbivory by crabs (Denis 1994). Extreme events could interfere with any or all of these factors, with the consequence that sexual recruitment in mangroves (and presumably also other types of peripheral vegetation) will vary from what is experienced under current-day conditions.

Impacts of climate change – a synthesis

Climate change is highly likely to have wide-ranging impacts on mangroves, saltmarsh and other types of peripheral vegetation around Western Port. Higher temperatures will probably affect the phenology of almost all the area's biota, including the timing of flowering and germination of plants, and may facilitate the spread of mangroves into coastal saltmarsh as winters get warmer and the incidence and severity of frosts decreases. An increase in the rate of evaporation from saltmarsh pools is likely to lead to increasingly saline conditions and perhaps the creation of hypersaline areas at the landward and least-inundated edges of existing saltmarshes; conversely, lower-lying saltmarshes that are subject to more frequent tidal inundation may experience less variable salinity fluctuations than they do at present. Either way, marked changes in plant distributions and in primary production are expected. Higher winter temperatures could also facilitate invasion by weed species that are currently temperature-limited or would be advantaged by increased inundation (e.g. **Spartina anglica*).

One of the major difficulties in predicting the impacts of climate change generally and of sea-level rise more specifically on the peripheral vegetation of Western Port is the current poor state of knowledge about the ecological niches of Australian coastal and wetland plants. This point was made not only in a recent review of the status of research into coastal wetlands in south-eastern Australia[98], but also in a synthesis now a decade old undertaken by the Australian Greenhouse Office on the impacts of climate change on coastal and marine ecosystems[99]. These remain critical knowledge gaps, but little attempt seems to being made to fill them in order to improve our understanding and predictive ability.

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[97] See, for example, Robinson *et al.* (2012)

[98] Boon (2012)

[99] Voice *et al.* (2006)

The most obvious impact of rises in relative sea levels is that coastal wetlands and other types of peripheral vegetation will be inundated more frequently and more deeply with sea water. Under this scenario, the simplest expectation is that saltmarshes would be replaced by mangroves, and mangroves by seagrasses. In more elevated positions along the coast, the frequency of inundation from either storm surges or floods will increase and this would be expected to have profound effects on the water and salinity regimes in fringing wetlands. Saltmarsh may invade into Swamp Paperbark woodlands, as has been observed to occur in the Gippsland Lakes[100]. In turn, Sea Rush and Swamp Paperbark may also migrate into the hinterland, into currently terrestrial plant communities dominated by, for example, Manna Gum.

Some attempts have been made to model likely spatial responses by mangroves and coastal saltmarsh to projected rises in mean sea levels and to storm surges (e.g. McInnes *et al.* 2009; Boon *et al.* 2010), but these have been extremely simplistic exercises. It is now widely recognized that the simple 'bath-tub' models used in such analyses are inadequate for predicting the responses of coastal wetlands to sea-level rise, in large part because they do not take into account the way that vegetation responds to higher water levels by increasing the level of surface sediments[101]. In other words, far from being simply passive receivers of the external physical conditions, coastal wetlands, via their plant communities, modify their own environment in ways that might ensure their continued survival in the face of perturbations such as sea-level rise[102].

In a recent assessment, Rogers *et al.* (2012) calculated that simple 'bath-tub' modelling indicated a loss of about 6% in the extent of coastal wetlands along the Hunter River estuary on the central coast of New South Wales. If, however, realistic rates of change in sediment elevation were included in the model, it was estimated that there may be a 16% increase in the area of coastal land suitable for colonization by mangroves and saltmarsh. It is, therefore, imperative that models of potential sea-level rise impacts on peripheral vegetation include a suite of rates of likely sediment elevation responses. If this information is not included, it is almost inevitable that substantial losses of vegetation will be predicted whereas, in fact, the vegetation may be able to respond via vertical accretion rather than merely a retreat into the hinterland or, if this is not possible, to be lost totally. A number of recent studies of the likely impacts of sea-level rise on coastal vegetation in New South Wales now explicitly include these factors (e.g. see Traill *et al.* 2011; Oliver *et al.* 2012). The conceptual model developed by Soares (2009) to show the response of mangroves to sea-level rise also includes as an explicit component changes in surface sediment elevations.

