Circular Head Region Coastal Foreshore Habitats: Sea Level Rise Vulnerability Assessment

[Boullanger Bay - Robbins Passage - Big Bay - Duck Bay]

July 2010

Final Report

For the **Cradle Coast NRM Region**
and the **Cradle Coast Authority**

Cradle Coast NRM

Project Team

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Photo library

A large image archive of about 5,000 geolocated photos taken during the project is freely available at <http://picasaweb.google.com.au/FarNWvulnerability>. Many of the images have the date, time and precise latitude and longitude visible on them and that information is also stored in the image file itself (EXIF header). Geolocated images can be viewed in position with Google Earth and Google Maps.

Assessment summary

- This project is about the relationship of people, especially the local people, to the natural environments of the extensive sheltered shores of the Circular Head region including Duck Bay, Big Bay, Robbins Passage and Boullanger Bay.
- This project is designed to focus on the **benefits that flow to people from the natural environments** (or **habitats**) in the area and then broadly assess whether or not they are vulnerable to **sea level rise** impacts.
- The Environmental Condition Assessment Framework (ECAF) was used to structure the project and the assessment. The **assessment process** was:
    - Collate the management objectives and the values associated with the habitats.
    - Assemble the information base about
        - The environmental history and context
        - The definition, description and functioning of the habitats
        - Threats and pressures acting on the habitats besides sea level rise
    - Identify the benefits (ecosystem services) that flow to people from the habitats
    - Assemble the available evidence about sea level rise effects
    - Drawing on the information base, broadly assess the vulnerability of the benefits to sea level rise impacts. The information base also provides an evidence base for more specific risk assessments.
- The **key findings** are that:
    - The habitats are indeed highly valuable **natural assets** that have a proven capacity to actively respond to changes in sea level. A large number of benefits flow now, and have flowed through time, from the habitats to the inhabitants of the area including:
        - Shoreline and seabed stability (baffling wind and wave energy) including rapid low cost responsiveness to sea level rise
        - Maintenance of water quality (filtering nutrients and sediments)
        - Support of food security (high rates of natural primary productivity and associated food webs e.g. fish)
        - Very strong contributions to carbon sequestration
        - Helping to preserve options for the region's future
    - **Sea levels are already rising** and though it is not by much so far, impacts are becoming apparent. The "signature" of sea level rise is apparent as follows:
        - A net rise of 5.4 cm in mean sea level since 1966 measured at Burnie tide gauge (rate of 1.4 mm per year)
        - A large and consistent net landwards movement of the shoreline with an onset around 1968-1975. This is particularly so for the 70% of the shoreline that is saltmarsh, which has an average net landwards movement of about 20 cm per year between 1951 and the present, or about 12 m.

    - Erosion of old sediment deposits – along many shores, old (26,000 to 36,000 yr before present) peaty deposits and Pleistocene dunes are exposed and experiencing active erosion. This is the first time that these locations have been exposed to wave attack since they were formed.
    - The erosion mechanisms doing the work, such as wind fetch waves, are consistent with expected sea level rise effects rather than other mechanisms.
    - Erosion of long lived trees and shrubs, such as *Melaleuca* (T-tree or paperbark) trees and *Tecticornia* shrubs
    - Net landward and upward movement of saltmarsh vegetation, including into the adjacent *Melaleuca* swamp forests and the dieback of *Melaleuca* trees, is consistent with the elevation of the tidal frame with sea level rise.
  - If sea levels continue to rise as predicted, the **most likely and significant impacts** that have **economic and social implications** include;
    - Changes in shoreline position as the foreshore profile responds to sea level rise including increased coastal erosion
    - Coastal flooding of low lying privately owned land
    - Seabed instability with associated decreases in water clarity
    - Changes in water quality through reduced filtering and sequestration of nutrients and sediments by habitats
    - Changes in the primary productivity of the habitats and an associated reduction in food security benefits
    - Reduced carbon sequestration rates and possible loss of large carbon reservoirs.
  - The **resilience of the habitats' natural capacity to respond** to sea level rise is affected by pressures other than sea level rise including:
    - Artificial barriers to tidal exchange and a lack of room for the habitats to move
    - Excess nutrients and sediments, e.g. eutrophication
    - Direct mechanical disturbance of the habitats e.g. trampling, grazing and vehicle damage
    - Weed invasions, e.g. Rice grass (Spartina anglica)

    These are the key pressures to manage to ensure the sustainability of the flow of benefits. Suggested management options are detailed in Section 9.

- The **primary audience** for this report (as identified in the associated Communication Plan by Tilden *et al.*, 2010) are those who are planning for adaptation to climate change impacts including dairy industry, aquaculture, tourism, health professionals, local councils and conservations groups.
    - Media and communication materials including detailed **pictorial conceptual diagrams** matched to the needs of the primary audience are presented. They were prepared for the closely associated Communication Plan (Tilden *et al.*, 2010).

- Extensive **new mapping and modelling data sets** were collected and created for the report. These include:
    - Updated habitat mapping including seagrass, sand, saltmarsh and reef
    - Shoreline landforms, substrate and erosion status mapping (130 km)
    - Coastal flooding (inundation) models using the new Climate Futures LiDAR digital elevation model (DEM)
    - New aerial photograph orthophotos and satellite imagery
    - Time series case studies back to the 1950s
    - Wind fetch modelling every 100 m along the shore
    - Stratigraphy study with profiles, cores and dating
    - Three new TASMARC sites established for accurately monitoring shoreline profile heights
    - Nutrient samples of intertidal sediments
- Fast facts for the project area
    - 250 km of shoreline and 220 square kilometres of coastal foreshore habitats
        - Over 90% of the mapped shorelines are saltmarsh or other erodible shores
        - 60 square kilometres of subtidal seagrass
        - 60 square kilometres of intertidal seagrass
        - 80 square kilometres of open sand and tidal channels
        - 11 square kilometres of saltmarsh
    - About a billion tonnes of water move in and out on each tide
    - Subtidal seagrass production rates are similar to pasture grass

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1. Introduction

This project is about the relationship of people, especially the local people, to the natural environments of the extensive sheltered shores of the Circular Head region. The ecology of the coast has been supporting and benefitting the people who have lived in this place for many thousands of years. This project is designed to focus on the benefits that flow to people from the coastal habitats in the area and then assess whether or not they are vulnerable to sea level rise.

To this end, the project team firstly seeks to answer the question, “Do the things people do and care about benefit from the coastal habitats found in the area, and, if so, how?” The project is then required to take into account sea level rise impacts. To do this the project team addressed the question, “Are those benefits vulnerable to sea level rise?”

In seeking to establish the answers to those questions the project team has made use of the Environmental Condition Assessment Framework or ECAF (Mount, 2008; see Box 1.1). This framework sets out the requirements for assessments of natural assets and explicitly includes the objectives and values of the people with an interest in the assets and provides direction on the type of assessment that is possible and the information base required for that assessment. The ECAF is explicitly intended to deliver reports to management that are useful for management purposes.

The project area consists of Duck Bay, Big Bay, Robbins Passage and Boullanger Bay. The habitats in focus are the coastal foreshore habitats including shoreline wetlands, intertidal flats and shallow subtidal areas down to about 7-8 metres depth. These habitats cover about 220 km^2 and the shoreline is about 250 km long, including the “inside” of Robbins and Perkins Islands (at the 1:25,000 map scale). They include *Melaleuca* (paperbark or “tea tree”) forests, saltmarshes, sandy intertidal flats, intertidal seagrasses and the larger, more robust subtidal seagrasses. It also includes the mud flats up in the estuaries, the tidal channels, large and small, and a few small areas of rocky shore and reef. The tidal range is about 3 to 3.5 metres and this means that about a billion tonnes of water flows in then back out on each tide.

Sea levels and whether they are rising, how far they are expected to rise and over what time frames are current hot topics of conversation that are often contested. There are a very wide variety of views on the subject, some of which can be alarming for many people including children. For this reason, the project team has sought calmly to assemble evidence directly relevant to this location. We have also brought all our training, knowledge and skills to bear on the problem and, while we have the limitations of our own perspectives, we hope we have added new ways of understanding this vast and extraordinary place. We have taken an approach that seeks to put the things we see today, such as shoreline erosion, into a longer time frame, in some cases reaching back thousands of years. The environmental history of the area is crucial to understand if the power and productivity of the natural environments are to be appreciated and sustainably utilised for the betterment of the local people as well as those from further afield.

Project aim

The aim of the project is to find out;

- Do the things people do and care about benefit from the coastal habitats found in the area and, if so, how? and
- Are those benefits vulnerable to sea level rise?

This aim was broken up and addressed by the project team as a series of questions:

1. What are the things people do and care about (activities and values)?
2. What do we know about the environmental history of the area?
3. What sorts of things grow and live around the shores (habitats) and how do they work today?
4. Do the habitats help people to achieve their hopes and goals (benefits)?
5. What signs or evidence is there of a change in the level of the sea (hazard)?
6. Are the benefits likely to be affected by sea level rise (risk)?
7. What can be done to maintain those benefits (treatment)?
8. The project has a complementary aim of communicating the results to those who can make the most of the information the project generates.

Box 1.1 Environmental Condition Assessment Framework (ECAF)

The Environmental Condition Assessment Framework (ECAF) provides the overarching approach for this project and indicates that assessments:

- require management objectives and values to be defined as part of any assessment process
- document the current understanding of the environmental asset of interest, the ecosystem processes and the pressures\threats acting on the asset
- are conducted by matching the information resources available to the information required by management

The ECAF was developed during the second round of the National Land and Water Audit within the Estuarine Coastal and Marine theme to guide the management of environmental information for assessment and reporting purposes (Mount 2008).