Whereas in the geological past plant communities were largely able to adapt to changes in mean sea level by migrating towards or away from the ocean, the intensive development of much of the coastline around Western Port now precludes such an adaptive response. In the case of mangroves and saltmarsh, changes in sediment elevation will be crucial to

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[100] Boon *et al.* (2011); see also Bird (1966) for a conceptual understanding of the processes involved.
[101] Rogers *et al.* (2012)
[102] See Mckee *et al.* (2007) for an example on the adaptive response in Caribbean mangrove swamps.

the long-term persistence if landward migrations are impossible because of the presence of human infrastructure. If the level of surface sediments can keep pace with increases in mean sea levels, coastal wetlands can survive the onslaught of sea-level rise. If, however, sediment elevations do not keep track with sea-level rise, the vegetation in affected areas will become progressively inundated with seawater and the floristic and structural composition of the peripheral vegetation change with the accompanying alterations to inundation and salinity regimes.

The predictions made above for the peripheral vegetation around Western Port are largely consistent with findings reached in the comprehensive assessment of the likely climate-change impacts on Australian biota undertaken by Steffen *et al.* (2009a, b, c). This series of studies addressed biodiversity on an Australia-wide scale and thus little attention could be given to the effects on mangroves and saltmarsh specifically. Even so, it was concluded that rise in mean sea levels could result in land-ward migration of mangroves and salinization of upstream wetland habitats, and that storm surges would result in increased erosion and sediment slumping and possibly also changes to the dynamics of wrack deposited on the shoreline. Human 'adaptive' responses, especially the construction of sea walls, were posited to likely interfere with species migration in the face of rising sea levels, and altered patterns of river discharge would affect inputs of detritus and nutrients into estuaries.

The conclusions are broadly consistent also with the more detailed assessment undertaken by Voice *et al.* (2006) for the Australian Greenhouse Office of the vulnerability of mangroves and coastal saltmarsh to climate change. Table 6 summarizes the findings reached by Voice *et al.* (2006) for coastal wetlands at a whole-of-nation scale, and this information remains a good starting point for describing likely impacts on peripheral vegetation around Western Port.

Table 6: Likely impacts of climate change on coastal saltmarsh and mangroves. Source: modified from Voice et al. (2006, Table 4a).

Climate-change driver	**Likely impact**	**Sensitivity & confidence**	**Known thresholds**
Rise in mean sea levels	Vegetation loss	High & Good	Unknown
Extreme storms	Reduction in vegetation cover	Low-Medium & Good	Tolerant of storms unless threat is combined with other stressors
Increased waves and wind	Reduction in vegetation cover	Medium-High & Moderate	Impact greater when combined with sea-level rise
Increased CO_2 concentration in atmosphere	Increased primary productivity	Low & Good	Increase in productivity up to 30%; limited by water stress and salinity
Increased air temperature	Altered productivity and changes in species composition	Low-Medium & Good	Impact depends on latitude: larger impacts at southern latitudes

Decrease in humidity	Altered productivity and changes in species composition	High & Moderate	Unknown
Decreased rainfall	Reduced productivity, invasion of mangroves into saltmarsh, hypersalinity in saltmarshes	High & Good	Unknown
Increased rainfall	Increased productivity and diversity	Low & Good	Unknown

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Appendix A – Summary of post-European changes in area and distributions of coastal wetlands around Western Port[103]

The Inlets

The Inlets have lost up to 40% of their original coastal marsh, mainly as a result of the loss of saltmarsh and estuarine wetlands rather than of mangrove. The once vast Koo Wee Rup swamp now discharges via large drains into Western Port. Between the Inlets, however, the imprint of the original tidal channels and portions of coastal marsh and other vegetation remains largely intact. The marsh is diverse, containing EVC 10 Estuarine Wetland, EVC 140 Mangrove Shrubland and EVC 9 Coastal Saltmarsh Aggregate of many kinds, including *Sarcocornia quinqueflora* herbland, *Tecticornia arbuscula* shrubland, and tussock-dominated saltmarsh of *Gahnia filum* or *Austrostipa stipoides*. The largest losses have been west of Lyall Inlet, whereas most of the marsh east of Lyall inlet apparently remains intact. This is not to say, however, that vast areas of other types of wetland (e.g. EVC 53 Swamp Scrub) have not been lost following the drainage of Koo Wee Rup Swamp.

Western Port coast

The Western Port coast retains a massive area of intact coastal marsh, including EVC 140 Mangrove Shrubland, EVC 10 Estuarine Wetland and EVC 9 Coastal Saltmarsh Aggregate dominated either by *Sarcocornia quinqueflora* or *Tecticornia arbuscula*. It has also suffered local historical losses as a result of infilling and drainage, and agricultural, urban and industrial development. The construction of the Hastings foreshore and marina resulted in the destruction of approximately 33 ha of saltmarsh, and the industrial developments at nearby Long Point resulted in the destruction of a further 23 ha. HMAS Cerberus near Sandy Point also required minor land-claims into former saltmarsh. Apart from these developments, infilling and drainage for pasture have also destroyed large expanses of marsh, particularly from Watson's Inlet around to Yallock Creek; and near Stockyard Point. In contrast, the marshes on Phillip Island and the Gurdies–Grantville coast remain largely intact despite being bordered by private land, and have suffered only slight losses through drainage and grazing. This retention of coastal wetland in the bioregion is presumably a function of the slightly steeper terrain at the inland border of the marshes. We estimate that overall losses have been proportionally small, probably <10%. Even so, because of the large original area of coastal marsh the total area thought to have been lost is substantial, at over 250 ha.

French Island

The vast stands of pre-European coastal marsh and mangroves on French Island remain almost entirely intact. Some losses have occurred as a result of clearing of Mangrove Shrubland and some estuarine wetland has been converted to pasture in the upper

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[103] Extracted and shortened from the detailed descriptions in Sinclair & Boon (2012)

Redbill Creek; extensive artificial ponds have modified but not removed much of the saltmarsh on the north-eastern coast.

Rhyll Inlet

Although it retains substantial areas of coastal marsh (mostly Mangrove Shrubland and *Tecticornia arbuscula* Coastal Saltmarsh), Rhyll Inlet has suffered losses since European colonization. The rubbish tip on Cowes-Rhyll Road has obliterated 5 ha of coastal marsh, and extensive drainage works on the eastern end near Cowes have destroyed more. A detailed early map suggests that the spit sheltering Rhyll Inlet has lengthened since colonization, and there may have been some modest expansion of coastal marsh at the eastern end of the inlet. Overall, losses have probably been <10% of the pre-European area.

Lang Lang Coast

The Lang Lang coast is unusual in that it shows a likely increase in the extent of coastal marsh since European colonization. At settlement, this section of the Victorian coast contained virtually no saltmarsh or mangroves, and was fringed instead with a dense stand of Swamp Paperbark *Melaleuca ericifolia* where the Tobin Yallock Swamp directly met the sea. Fresh water spilled from this swamp, an event described at the time as 'numerous rills of freshwater continually running'. The coast at this time was probably cliffed and eroding. Drainage, however, has left the former landscape unrecognisable. A series of bund walls now line the coast, and fresh water is channelled to the sea. A band of saltmarsh has formed on and in front of the bund walls, above the intertidal zone, and presumably receives salty water from ocean spray. This marsh is mostly species-poor *Sarcocornia quinqueflora* herbland. Small areas of remnant marsh occur only at the abandoned mouth of the old Yallock Creek.

Bass River

Pasture-creation has destroyed a large proportion of the marsh on the Bass River estuary, with almost the entire margin being bounded by walls, drains or fill. The invasive Cord-grass (**Spartina* spp.) grows in extensive mats in channels and on mudflats throughout the marsh, and has resulted in the exclusion of native-dominated marsh in places. Interestingly, an early plan of Western Port does not show any mangroves at the mouth of the Bass River, despite showing them elsewhere, including nearby at Settlement Point. Whether the extensive stands which now exist are a recent invasion is doubtful, and it is conceivable that the survey plan was incomplete. Overall, losses of coastal marsh may have been of the order of 25%.

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APPENDIX B SPECTRAL WAVE MODEL DESCRIPTION

1. 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 derived from a combination of the following bathymetric data sets, and interpolated onto the mesh using a prioritization routine to ensure the most recent data were used where available.