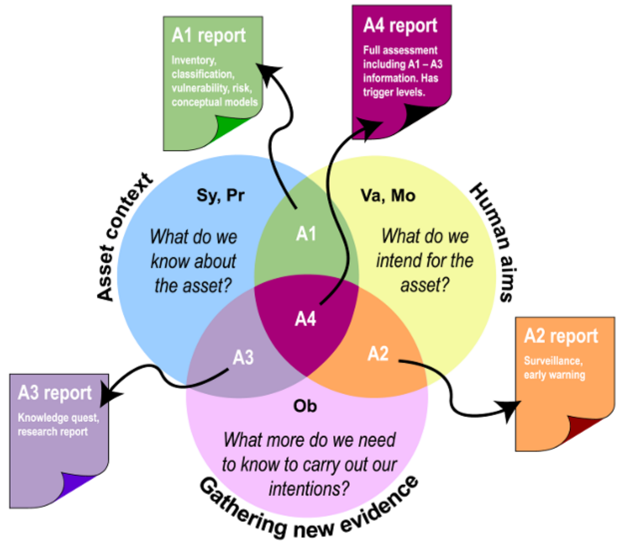

Table 1 Information in report card "conceptual domains"[1]

Information domain component		Example
Sy	Where it is, how it works, system type	Shallow, tropical, turbid shelf waters
Pr	Direct and indirect human impacts, pressures or threats	Catchment clearing High fishing effort
Ob	What else we need to know, observations through time	Turbidity measurements for monitoring
Va	Why we care about it, values	Ecosystem (biodiversity) & human use (tourism)
Mo	Management intentions that exist for it, management objectives	By-catch objective

Table 2 Types of reports generated by combining domains

Report/output examples		Weakness
A1	Inventory, classification, vulnerability, risk, conceptual models	Not informed by monitoring & trends not available
A2	Surveillance, early warning	Poor causal linkages
A3	Knowledge quest, research reports	Lack of management relevance
A4	Full assessment including A1 – A3 (with trigger values)	Complex, long timeframes, expensive

1 Colour coding in both tables corresponds to the diagram to the left

Figure 1. Environmental Condition Assessment Framework (ECAF), showing domains of information sampled in environmental assessment and reporting, the types of assessments and reports produced and the weaknesses of the different report types

The ECAF is currently being integrated into the Common Assessment and Reporting Framework (CARF) that is currently being trialled by the Australian Government for estuarine, coastal and marine ecosystem based management purposes.

2. Management values and objectives

Primary Authorship: Vishnu Prahalad

This section is mostly a compilation of the values and management objectives already identified in the reports and documents available for the area. There have been recent extensive efforts to synthesise these (e.g. TLC *et al*., 2006) so this section is simply designed as a reference to the most pertinent objectives and values to this particular sea level rise assessment. The values and objectives are important to keep in mind, particularly when framing the study, during the actual vulnerability assessment (see Section 7) and, finally, when concluding the study, where linkages are made to some of them in Section 9 the "Management options summary".

2.1. Management values

The Circular Head coastal foreshore area has a range of special values which make it a singularly important area in Tasmania socially, economically and environmentally. These values are often interwoven and closely related to each other. For example, the area holds immense cultural value for both Aboriginal people and European settlers. This cultural value is strongly related to the natural resources (both from the land and the sea) with which the area is liberally endowed owing to its unique environmental setting (see Section 3 Environmental context and history). Yet often, social, economic and environmental values are viewed as being separate from each other resulting in the inappropriate management of these values. To counteract this tendency to separate the three kinds of values, there is an increasing trend towards using a triple-bottom-line (TBL) approach to management (Rogers and Ryan, 2001), which essentially recognises the social, economic and environmental values as interrelated when considering management values and objectives.

The management values listed below have been obtained primarily from the *Cradle Coast Natural Resource Management Strategy* (Cradle Coast NRM Committee, 2005), the *Community-based draft Management Plan for the Robbins Passage/Boullanger Bay wetlands* (TLC *et al*., 2006), and the *Values Mapping Project* detailed by Elix and Lambert (2007). Among other sources (e.g. van de Geer, 1981; Spruzen, 2008; Schahinger, 2009), material has been drawn from the Boullanger Bay/Robbins Passage Ramsar site nomination reports (Dunn, 2000, 2001), the *Tasmanian Wetland Strategy* (DPIWE, 2003) and the *Marine Farm Development Plan: Far North West* (DPIWE, 1999).

2.1.1. Social values

The area has rich historic and current day cultural values strongly related to the natural resources of the area (Pink and Ebdon, 1988). The Aboriginal people have identified that cultural education, such as in the traditional uses of the land and sea for food gathering, are of significance. The European settlers have used the area for fishing, duck-hunting and mutton-birding among others. Currently, the area has important recreational value for both the local residents and visitors. Recreational pursuits in the area involve a wide range of activities such as fishing, duck-hunting, recreational driving and riding, bird watching, diving, snorkelling, kayaking, boating and camping among others. In general, people have a strong connection to the area with a clear "sense of place" and belonging (Pink and Ebdon, 1988).

2.1.2. Economic values

Several economic activities, such as agriculture, forestry, manufacturing, mining, retail and tourism, are identified by the Cradle Coast Authority as being important for the area (Cradle Coast Authority, 2010). Agriculture, mainly dairying and beef cattle, is the primary industry in the area and contributes far in excess of the State's average agricultural production. The area is considered to be the largest diary and prime beef producer in the State. Agricultural productivity in the area greatly benefits from the mild climate and relatively high rainfall, with the marketing of the produce inter-State and internationally benefitting from Tasmania's "clean, green" image. The last few decades has witnessed a considerable expansion of agricultural activity in this area.

Other major industries in the area include fishing, aquaculture, tourism and the processing of food (vegetables, meat, milk and seafood) and timber. Commercial fishing is primarily for rock lobster and abalone, which are processed near Smithton and Stanley. Given the high populations of both rock lobster and abalone in the area, recreational fishing for these species is popular. Marine farming for Pacific oysters is being carried out in Duck Bay, Big Bay and at the mouth of the Montagu River, and is heavily dependent on the high water quality of the area. The Marine Farm Development Plan for the area (DPIWE, 1999) identifies the area to be highly suitable for marine farming with potential for future expansion. The plan lists the following advantages:

- water temperatures are suitable for the production of shellfish;
- there is no history of marine farm closures due to toxic dinoflagellate blooms;
- it contains additional intertidal areas suitable for culture of oysters. For a number of reasons such areas are becoming scarce in the State;
- the region is already established as a productive marine farming area and operators have a wide range of experience in local conditions;
- there is a skilled labour force available in the region and the local industry is willing to develop techniques and farming practices to deal with more exposed conditions;
- there are no major sources of industrial pollution.

Tourism, especially nature-based tourism, is considered important in the Circular Head area for the employment opportunities it provides. Wind farming has recently been developed in the area which now is the home to one of the larger wind farms in the State (at Woolnorth).

2.1.3. Environmental values

The area is one of the most extraordinary natural environments in Tasmania containing intertidal flats, reef assemblages, seagrass beds, saltmarshes and *Melaleuca* swamp forests. With its unique environmental setting (see Section Environmental context and history), the study area has some of the most extensive intertidal flats, seagrass beds and saltmarshes mapped in the State (see Section

The habitats and their benefits to people). These areas provide habitat for a range of fauna, some of which are commercially important (e.g. abalone and rock lobster) while others are important for biodiversity conservation (e.g. shorebirds). The Boullanger Bay-Robbins Passage wetlands are known to have the largest diversity and density of resident and migratory shorebirds in the State. Over 25,000 shorebirds have been recorded in the summer months, suggesting that the area supports more shorebirds than the rest of Tasmania combined (Spruzen, 2008). The area provides an important habitat for 15 bird species listed under international migratory bird agreements and two resident species, little tern and hooded plover, listed as endangered and vulnerable respectively. The area is home to large populations of the rare saltmarsh herb *Limonium australe* (listed as Rare under State legislation) and extensive tracts of saltmarsh dominated by the succulent shrub *Tecticornia arbuscula*, which is a structurally dominant vegetation in Tasmanian saltmarshes.

The rich and unique natural values in the area have been identified through its listing in the Directory of Important Wetlands of Australia (Ref. No. TAS089). Tasmania has 89 wetlands in the list and this area is the only one to fulfil all six criteria for listing (Environment Australia, 2001). The area is on the Register of National Estate (Place Id. 19961) for its natural values, mainly including the shorebirds, saltmarshes and tidal flats. This area fulfils several criteria for being considered as a Wetland of International Importance under the Ramsar Convention on Wetlands (Dunn, 2000, 2001). However, the nomination for Ramsar listing was rejected by the State government following local opposition to the listing (Prahalad and Kriwoken, 2010).

2.1.4. Protected Environmental Values

Protected Environmental Values (PEVs) are set under the *State Policy on Water Quality Management 1997* to define the current uses and values of waterways in Tasmania. PEVs are being set around the State for all surface waters, including that of the Circular Head foreshore area which mainly includes estuarine and coastal waters (DPIWE, 2000). The PEVs are categorised into: Protection of Aquatic Ecosystems; Recreational Water Quality and Aesthetics; Raw Water for Drinking Water Supply; Agricultural Water Uses; and Industrial Water Supply. Of these five categories, the three that are of relevance to the study are:

- *Protection of Aquatic Ecosystems* (ensuring the healthy function of the unique and wide range of aquatic/wetland habitats in the area);
- *Recreational Water Quality and Aesthetics* (maintaining the water quality required for recreational pursuits and general aesthetics);
- *Industrial Water Supply* (supplying clean water for fishing, aquaculture and tourism industries in the area).

PEVs are established by the Environmental Management and Pollution Control Board and regional planning authorities including land managers to provide a framework for co-operative management of water resources for its long term sustainable use.

2.2. Management objectives and strategies

The *Cradle Coast NRM Strategy 2005*[1] has set three main management objectives or targets for the area. They are:

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[1] *See*: Cradle Coast NRM Strategies and Proposals, at <http://www.nrmtas.org/library/cradle/strategiesProposals.shtml>, accessed 21 April 2010.

- "aspirational target" to maintain the integrity of the nationally significant coastal wetland, salt marsh communities, intertidal zone and associated seagrass beds at Robbins Passage and Boullanger Bay.
- "resource condition target" for maintaining the wetlands integrity by maintaining or improving the condition and extent of Robbins Passage/Boullanger Bay: ongoing/by 2020.
- "management action target" to complete and implement a management plan for Robbins Passage/Boullanger Bay: by 2009.

The *Tasmanian State Coastal Policy 1996* (revised twice in 2003 and 2009)[2] has several strategies encouraging the "protection of natural and cultural values of the coastal zone" and the "sustainable development of coastal areas and resources". The policy sets the following objectives:

- to promote the sustainable development of natural and physical resources and the maintenance of ecological processes and genetic diversity; and
- to provide for the fair, orderly and sustainable use and development of air, land and water; and
- to encourage public involvement in resource management and planning; and
- to facilitate economic development in accordance with the objectives set out in the preceding objectives; and
- to promote the sharing of responsibility for resource management and planning between the different spheres of government, the community and industry in the State.

Of particular relevance here is the Outcome 1.1.9 of the policy which states that "**[i]mportant coastal wetlands will be identified, protected, repaired and managed so that their full potential for nature conservation and public benefit is realised. Some wetlands will be managed for multiple use, such as recreation and aquaculture, provided conservation values are not compromised.**"

The *Circular Head Planning Scheme* provides planning guidelines to implement the *State Coastal Policy 1996* and to ensure coastal protection in general. Especially, Clause 6.5.1 states that, "[i]n order ... to maintain the natural functions of ... the coastal environment ... any development within 30 metres of any tidal flat, saltmarsh, or lagoon; or involving the dumping of rubbish or landfill on or into any tidal flat, saltmarsh or lagoon or the filling or reclamation of any such area" is subject to planning guidelines and approvals. Clause 6.6.1 provides for the protection of "the natural drainage functions and botanical, zoological and landscape values of streams, rivers or wetlands within the Municipality." It is an offence under the *Land Use Planning and Approvals Act 1993* to carry out works without any permit required under a planning scheme.