- Terrestrial Coastal LiDAR survey captured as part of the Coordinated Imagery Program.
- Bathymetric multibeam survey data of Western Entrance Channel, Lower North Arm, the deep channel along the western Upper North Arm and the East Arm.
- Bathymetric LiDAR
- A 50m resolution bathymetric grid of Western Port Bay provided by the EPA

1.1.1 Domain Schematisation

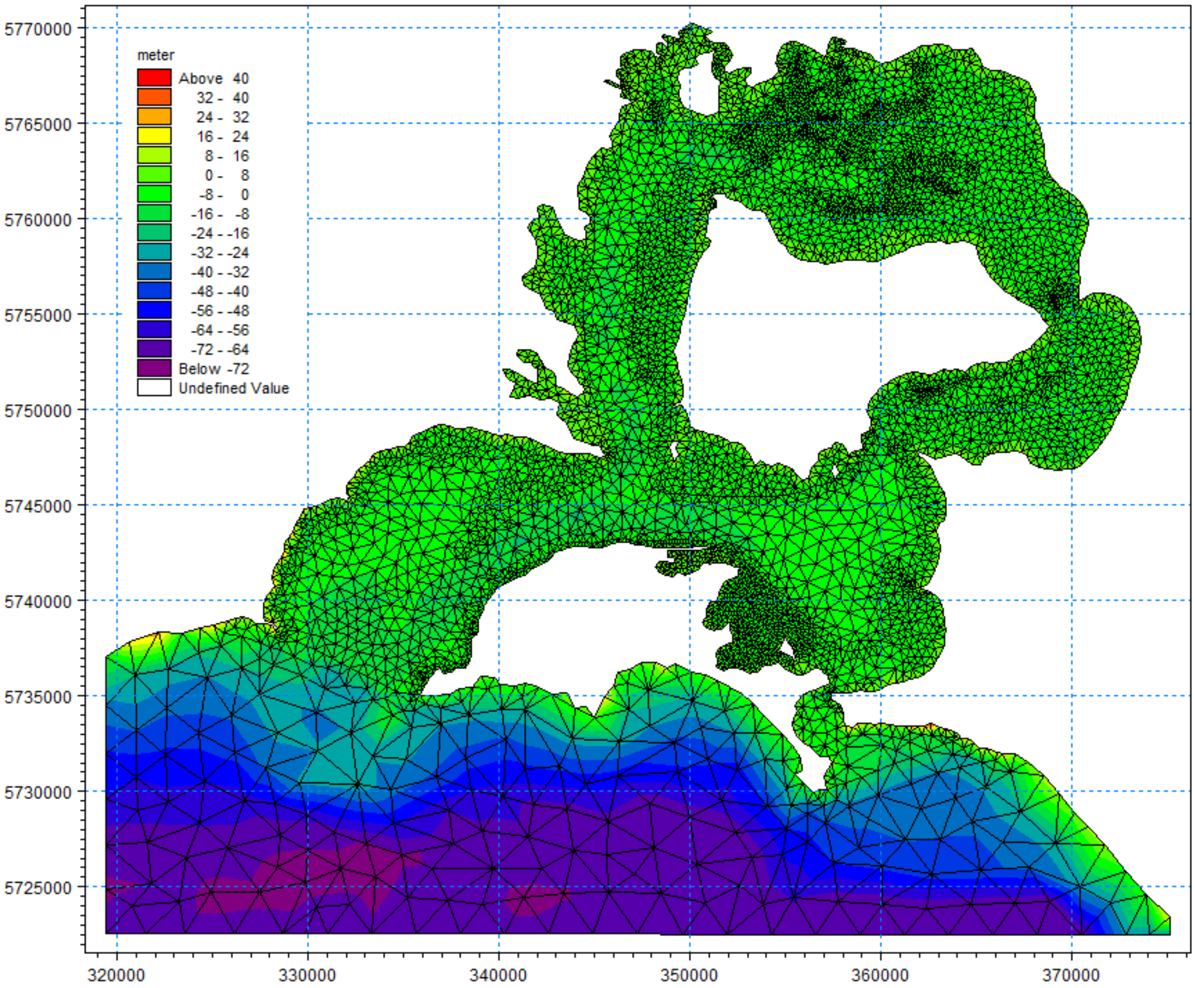

Figure 1-1 **Western Port Bay Spectral Wave Model Bathymetric Mesh and Domain Schematization**