[2] *See*: Department of Primary industries, Parks, Water and Environment: Coastal and Marine (under review), at <http://www.environment.tas.gov.au/index.aspx?base=6192>, accessed 21 April 2010.

The *State Policy on Water Quality Management 1997*[3] has several objectives to support the setting and the subsequent implementation of the PEVs. The main objectives of the policy include:

- focus water quality management on the achievement of water quality objectives which will maintain or enhance water quality;
- ensure that diffuse source and point source pollution does not prejudice the achievement of water quality objectives;
- ensure that efficient and effective water quality monitoring programs are carried out;
- facilitate and promote integrated catchment management;
- apply the precautionary principle;

The policy further states that "[i]n giving effect to this Policy, governments and other decision-makers must examine the most appropriate mix of regulatory measures, economic instruments and communications strategies to achieve the objectives of the Policy."

The *Tasmanian Wetlands Strategy 2003* (DPIWE, 2003) identifies wetlands as one of the State's most important natural assets and sets out several strategies for their conservation management grouped under four major themes, including:

- protecting sites of conservation and cultural heritage significance;
- reducing the threats to wetlands through integrated natural resource management;
- promoting and supporting the participation of stakeholders in wetland management;
- improving the knowledge underpinning wetland management and making this available to stakeholders and the broader community.

The strategy states that "**[d]ecisions concerning the future conservation and management of all wetlands in the State are to be made with due consideration of their full ecological, social and economic values, and, where this is not possible, the precautionary principle is be applied in decision making.**" With regard to the application of the precautionary principle, the strategy states that "**where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing measures to prevent environmental degradation (Australian Natural Heritage Charter).**"

The *Community-based draft Management Plan for the Robbins Passage/Boullanger Bay (RPBB) wetlands 2006* (TLC *et al*., 2006) is of particular importance here as the plan has essentially distilled many of the general management strategies and identified particular strategies of relevance to the study area.

They include:

1. Ensure that continued human use and development does not lead to a level of habitat loss and fragmentation that impacts on long term sustainability of natural, cultural and economic values:

[3] *See*: Department of Primary industries, Parks, Water and Environment: Water Quality Policy, at <http://www.environment.tas.gov.au/index.aspx?base=234>, accessed 21 April 2010.

- Increase knowledge, understanding and awareness among local community, land owners and managers and council staff about the values of the wetlands and impacts of human use and development on the RPBB wetlands.
- Support community groups and private land owners to maintain and enhance coastal, estuarine and wetland habitats.
- Increase the effectiveness of existing regulatory frameworks, particularly Circular Head Planning Scheme in protecting the values of the RPBB wetlands.

2. Ensure that water quality is maintained or improved to a level that leads to the long term sustainability of natural, cultural and economic values:
   - Improve community understanding of water quality in the RPBB wetlands and the biological, physical and human use and development factors affecting water quality in the wetlands.
   - Develop an effective and robust system of water quality monitoring and reporting to allow comparison of ecosystem health year-to-year.
   - Improve regulation of point source pollution.
3. Minimise disturbance to shorebird habitat by public access to the RPBB wetlands, so that the long-term sustainability of natural, cultural and economic values are maintained:
   - Increase public awareness of shorebirds, shorebird habitat and appropriate behaviour in and around important shorebird habitat.
   - Improve control over access to important shorebird habitat for vehicles, dogs and other human use and developments.
   - Support private landowners to maintain and protect coastal, estuarine and wetland habitats.
   - Implement new regulations where practicable to improve the protection of important shorebird habitat.
4. Prevent, control and, where possible, eradicate invasive animals to minimise the long-term impact on natural, cultural and economic values:
   - Support existing pest management strategies.
   - Adopt municipal cat registration program.
5. Ensure harvesting of natural resources and management of wild populations within the RPBB wetlands is sustainable in the long-term:
   - Improve understanding of ecology, population dynamics and sustainable yields for target species and potential future target species.
   - Improve community education and knowledge of hunting, fishing and muttonbirding best practices and the relevant regulations.
6. Protect Indigenous and non-Indigenous cultural heritage values in the RPBB wetlands and increase local community knowledge of cultural heritage values:
   - Support Indigenous and non-Indigenous community groups to increase their knowledge of cultural heritage in the RPBB wetlands.
   - Maintain cultural activities occurring in the RPBB wetlands, ensuring that these are sustainable in the long-term.

- Integrate cultural knowledge of land management issues into the management of the RPBB wetlands.

3. Environmental context and history

3.1. Geology and geomorphology

Primary Authorship: Chris Sharples

3.1.1. Geology

The bedrock geology underlying Quaternary sediments or exposed along the study area shore is a fundamental control on landform type and development, hence a brief outline is provided here. Further details can be obtained from the references cited.

Bedrock geology mapping of much of the study area shore and adjoining hinterland areas has been compiled and published by the Geological Survey of Tasmania (1:250,000 scale: Calver *et al* 1995; 1:50,000 scale: Lennox *et al.*1982, Seymour and Baillie 1992; 1:25,0000 scale: Hall *et al.*2006, Seymour 2004a,b, 2005, 2006, 2008). However it should be noted that for some portions of the study area shores, these published maps were based only on extrapolation and air photo interpretation without ground-truthing (for example between Welcome Inlet and the Harcus River mouth). Several shoreline bedrock outcrops which are not shown on the published geological maps were identified in such areas during this project; these are referred to below where relevant (for example, Tertiary-age limestone shore platform outcrops on the east side of Welcome Inlet, where the published geological mapping infers only Quaternary-age cover sands).

The following summary outline of the bedrock geology and geological history of the study area is largely based on Burrett and Martin (1989), Seymour and Calver (1995), and the published geological mapping listed above.

Precambrian basement rocks

The oldest rocks exposed in the study area are the Precambrian-age quartzites, siltstones, mudstones and slates of the Rocky Cape Group, which outcrop at Cape Woolnorth and on Robbins Island, and elsewhere form the basement underlying the younger rocks of the Smithton Basin (see below and Figure 3.1). The Rocky Cape Group represents sediments deposited in a quiet marine shelf environment circa 1,100 million years ago, which were subsequently deformed and metamorphosed during later tectonic events (Turner in: Burrett and Martin 1989, p.5; Seymour and Calver 1995).

Smithton Basin Precambrian – Cambrian rocks

The Smithton Basin comprises a complex sequence of sedimentary and volcanic rocks overlying the Rocky Cape Group and constituting the hard bedrock exposed or immediately underlying soft Quaternary-age sediments along most of the study area coast (see Figure 3.1). The rocks of the Smithton Basin are collectively known as the Togari Group (Seymour and Calver 1995) and were deposited in an intermittently unstable marine environment during Late Precambrian times from circa 750 to 550 million years ago. The Togari Group sequence dominantly comprises two extensive horizons of carbonate sedimentary rocks which were deposited in quiet shallow marine conditions (the Black River and Smithton Dolomites), separated by the complex volcaniclastic rock sequence of the Kanunnah Subgroup, which was deposited during an intervening phase of volcanism, tectonic instability and extensional rifting in the marine depositional trough (see Figure 3.1). This subgroup includes basaltic lavas of the Spinks Creek Volcanics interbedded with poorly sorted conglomerates and sandstones ("wackes") having a high volcanic mineral content. The dolomite units are not exposed along the shoreline, being of low relief and generally covered by Quaternary sediments, however the interbedded basalts and volcaniclastic rocks are more resistant to erosion and outcrop extensively along the shoreline in the Smithton and Brick Islands – Robbins Crossing areas.

These rocks are truncated by an erosional break (unconformity) resulting from tectonic uplift during a middle Cambrian-age tectonic (mountain-building) event dated to circa 500 million years ago, which is thought to be the result of a continental collision event (Seymour and Calver 1995). This compressional event folded the Togari Group sediments into the complex synclinal (down-warped) structure of the Smithton Basin (see cross-section A-B on Figure 3.1). Following erosion of uplifted areas, the resulting erosion surface was in turn overlain by younger poorly sorted fossiliferous conglomerates, sandstones and siltstones of the Middle to Late Cambrian – age Scopus Formation (circa 495 – 500 million years old), which represent a return to depositional conditions in a tectonically unstable marine trough. Resistant bedrock units of the Scopus Formation outcrop extensively along the shoreline around the Stony Point area at Montagu.

Tectonic uplift of what is now far north-west Tasmania took place in Late Cambrian times circa 495 million years ago, and the area of the Smithton Basin is thought to have remained a continuously non-depositional terrestrial environment for a very long interval (400 million years or more) from then until Early Tertiary times when marine transgressions again began depositing sedimentary rocks in the region (see below). During this long interregnum several phases of extensive marine transgression and sedimentation took place over other large parts of what is now Tasmania; however a shoreline corresponding roughly to a line between Pieman Heads and Wynyard mostly persisted through these depositional phases with the Smithton Basin region being thought to have largely remained dry land throughout[4]. Further tectonic uplift and folding of the Smithton Basin including the Scopus Formation took place during this terrestrial interval, particularly in the Devonian-age mountain – building event known as the Tabberabberan Orogeny (circa 385 million years ago) which produced a large (Himalayan-scale) mountain range occupying most of what is now eastern Australia.

Tertiary geological history

After a long period of stability and non-deposition in the Smithton Basin region, crustal extension and block faulting related to the break-up of the former supercontinent of Gondwanaland rejuvenated landscape development processes in what became Tasmania. The separation of Australia from Antarctica between early Cretaceous times (circa 118 million years ago) and early Tertiary times (circa 55-50 million years ago) resulted in both the creation of Bass Strait (as a tectonically downthrown "failed" rift zone basin) and the opening of the Southern Ocean (a successful rift zone) to the west and southwest of Tasmania (Veevers *et al.* 1991). At a coarse scale, the broad planforms and location of

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[4] Note that Tasmania was at the time part of a much larger continent later to become Gondwanaland, such that areas to the west of present-day far northwest Tasmania were not then sea (as they are now) but rather were inland areas of a former larger continent from which Australia (including Tasmania) was rifted in much more recent Cretaceous to Tertiary times. In other words, for much of the last 500 million years or so, far northwest Tasmania has not been a peninsula surrounded by sea on two sides, but rather was a small coastal region on the edge of large continent, and so was backed by land to the (present-day) west and by sea to the (present day) east and south-east – essentially the reverse of the present day situation!

the coasts of northwest Tasmania essentially date from and were produced by these continental rifting events.

As the new coastlines were being formed by the rifting of Antarctica from southern Australia during the early to mid -Tertiary period, major marine transgressions flooded the new continental margins including the coastal regions of far north-west Tasmania. Marine limestones and other sediments were deposited in north-west Tasmania during the Miocene part of the mid - Tertiary period (circa 16 -20 million years ago), and are discontinuously preserved at locations such as Rebecca Creek, Marrawah and Wynyard (Sutherland and Corbett 1967). Within the study area, marine limestones of probable Tertiary age outcrop in shore platforms on the eastern side of Welcome Inlet where they were recorded by Geer (1981), but are not shown yet shown on current published geological mapping (Seymour 2008).

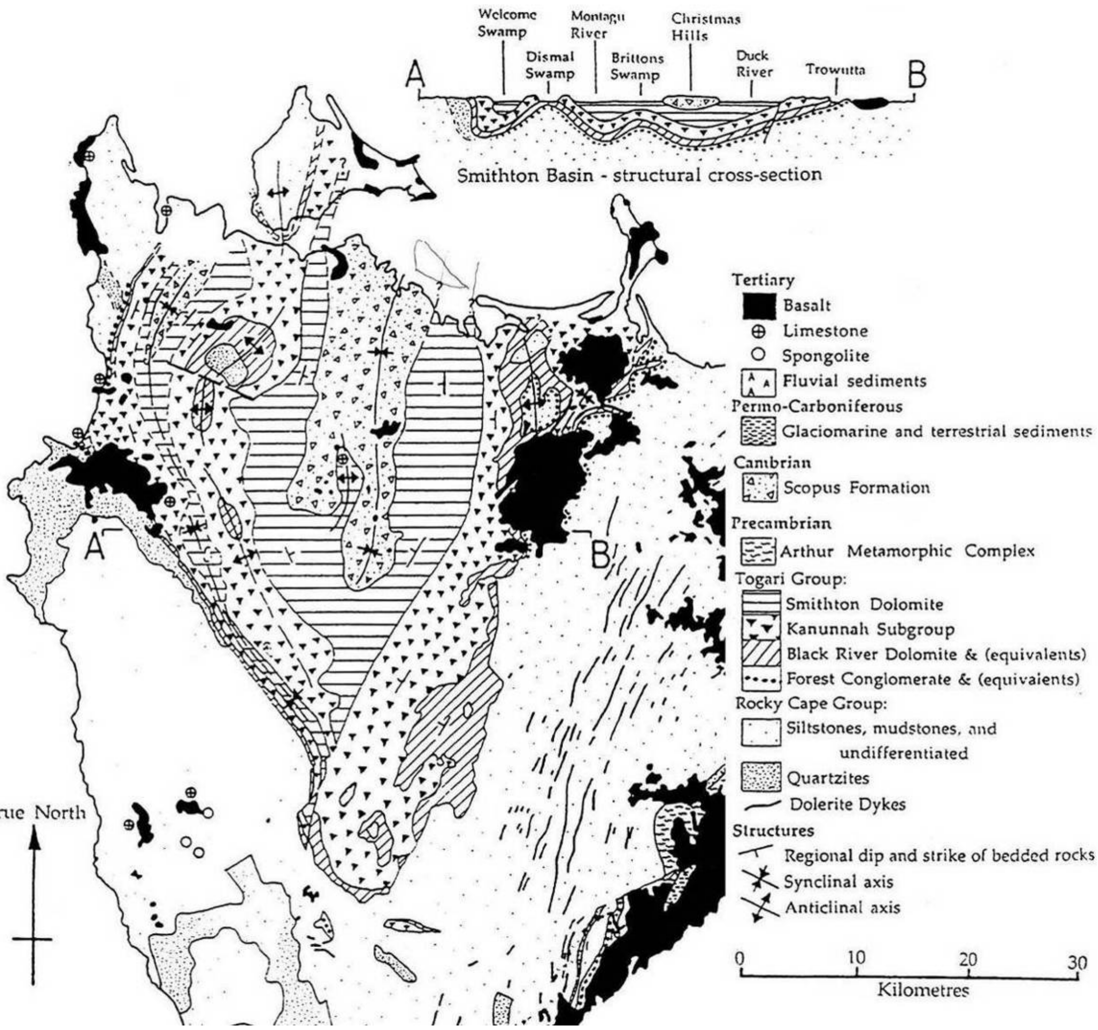

Figure 3.1: Interpreted bedrock geology of the Smithton Basin and surrounding areas, based on Calver *et al.* (1995) with additional interpretation of geological structures by Chris Sharples based on extrapolation of known structures and inferences based on large-scale regional gravity and magnetic mapping (Sharples 1996). Much of the bedrock depicted here is mantled by aeolian sands and other Quaternary-age sediments; hence some structural interpretations shown - especially near the Boullanger Bay to Duck Bay coast – may prove inaccurate.

Onshore, the large-scale extensional block faulting associated with continental separation initiated new drainage patterns and dramatically increased landscape relief which - combined with a warm humid early Tertiary climate - led to an early Tertiary phase of increased fluvial erosion and deposition on and around the newly-created island of Tasmania (Colhoun in: Burrett and Martin 1989, p. 403-405; Hill 1990).

Continental rifting was also accompanied and followed by widespread volcanism in Tasmania, which included episodes of subaerial and submarine volcanism in northwest Tasmania ranging over much of the Tertiary period from late Eocene to late Miocene times, circa 38 to 8.5 million years ago (Sutherland and Wellman 1986). These volcanic episodes produced basalt and tuff (ash-fall) deposits at Cape Grim, Trefoil Island, Montagu area and many other locations inland of the present coast. In some areas the volcanic deposits are interbedded with limestones and other marine sedimentary rocks.

Planation and geological controls on topography

A stepped series of broad-scale planar landscape surfaces form a major element of the physiography of Tasmania, and commonly truncate steeply-dipping bedrock units on near-horizontal planes. Davies (1959) recognised these as erosion surfaces developed at or near state-wide base levels during extended periods of tectonic stability, with planation being interrupted by intermittent uplift (or accelerated uplift), such that the higher surfaces are oldest, and each surface is dissected by river valleys that have incised to lower levels following uplift. These surfaces are considered to have mostly formed after the main phase of early Tertiary block faulting associated with continental rifting, but probably prior to Late Tertiary times (Colhoun in: Burrett and Martin 1989). The causes of uplift between each planation cycle remain poorly understood but are likely to include isostatic rebound, magmatic crustal doming and other processes. Although they are pervasive elements of the Tasmanian landscape, the origins and ages of the surfaces remain surprising little studied despite the insights their further study could no doubt provide into Tasmania's mid to late Tertiary tectonic and landscape history.

The lowest and best preserved of these surfaces is known as the "Lower Coastal Surface" (Davies 1959). Fluvially-dissected fragments of this surface occur in all Tasmanian coastal regions, but it is a particularly prominent landscape feature along the west coast from Circular Head area to Port Davey. This surface represents the most recent Tasmania-wide erosion surface, and the extensive plains of the Smithton Basin region were dominantly formed by this phase of erosional planation. The age of the surface is poorly constrained, although some evidence of an erosion age between late Eocene and early Miocene times (between circa 34 to 18 million years ago) is provided by indications that the surface was eroded across sediments of Eocene age (Baillie in: Baillie and Corbett 1985) and that Miocene spongolites, limestone and basalts were deposited over the planed and subsequently incised surface (Sharples 1996, Vol. **2**:25).

However with Pleistocene (and present) sea-levels being lower than the former Lower Coastal Surface base level, there has been some subsequent landscape incision. Such landscape relief as has developed is due mostly to the contrast between the relatively erosion- resistant ridges of volcanic and volcaniclastic rocks, and preferential incision and lowering of intervening extensive plains of soluble ("karstic") dolomite bedrock.

Nonetheless the mostly low relief (flat) topography of the Smithton Basin and the northwest region of Tasmania has been a key control on the coastal landform types and sediment deposits which developed through Quaternary times (following the Tertiary Period), particularly insofar as the gentle topography enabled Pleistocene wind (aeolian) processes to transport large volumes of sand across northwest Tasmania from the west coast. The broad planar topography was also a key factor in the development of the extensive tidal flats of the study area, which in turn have been directly responsible for the large tidal ranges[5] and consequent strong tidal currents of the region, as well as providing more extensive sea-grass and saltmarsh habitat than would have been the case on a coast of steeper basement relief.

Neotectonics

As discussed above, considerable vertical and horizontal tectonic (land) movement occurred in Tasmania during the Tertiary Period, initially in response to continental break-up and subsequently through isostatic adjustment, magmatic and probably other processes. In comparison, Tasmania has been mostly tectonically stable during the last two million years of the Pleistocene, albeit this is in the context of the ongoing northwards horizontal movement of the Australian tectonic plate as a whole. Nonetheless there is evidence that some relatively small-scale vertical tectonic movements have occurred during these geologically recent times.

Shorelines developed during the Last Interglacial climatic phase (circa 125,000 years ago) are widely developed around Australia and elsewhere, but mostly stand around 2 to 6 metres above present sea-level in tectonically stable areas, reflecting the slightly higher global sea-level of the Last Interglacial (Murray-Wallace and Belperio 1991). It is therefore significant that shorelines and other coastal features of Last Interglacial age have been identified at up to 20 metres above present sea-level in far northwest Tasmania (van de Geer *et al.* 1979, van de Geer 1981, Bowden and Colhoun 1984, Murray-Wallace and Goede 1991). This difference has been interpreted by these workers as implying that Tasmania has been uplifted relative to mainland Australia at some (uncertain) time since the Last Interglacial, possibly due to doming over a mantle hot-spot or other crustal adjustments. Whilst the timing of such uplift remains poorly constrained, there is no evidence that it has continued up to the present

It is possible that a small amount (around 1 metre?) of vertical land movement may have occurred in the study area during mid-late Holocene times (circa 6000 – 2000 years ago) due to hydro-isostatic adjustment[6] as Bass Strait was flooded by the post-glacial marine transgression (see Section 3.1.2 below). Similar adjustment is considered to have resulted in a 1.5m late Holocene uplift (i.e., relative drop in sea-level) of shorelines in southeast NSW (Lambeck and Nakada 1990, Sloss *et al.* 2007), however no related adjustment has yet been demonstrated for north-west Tasmania. It was intended to use the saltmarsh sediment record to test for relative Holocene sea-level changes as part of the present study, however this aim was frustrated by the thinness (typically <0.5m) of Holocene saltmarsh sediments (Brigid Morrison *pers. comm.*). See also Appendix 4 Stratigraphy analysis – Technical Report.

There is no evidence that Tasmania is undergoing present-day vertical tectonic movement on a scale sufficient to noticeably influence coastal processes. High-precision geodetic measurements at near Hobart, and at Round Hill (Burnie) during 2009, have failed to detect any persistent vertical land movements greater than the error margins of

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[5] Tidal shoaling across the extensive tidal flats of the Boullanger bay – Duck Bay region is one of the reasons for the large tidal ranges in the area, the other key reason being the meeting in Bass Strait of tidal waves refracting into both the eastern and western ends of the strait.