1.1.2 Boundary Conditions

Wind Conditions

Wind 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 were available from the 1/1/1948 to present. The model results are provided on a rectangular grid, 2.5^0 N by 2.5 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 grid encompassing Western Port Bay. The u and v wind velocity grids were then applied as forcing conditions over the spectral wave computation domain displayed in Figure 1-1

Wave Conditions

The western and southern open ocean boundaries were forced by wave conditions extracted from Water Technologies Bass Strait Wave Model. The Bass Strait wave model has been developed using DHIs Spectral Wave Model and covers the Bass Strait, and part of the Southern Ocean (Figure 1-2). The model was forced along the open boundaries by wave conditions derived from the NOAA

WAVEWATCH III (WWIII) global wave model, and a spatially varying wind field extracted from the NCEP global weather model was applied over the model domain.

Measured wave data from the Pt Nepean Waverider buoy were available covering the period between 01/01/2000 to the 15/11/2000. Wave conditions along the western, southern and eastern boundaries were extracted from the NOAA WWIII global model spanning the same time period as the Pt Nepean wave buoy data and used to force the Bass Strait spectral wave model. The Bass Strait wave model was calibrated by comparing measured and modelled significant wave heights, peak periods, and wave directions from the Pt Nepean Waverider buoy and is displayed in Figure 1-3.

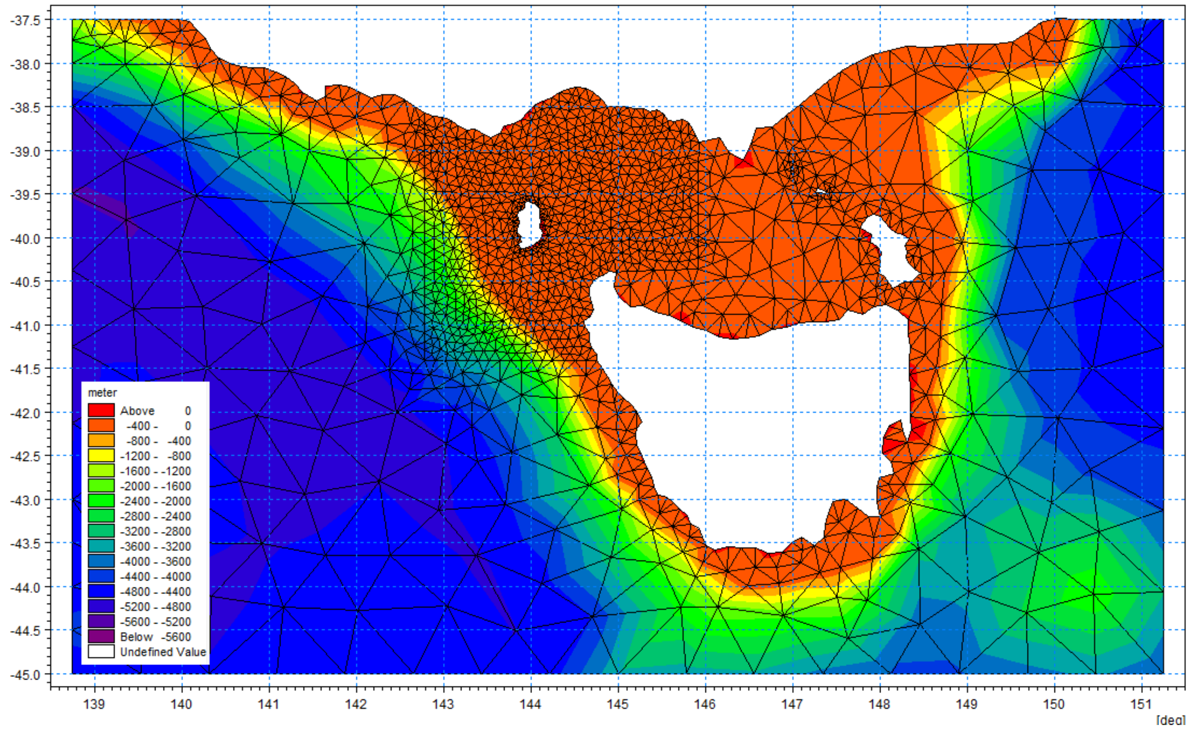

Figure 1-2 **Bass Strait Spectral Wave Model Bathymetric Mesh and Domain Schematization**