[6] "Hydro-isostatic adjustment" refers to crustal warping whereby the inner continental shelf & shoreline flex up as the outer shelf is pushed down by the addition of a large mass of water as the sea-level rises over the continental shelf.

the instrumentation which are of the order of ±0.1mm per year (Dr Chris Watson, Uni. of Tas., *pers. comm*.). In the absence of any direct measurement of present-day vertical land movement in the Circular Head region, the best available boundary estimate of conceivable present day vertical land movement in Tasmania is an approximate figure of 0.2 ± 0.2 mm/year upwards land motion calculated by Hunter *et al.* (2003), based on glacio-isostatic adjustment modelling and known uplift since the Last Interglacial (see above).

3.1.2. Geomorphology

Although Geological Survey mapping (see Section 3.1.1. Geology above) and a number of detailed geomorphic and palaeo-environmental studies such as Gill and Banks (1956) and van de Geer (1981) have contributed considerable insights into the landscape history and landform development of the Circular Head area, no up-to-date synthesis of this information is available. This section endeavours to provide a brief overview of current understanding of the geomorphic (landform) history and processes of the study area, based in part on relevant insights from older syntheses of Tasmanian geomorphology including Davies (1974), Colhoun (in Burrett and Martin 1989, p.410-418) and Scanlon *et al.* (1990), partly on site-specific studies as cited in following sections, and partly on new insights from field studies undertaken during the present project. Figure 3.2 provides a schematic summary of the inferred geomorphic history of the study region that is described below.

Overview – Quaternary landform processes in north-west Tasmania

The last two million years of Tasmania's history following the end of the Tertiary Period is known as the Quaternary Period, which comprises the older Pleistocene sub-division and the younger Holocene (10,000 years ago until present). The Quaternary has been dominated by repeatedly alternating glacial (colder) and interglacial (warmer) climatic phases. Over this time, glacial, periglacial (freeze-thaw), aeolian (wind), karstic (rock-solution), fluvial (river), lacustrine (lake), palludal (swamp), coastal and marine processes have continued to modify the Lower Coastal erosion Surface that was eroded across the older basement rocks during the Tertiary Period, to produce the present landscape of far north-west Tasmania including the Boullanger Bay to Duck Bay region.

During the repeated glacial climatic phases, intense glacial and periglacial erosion of west coast ranges in the headwaters of the Arthur, Pieman, Henty, King and Gordon Rivers supplied large quantities of glacio-fluvial outwash sediments including siliceous sand to the western coastal plains, including coastal plains that were exposed on the continental shelf and Bass Strait during low glacial sea-stands but are now covered by sea.

Under the generally arid and sparsely vegetated conditions of the glacial climatic phases, swell-driven littoral drift up the west coast and aeolian (wind) processes moved these abundant outwash sands northwards up the west coast and north-eastwards inland, across much of what is now north-west Tasmania and onto the then-dry Bassian plain. Much of the low-lying plains area, north-west of a line roughly between Marrawah and Smithton, is mantled by wind-blown sands moved from the western coastal plains and across north-west Tasmania in this way during the Pleistocene glacial phases (hillier

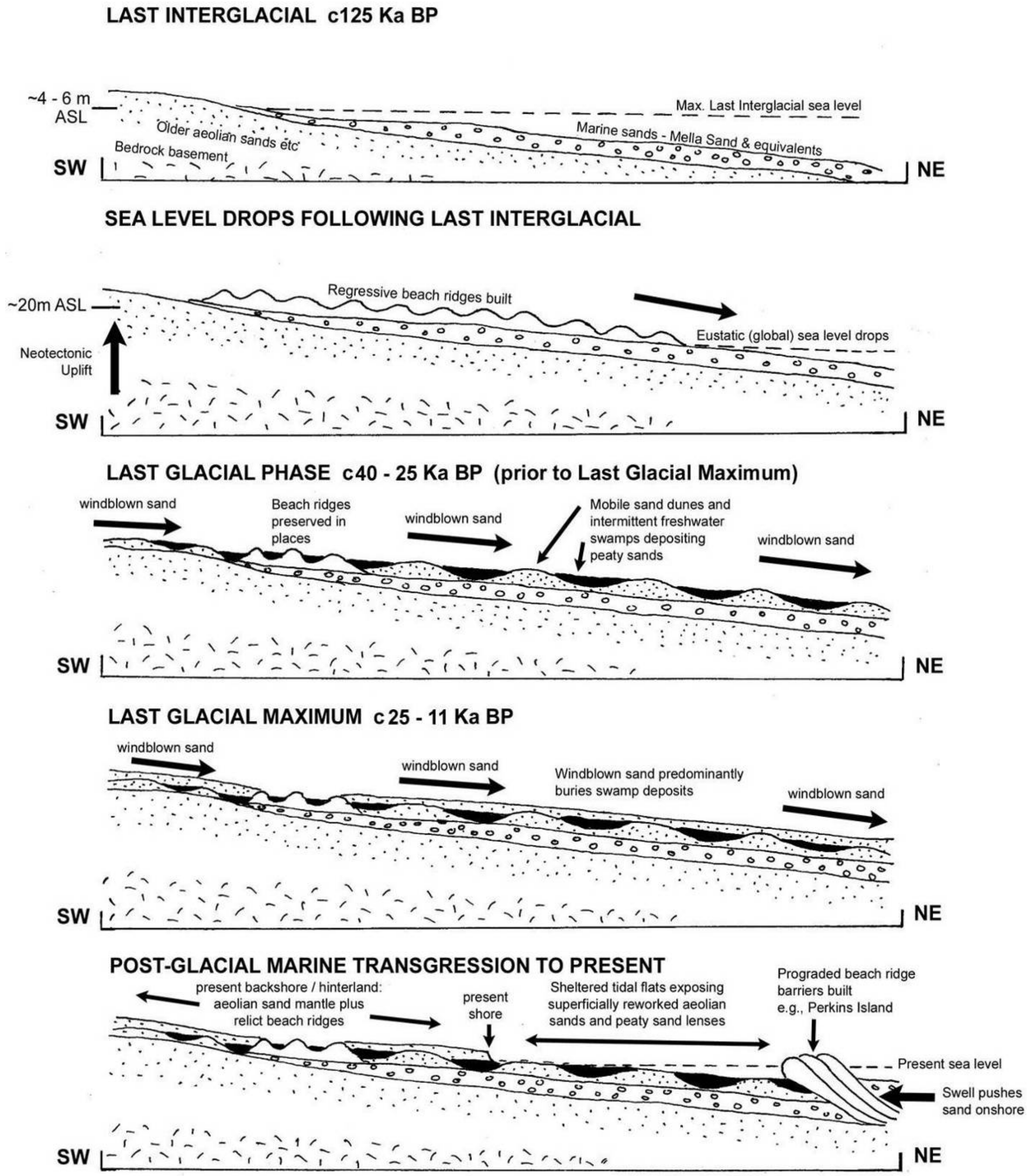


Figure 3.2: Schematic summary of the inferred Late Quaternary (Late Pleistocene – Holocene) geomorphic history of the Boullanger Bay – Duck Bay region. See text for explanation. Note "Ka BP" = "thousands of years before present", "ASL" = "above present-day sea level". These schematic diagrams are not to any particular scale, and are generalised conceptual diagrams which do not refer to any specific transect across northwest Tasmania.

regions such as Christmas Hills have less aeolian sand cover, partly due to less original aeolian sand deposition on the higher steeper terrain, plus more subsequent fluvial erosion on the higher relief ground). See Figure 3.3.

Within the Boullanger Bay–Duck Bay catchments, fluvial sediment transport was most active during Pleistocene glacial climatic phases, with more energetic seasonal melt waters and periglacial erosion plus aeolian sand movement supplying much greater quantities of sediment to the Duck, Montagu, Harcus and Welcome Rivers than is the case today. During interglacial periods such as today, with well-vegetated catchments and reduced rates of catchment erosion, these rivers transport relatively little sediment (mainly silt and clays) to the coast, except where artificial catchment disturbance (especially land clearance) has increased soil erosion rates.

Karst processes have been ongoing throughout with solutional corrosion down to the water-table producing broad flat poorly-drained karstic plains across the broad areas of dolomitic bedrock, and leaving the less erodible interbedded clastic and volcanic basement rocks as intervening hills and ridges. It is likely that lower base levels (implying deeper vertical karst corrosion) and more sand mantling of the dolomite (conversely inhibiting karst development) both occurred during glacial climatic phases. The very broad flat low-lying poorly-drained karst plains formed in this region are some of the most extensive in Tasmania, and their low topography has probably played a role in facilitating large scale aeolian sand transport and deposition.

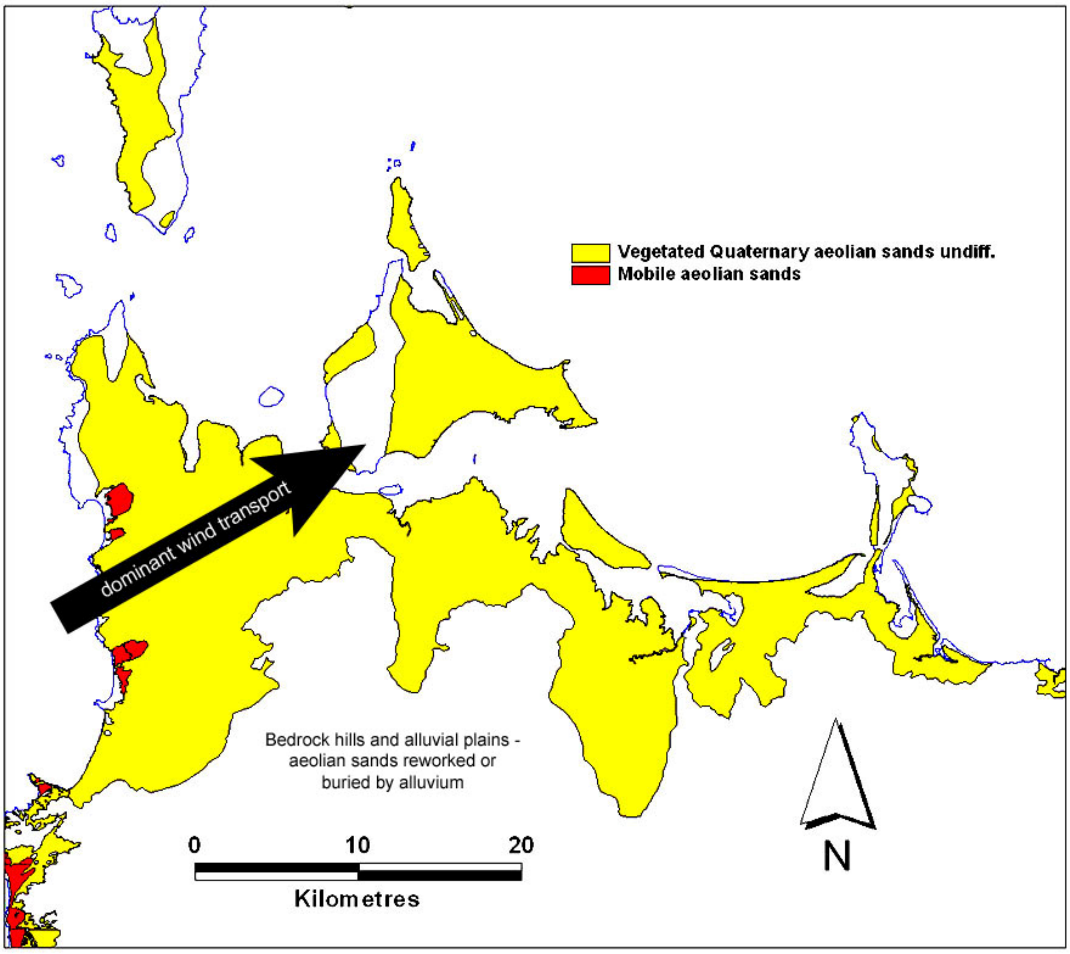


Figure 3.3: Approximate extent of mapped onshore Pleistocene windblown sands (with interbedded peaty freshwater lake and swamp sediments) across north-west Tasmania (based on Calver *et al.* 1995 with additions). Present-day mobile and vegetated sands are indicated. During the Last Glacial climatic phase, most of the sands shown would have been mobile, and some additional thin sand sheets may have extended onto hilly areas (e.g. Christmas Hills) from which they have been subsequently removed by Holocene fluvial erosion. Aeolian sands were probably more extensive in low-lying areas during glacial phases than is shown here - those mantling areas such as the Montagu River plains have probably been subsequently buried by or reworked into younger alluvial and palludal (swamp) deposits. Note that during the Pleistocene glacial climatic phases, sea-level was approximately 130 metres lower than at present, and aeolian sand sheets would have then extended from coastal plains now flooded off the west coast, continuously north-eastwards across the now – flooded Bassian plain; rising seas at the end of each glacial phase then reworked these sands into marine and coastal sand deposits.

Whilst marine, aeolian, lacustrine and palludal processes have undoubtedly shaped the Boullanger Bay region throughout numerous repeated glacial – interglacial cycles of the Quaternary, to date only landforms and sediment deposits formed by the processes from the Last Interglacial phase onwards to the present have been identified, since the high sea-stand of the Last Interglacial has probably reworked most dunes, beach-ridges and other surface sediment deposits produced by earlier glacial and interglacial climatic cycles. The following sub-sections outline what is known of the landform history of the study area from the Last Interglacial climatic phase to the present.

Last Interglacial landforms and sediments

The Last Interglacial high stand sea level at circa 125,000 years ago reached levels up to approximately 20 metres above present-day sea level in northwest Tasmania (van de Geer 1981, van de Geer et al. 1979, Bowden and Colhoun 1984). This apparently higher stand than elsewhere in Australia is likely due to local neo-tectonic uplift subsequent to the Last Interglacial high sea stand at approximately 4–6 m above the present global eustatic sea level (Murray-Wallace and Belperio 1991, Murray-Wallace and Goede 1991). During the Last Interglacial phase wave and tidal current activity probably largely reworked dunes, beach ridges and sediment deposits from earlier glacial and interglacial cycles up to the maximum level reached by the sea. Marine and beach sands deposited across much of north-west Tasmania during the Last Interglacial were thus being deposited at up to about 20 m above what is today sea level; these marine sands have been stratigraphically defined as the Mella Sand near Smithton (Gill and Banks 1956).

Numerous ancient beach ridges on Robbins Island, in the Montagu area and elsewhere have been interpreted as regressive beach ridges, formed as global eustatic sea levels dropped following the Last Interglacial high sea stand, and local neotectonic uplift raised the relict Last Interglacial shoreline to its present level (van de Geer 1981, Bowden and Colhoun 1984). See Figure 3.2.

Last Glacial climatic phase

Following the Last Interglacial high sea stand, increasingly cooler climates and sea-levels well below present levels prevailed for about 100,000 years, with numerous minor warmer (wetter) and cooler (drier) phases, before reaching the coldest and driest conditions and lowest sea levels (about 130 metres below present sea-level) at the Last Glacial Maximum (LGM) circa 20,000 - 30,000 years ago (see Figure 3.4).

During this long period of cooling and drying climatic conditions, the more arid and less vegetated landscape allowed windy conditions to remobilise some of the uplifted Last Interglacial marine sands and aeolian sands deposited in earlier glacial phases, as well as introducing additional new windblown sand ultimately derived from renewed glacial erosion sources further down the west coast.

Aeolian processes produced widespread mobile linear dunes and lunettes (with associated depression hollows) across NW Tasmania (Lennox *et al.*1982, Seymour and Baillie 1992) and undoubtedly also across the sandy Bassian Plain at this time, many of which are preserved onshore today, along with broader mobile aeolian sand sheets. It is perhaps surprising that the older Last Interglacial regressive beach ridges were not entirely reworked by these later aeolian processes; however Seymour and Baillie (1992) depict cross-cutting relationships between younger linear dunes and older preserved beach ridges in parts of the study area hinterland.

Widespread deposits of peaty freshwater sediments associated with the aeolian sands are evidence that, at least during the warmer and wetter intervals of the period leading up to the LGM, swamps and lakes developed widely across the region, in swales between regressive Last Interglacial beach ridges and later aeolian dunes, in deflation hollow basins scoured out by wind during the drier periods and generally where mobile aeolian sands impeded drainages[7]. Peats and peaty sands were deposited in these freshwater lakes and swamps, which also became graves for many marsupial megafauna, behemoths such as *Nototherium*, the giant wombat *Phascolonus*, large kangaroos, and emus (Gill and Banks 1956) which presumably became stuck in their soft peaty sediments and drowned. Gill and Banks (1956) described such sequences at Mowbray Swamp near Smithton, where digging of drainage channels on the swampy Duck River plains exposed Last Interglacial marine sands (which they termed the "Mella Sand") overlain by peaty sands deposited in swales between dunes or beach-ridges, and containing mega-faunal and freshwater fossil assemblages . Gill and Banks obtained radio-carbon dates of >37,760 years from several samples of the peat. Towards the higher southwest Christmas Hills side of Mowbray Swamp, Gill and Banks (1956, p. 13-15) described a deposit of very well-podzolised windblown sand containing terrestrial plant pollens, which probably overlies the freshwater peaty sands. Although not dated the degree of podzolisation is indicative of a Pleistocene age.

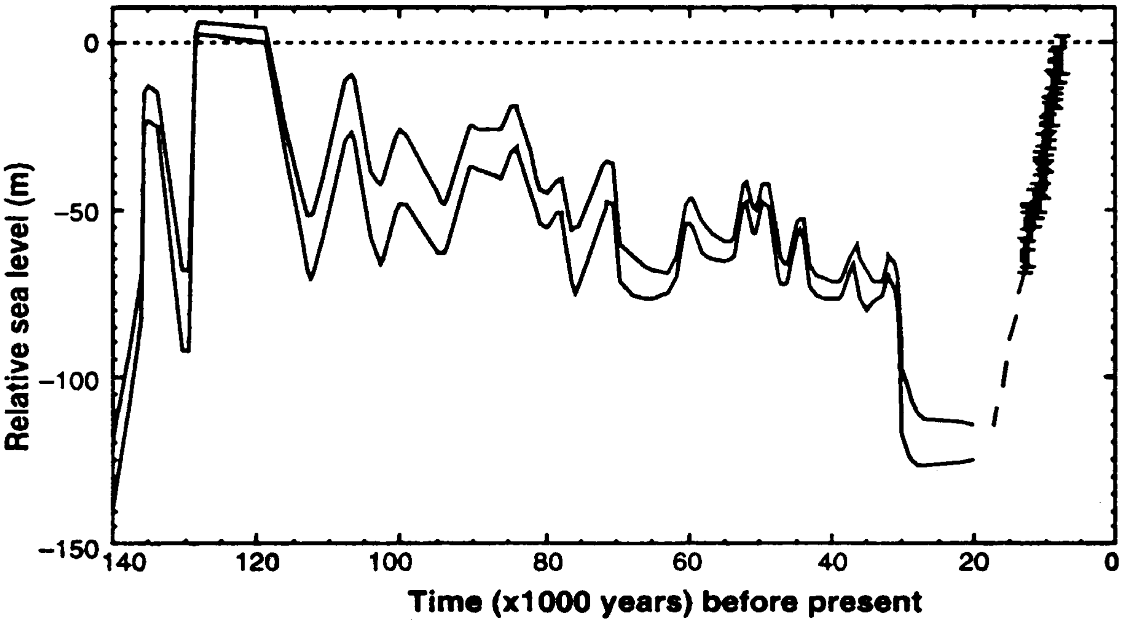


Figure 3.4: Global sea-level variations from the Last Interglacial (circa 125,000 years ago) through the Last Glacial Maximum (circa 20,000 years ago) to the present (Lambeck and Chappell, 2001) Note that the gradual lowering of sea-level (accompanied by cooler and more arid climatic conditions) was interrupted many times prior to the Last Glacial Maximum by temporary warming phases which were also wetter times, however following the Last Glacial Maximum there was a rapid and continuous rise of sea level (accompanied by generally warming and more humid climates) until sea-level stabilised at approximately its present level circa 6,500 years ago. Note also that the Last Interglacial high sea-stand occurred globally at about 4–6 metres above present sea level. The ostensibly much higher (~ 20m ASL) Last Interglacial sea levels identified in north-west Tasmania have been interpreted as evidence for local neotectonic uplift of Tasmania since the Last Interglacial (Bowden and Colhoun 1984, Murray-Wallace and Goede 1991).

[7] Present-day examples of lakes formed by dune-impeded drainage can be seen today in the Waterhouse dunefield (north-east of Bridport) and in dunefields north of Sandy Cape (south of Marrawah).

Figure 3.5: Two views of an eroding shoreline profile at Sealers Springs showing a well-podzolised sand unit overlying a distinctly more indurated dark peaty sand unit. This sequence is interpreted as a late Last Glacial Maximum phase aeolian (windblown) sand overlying an older Last Glacial phase freshwater lake or swamp peaty sand, and is similar to shoreline exposures at other coastal sites in the study area including Welcome Inlet and near The Jam, as well as to sequences at Mowbray Swamp – Christmas Hills (near Smithton) described by Gill and Banks (1956). Ages of circa 27,000 and 37,000 years have been obtained from similar and probably correlated peaty sand deposits near the photographed location (see Appendix 4 Stratigraphy analysis – Technical Report), which supports this interpretation. Figure 5.6 (C) provides an interpretative cross-section of this type of shoreline. It is noteworthy that the bones of extinct megafauna described near Smithton by Gill and Banks (1956) came from similar peaty freshwater deposits of roughly comparable or slightly older ages.