Bass Strait Wave Model Calibration

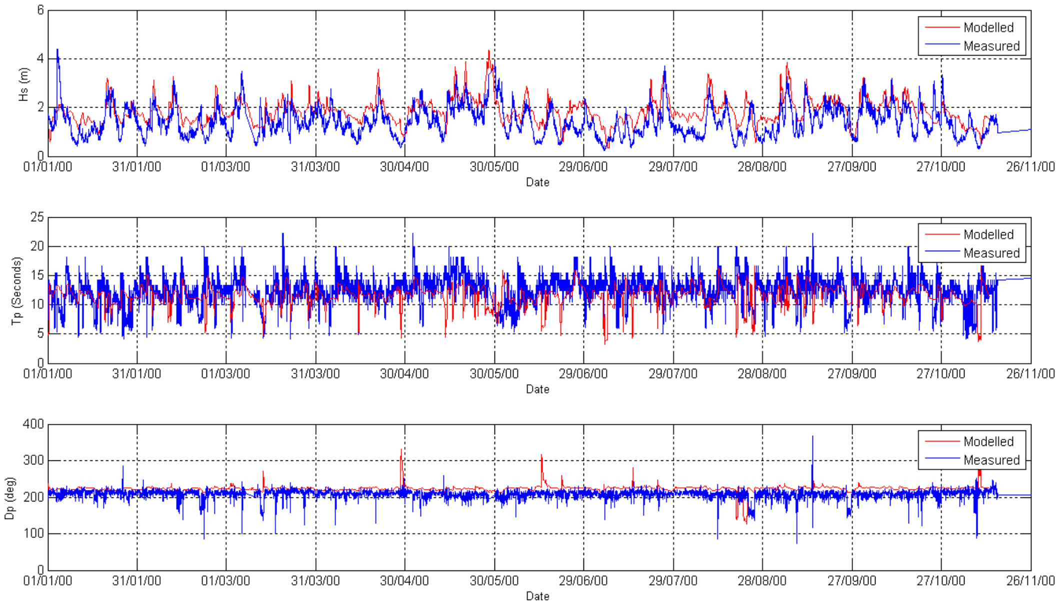

Figure 1-3 **Comparison of Modelled and Measured Wave Conditions at the Point Nepean Wave Buoy**

1.2 Model Calibration

The Western Port Bay Spectral wave developed for this study was calibrated against measured wave data recorded in the intertidal zones at Jam Jerrup, Grantville and Lang Lang, between the 11th of February and the 13th of April, 2011.

Figure 1-4 to Figure 1-6 display comparisons of modelled and observed significant wave heights and peak periods over the calibration period. One of the key processes operating on wind waves within Western Port is the change in water depth, and thus wave attenuation, associated with the rise and fall of each tide. The time series results shown in Figures 1-4 to 1-6 demonstrate the Western Port Bay Spectral Wave models ability to successfully simulate the wind wave climate at all three of the calibration locations, to an appropriate level for this project, given the limited spatial resolution of available wind data to force the model, and wave data for which to calibrate the spectral wave model against.