Shoreline exposures observed during the present project at Sealers Springs, Welcome Inlet, east of The Jam (south of Perkins Island) and elsewhere, comprising semi-indurated peaty sands overlain by strongly podzolised aeolian sands (see Figure 3.5), are comparable to the Mowbray Swamp sequences described by Gill and Banks (1956). These shoreline sequences were studied in detail by Brigid Morrison, who obtained radio-carbon dates of circa 27,000 and 37,000 years from peaty sands at Sealers Springs, which brackets those sediments in roughly the same age range as (or slightly younger than) the Mowbray Swamp peats (further details of the shoreline peaty sand sequences are provided in Appendix 4 Stratigraphy analysis – Technical Report). The semi-indurated sands are also widely exposed or only shallowly mantled by superficial sand across the study area tidal flats where they form "peat platforms" (see Section 4.3.1) which are a significant structural landform component of the tidal flats.

Ongoing mobile aeolian sand movements ultimately infilled and buried the freshwater lakes and swamps, producing buried layers and lenses of peaty sand of varying thickness and lateral extent. This process of the formation and burying of freshwater swamps and lakes would probably have repeated itself many times as the aeolian sands shifted and the climatic fluctuations leading up to the LGM repeated produced drier and wetter intervals, resulting in a complex sequence of aeolian sand sheets interbedded with peat and peaty-sand lenses representing the ephemeral swamps and lakes. Van de Geer (1981) and Colhoun *et al.* (1982) have used mound spring deposits preserving fossil flora assemblages to identify wetter (warmer) and drier (colder) intervals in the Late Pleistocene history of Pulbeena Swamp (near Smithton), and Brigid Morrison has used further data obtained in the present study to relate dated peaty sand swamp / lake deposits on the study area shores to this variable climatic history (see Appendix 4 Stratigraphy analysis – Technical Report)

However with the final onset of the coldest and most arid conditions at the Last Glacial Maximum circa 25,000 years ago, it is likely few lakes or swamps persisted and most of the landscape at that time, including former swamps and lakes, was probably blanketed with actively mobile windblown sand, stabilised deposits of which today still blanket much of the inland regions of the study area. This change is evident from stratigraphic sequences described in the Mowbray Swamp – Christmas Hills by Gill and Banks (1956), and from probably correlated sequences exposed on the study area shoreline at several locations including Sealers Springs and east of The Jam. At these sites the Pleistocene freshwater peaty sands are overlain by thick sand deposits exhibiting very well-developed podzolic profiles of grey-white bleached A horizon sands under an organic surface layer and over well-developed ferruginous B horizons and hard pans (see Figure 3.5). The very well-developed podzolic sand profiles are indicative of Pleistocene ages, and the sands – which have been mapped as blanketing extensive areas inland of their shoreline exposures (Lennox *et al*.1982, Seymour and Baillie 1992, Seymour 2008) - are interpreted as Late Pleistocene aeolian sand mantles[8].

[8] It is notable that van de Geer (1981) mapped some areas of these sands as aeolian, but mapped others – including those exposed in shore scarps at Sealers Springs (e.g., Figure 3.5) and Welcome Inlet – as Pleistocene alluvium. Van de Geer provides no clear evidence of these being alluvial sand. The present writer (CS) observed no clear evidence of alluvial origin in exposures of the sands at Sealers Springs and Welcome Inlet (such as the inter-bedded pebble bands and muddy beds that frequently characterise sandy alluvial deposits). Given this, and that their occurrence as well-podzolised sands over peaty sands dated to 27-37,000 years at Sealers Spring implies a likely age around the coldest driest parts of the Last Glacial Maximum when aeolian deposition was undoubtedly widespread; and also given that more recent

The post-glacial marine transgression

Following the Last Glacial Maximum, rapid climatic warming combined with a rapid and continuous sea-level rise of around 130 metres vertically (see Figure 3.4) led into the present (Holocene) interglacial climatic phase.

As sea level rose rapidly (averaging circa 1 m per 100 yrs with some intervals of even faster rise) across the Bassian plain, the large amounts of windblown sand previously deposited on that plain would have constituted an excess coastal sand supply, which constructive swell waves would have pushed continuously onshore as the sea level rose.

As the post-glacial marine transgression finally slowed and settled at close to its present level circa 6,500 yrs ago, the sand pushed continuously shore-wards by the rising seas would have finally been able to stabilise and pile up as a barrier of rapidly prograded beach ridges along what is now the north-east shore of Robbins Island, and in the Perkins Island – Anthony Beach coastal sand barriers (see Figure 3.6). As has been demonstrated elsewhere in south-eastern Australia (Thom 1974, Thom and Roy 1985), rapid progradation (accretion) of these barriers probably continued for several thousand years following stabilisation of sea level, until the excess sand had been mostly pushed onshore

Figure 3.6: Schematic diagram illustrating how constructive swell at the end of the post-glacial marine transgression piled sand onto the prograding coastal barriers of Robbins Island, Perkins Island and Anthony Beach, while leaving the sheltered coastal waterways of Boullanger to Duck Bay, behind the barriers, unaffected by the sand influx. Hence the sands now found in the sheltered tidal flats of Boullanger – Duck Bay are essentially the same Pleistocene-age aeolian sands and associated semi-indurated peaty freshwater sands deposited there during the Last Glacial phase, which have been only superficially reworked by tides and local wind-waves. INSET: Swell diagram showing how the south-westerly swell – which predominates in western Bass Strait - refracts around the far northwest tip of Tasmania to produce a swell-sheltered region in the Boullanger Bay region, yet in the final stages of the post-glacial marine transgression would have been capable of pushing excess sand from the Bassian Plain onto the coastal barriers of Robbins Island, Perkins Island and Anthony Beach. Figure adapted from (Scanlon et al. 1990).

geological mapping similarly identifies them as aeolian sands, an aeolian origin around the Last Glacial Maximum seems more probable for these sands than a fluvial one.

by constructive swell waves and the beaches had subsequently settled into more-or-less equilibrium (elsewhere in south-east Australia, this commonly occurred by 3000 – 4000 years ago: Thom 1974, Thom and Roy 1985).

It is evident that the area to landwards of these barriers – Boullanger to Duck Bay – was also shallowly flooded by the rising seas, however the refraction of the predominantly south-westerly swell around the rocky barriers of Cape Woolnorth, Hunter, Robbins and Three Hummock Island (and associated rocky islets) meant that as sea level approached its highest level around 6,500 years BP, the area landwards of Robbins Island was largely sheltered from the swell (see Figure 3.6).

Investigations during the present study have demonstrated that the sheltered tidal regions landwards of Robbins and Perkins Islands are not blanketed by thick marine sands, but rather the extensive tidal flats in that area mainly comprise relict older Pleistocene aeolian sands and peaty freshwater lake or swamp deposits forming “peat platforms” (as described above and Section 4.3.1 and Appendix 4 Stratigraphy analysis – Technical Report) that are only superficially and incompletely mantled with a thin marine sand veneer resulting from tidal and wind-wave stripping and reworking of the underlying Pleistocene sediments In other words the extensive tidal flats of the Boullanger Bay to Duck Bay waterways behind Robbins and Perkins Islands are not the result of sand infilling those bays during the post-glacial marine transgression as might be at first assumed; on the contrary the tidal flats are instead a relict or “fossil” Pleistocene landscape surface, probably at least in part preserved because of the relatively indurated and erosion-resisting nature of the Pleistocene peaty sand “peat platforms” which occur at or just below much of the tidal flat surfaces.

Consequently it is evident that the sands brought up from the Bassian Plain by the rising seas were not pushed into the sheltered Boullanger – Duck Bay area, but rather were mainly deposited at the limit of swell penetration in prograded sand barriers along the north-east shore of Robbins Island and in the Perkins Island – Anthony Beach sand barriers. The extensive sediments in the swell-sheltered study area tidal flats are essentially only what was there prior to the post-glacial transgression and have not accumulated an additional sand supply during the post-glacial marine transgression.

Present-Day (Holocene-Anthropocene[9]) landforms

The preceding sections provide a basis for understanding the nature of the present day landforms and shoreline types of the study area, which are further described in detail in other sections of this report, including Sections 5.2.2 (Shoreline mapping: types and erosion status), 4.0 (The Habitats) and Appendix 4 Stratigraphy analysis – Technical Report.

[9] Whereas the period of geological time from 10,000 years ago to the present (constituting the present Interglacial climatic phase) has been generally referred to in the scientific literature as the ‘Holocene’, growing recognition that human activities have begun to fundamentally alter surface environmental processes - including coastal and fluvial (river) processes – has resulted in recent suggestions that a new geological time period (the ‘Anthropocene’) should be defined covering the last 250 years or so since the Industrial Revolution. This suggestion is supported by this writer (CS), who expects to see the Anthropocene formally defined in the geological literature once more geologists have got over their current climate change denial phase.

4. The habitats and their benefits to people

Primary Authorship: Richard Mount and Vishnu Prahalad

4.1. Habitats defined

The earth's surface can be broadly divided into two major environments – terrestrial and marine, with the coast being the interface between the two. Several environmental factors determine the size of this coastal interface and the diversity of habitats within it (e.g. Harris *et al*., 2002; Short and Woodroffe, 2009). The unique environmental setting and history of the Circular Head foreshore area (see Section 3) has given rise to extensive coastal habitats along with high habitat diversity. Of the 89 wetlands in Tasmania listed in DIWA, the Boullanger Bay/Robbins Passage wetlands has by far the largest extent (28,000 ha) and highest number of habitat types (seven) (Environment Australia, 2001). For the purposes of this project, the habitats of the study area have been divided into three main groups based on the extent of marine influence. These groups are: Shoreline Wetlands; Intertidal Flats; and Shallow Subtidal Areas (see Figure 4.1). The three main groups can be further subdivided into 13 different habitat types based primarily on land cover, inundation regime and degree of marine influence. They are:

- **Shoreline Wetlands**, encompassing:
    1. Saltmarshes
    2. *Melaleuca* swamp forests
    3. Sand, shingle, pebble or cobble beaches
    4. Rocky shorelines
    5. Tidal channels and inlets*

* Tidal channels within the shoreline wetlands are almost always associated with saltmarshes and hereafter will be considered to be part of the saltmarshes.