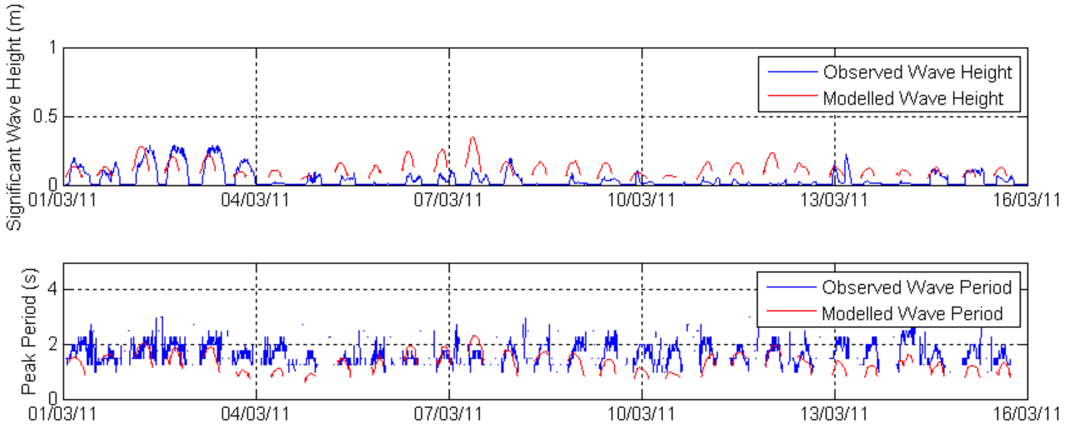

Figure 1-4 **Comparison of Modelled and Observed Significant Wave Height and Peak Wave Period at Grantville**

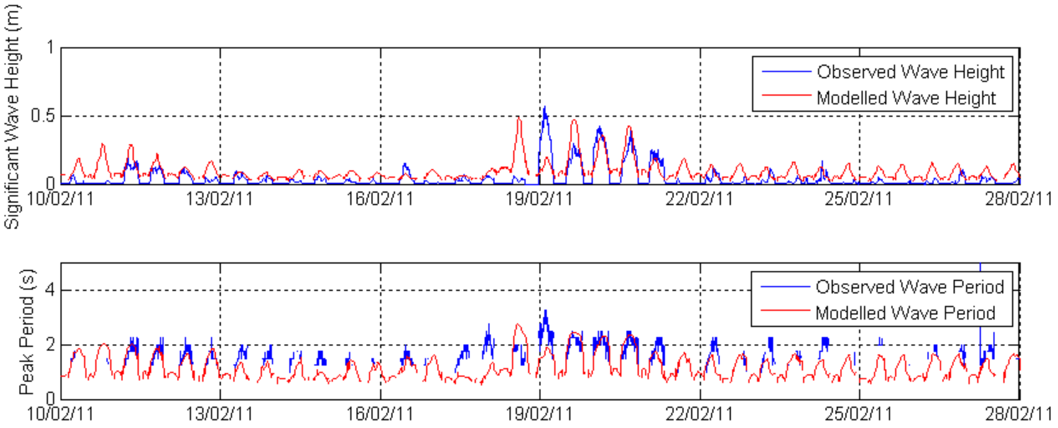

Figure 1-5 **Comparison of Modelled and Observed Significant Wave Height and Peak Wave Period at Jam Jerrup**

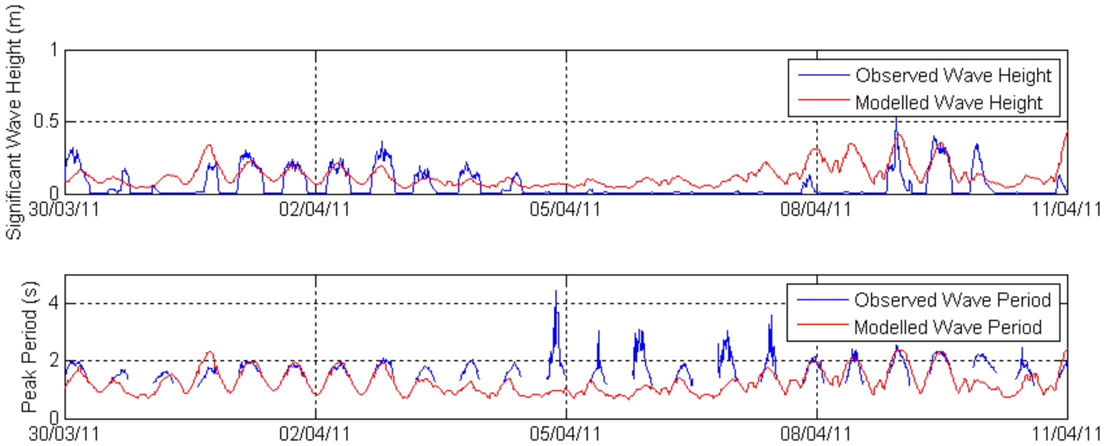

Figure 1-6 **Comparison of Modelled and Observed Significant Wave Height and Peak Wave Period at Lang Lang**