- **Intertidal Flats**, encompassing:
    1. Intertidal sand or mud flats
    2. Intertidal seagrass
    3. Tidal channels

- **Shallow Subtidal Areas**, encompassing:
    1. Subtidal seagrass beds
    2. Subtidal reefs
    3. Subtidal unconsolidated sediment (sand, pebbles, cobbles)
    4. Tidal channels

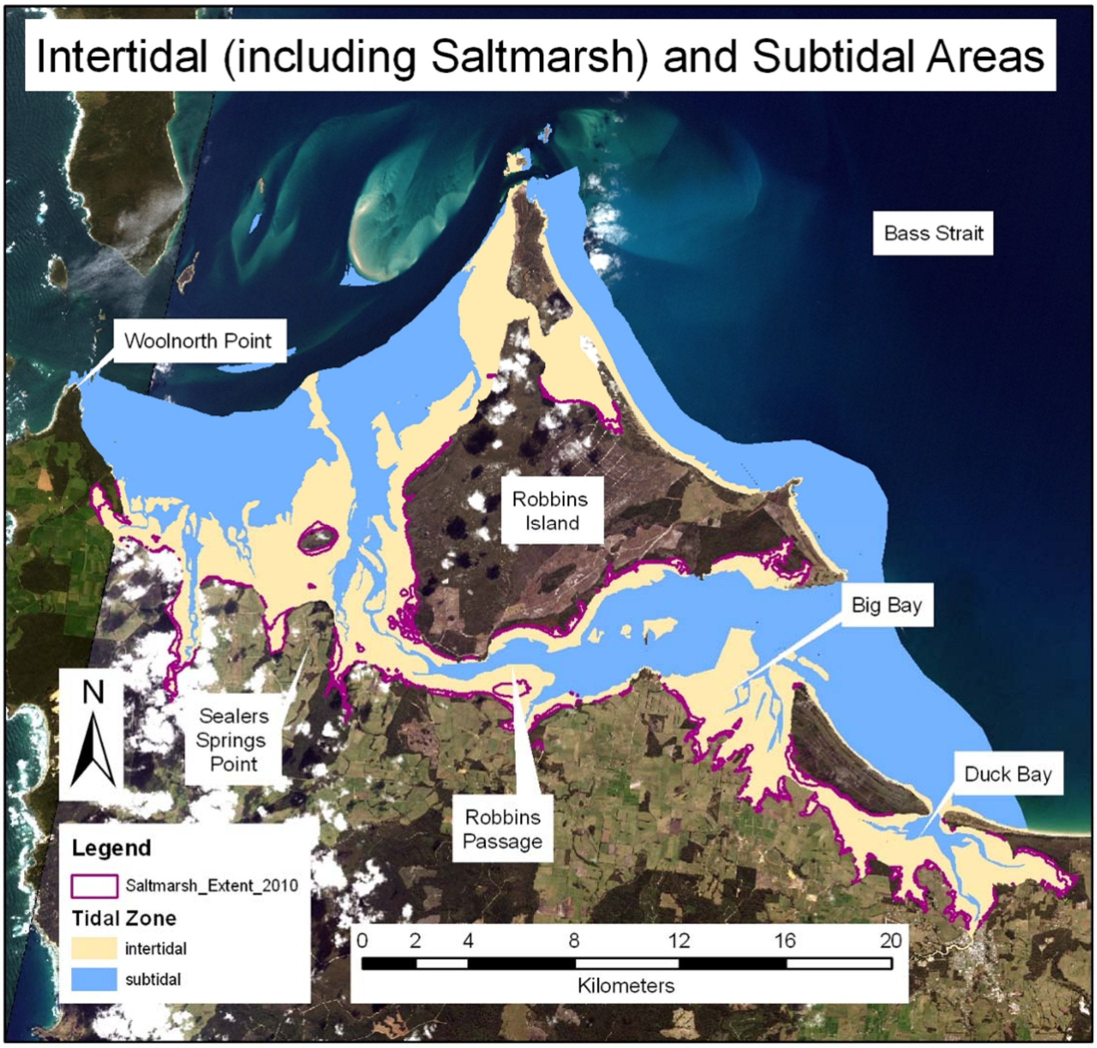


Figure 4.1 The intertidal area, including saltmarsh and the subtidal areas

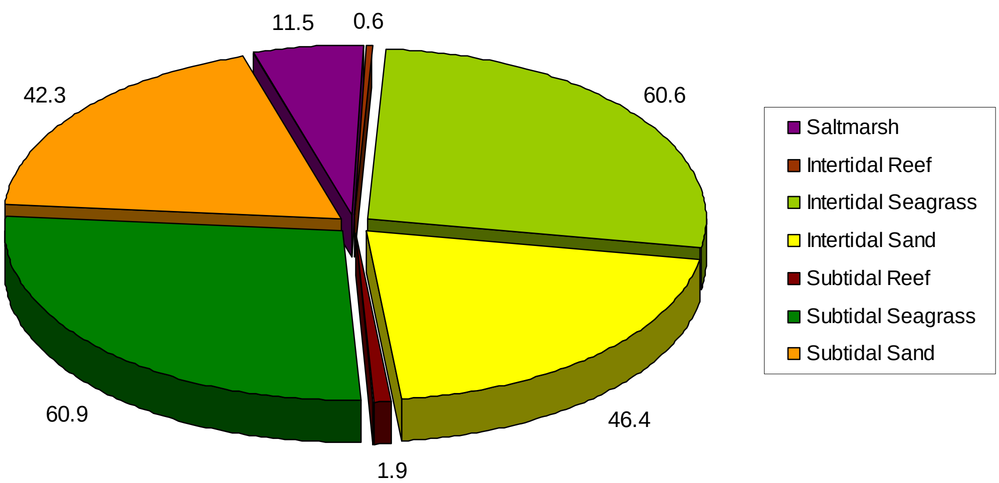


Figure 4.2 Areas of the habitats (km^2) mapped in this study

4.2. *Shoreline Wetlands (saltmarshes, beaches, tidal channels and* Melaleuca *swamp forests)*

Primary Authorship: Vishnu Prahalad

4.2.1. Description of Shoreline Wetlands

A shoreline is a "zone" on the coast where the marine environment transitions into the terrestrial environment. This zone can be a few metres wide (as in coastal cliffs) or several kilometres wide (as in saltmarshes and tidal freshwater wetlands) depending on its environmental setting. Since the shoreline has a strong marine influence, and often a terrestrial aquatic influence (freshwater inflows), it is permanently or intermittently wet and hence shoreline wetlands form. The type and physical extent of these wetlands are driven to a greater or lesser extent by factors such as: landscape topography, lithology, climate, wind, sea level, sedimentation and biotic factors (see Perillo *et al*., 2009). Of these, sea level (the level of the sea with respect to the land) can be said to be the most important factor as it can effectively "move" the shoreline as it rises or falls.

The recent accelerated rise in sea level has been a major influence on shoreline wetlands as they constantly readjust their position in response to the rising sea (Pethick, 1993; FitzGerald *et al*., 2008). Different shoreline wetland types respond to the sea level rise differently. The "soft" shores made up of sandy, muddy, clayey and gravelly substrates are dynamic environments which change more rapidly than "hard" shores made up of rocks and boulders (Sharples, 2006). Among the shoreline wetlands identified within the Circular Head foreshore area, saltmarshes (along with the associated tidal channels) and *Melaleuca* swamp forests are of particular focus given their soft vulnerable sediments, large extent and critical ecological function on the foreshore compared to other wetlands.

The definition of saltmarsh has been obtained from Prahalad (2009), as "**tracts of land tidally connected to the sea and covered with phanerogamic halophytic vegetation comprised of herbs, shrubs, grasses, sedges and rushes, and including the associated tidal channels, salt flats and marsh pools**."[10] This definition includes the TASVEG classes of *succulent saline herbland* (AHS), *saline sedgeland/rushland* (ARS), *coastal grass and herbfield* (GHC) and the generic *saltmarsh (undifferentiated)* (AUS) class (Harris and Kitchener, 2005). The definition also includes the tidal channels, salt flats and marsh pools as being an integral part of the saltmarsh ecosystem. Employing this definition, 1,153 ha of saltmarsh has been mapped as a part of the project (Figure 4.1), making it one of the largest areas of saltmarshes mapped within any one coastal region in Tasmania. The area accounts for about 20% of saltmarshes mapped across the State. The absence of mangroves in Tasmania means saltmarshes are the major shoreline wetland type within the highly productive enclosed waterways (i.e. tidal re-entrants such as estuaries, embayments and lagoonal inlets). Saltmarshes currently have no reservation status under State legislation other than being considered as providing a **critical ecological function**.[11]

The definition for *Melaleuca* swamp forests has been obtained from Harris and Kitchener (2005) as: "**[t]he community typically occurs as pure or almost pure stands of *Melaleuca ericifolia* with trees generally 10–12 m in height (but reaching 20 m)**

[10] Phanerogamic refers to seed-producing plants; Halophytic refers to salt-tolerant plants.
[11] *See*: Resource Planning and Development Commission, *Extent of Non-Forest Native Vegetation*, <http://soer.justice.tas.gov.au/2009/indicator/69/index.php>, accessed on 27 April 2010.

forming a dense canopy over a simple, sedgy understorey. It includes all successional growth stages." TASVEG mapping indicates that 882 ha of *Melaleuca* swamp forest (NME) exist in the area. These forests are biogeographically restricted to the north of the State with a significant proportion (about 11% of the State's total mapped extent) contained within the study area. While they can occur inland from the coast, they are generally a coastal or near-coastal community that fringes saltmarshes and rivers. A large proportion of the pre-European extent of these forests has been cleared and is still being cleared. Hence, they have been listed as a "**threatened native vegetation community**" under Schedule 3A of the *Nature Conservation Act 2002*. Their current "endangered" status recognises that "its distribution on a State-wide basis [has] contracted to less than 10% of its former area."[12]

4.2.2. How Shoreline Wetlands function

Coastal saltmarshes are dynamic ecosystems which support highly specialised flora and fauna species (saltmarsh obligates), and provide temporary habitat for numerous facultative (nonobligatory) species which use saltmarshes opportunistically, regularly or sporadically. Vegetation plays the central role in structuring the saltmarsh ecosystem and provides the habitat occupied by fauna (Adam, 1990). The halophytic saltmarsh vegetation (salt-tolerant plants) are highly specialised in that they have several physiological adaptations to overcome the severe stresses presented by the saltmarsh environment, primarily excess salt and waterlogging. These two environmental variables determine, to a large extent, the position of each type of saltmarsh vegetation within the marsh (Clarke and Hannon, 1971; Kirkpatrick and Glasby, 1981). Both salinity and waterlogging are predominantly controlled by the tidal regime, which is regarded as the single most important factor in the development, extent and function of the saltmarsh ecosystem (Chapman, 1974; Huiskes, 1990). Salinity and waterlogging could be highly variable within the saltmarsh with factors such as freshwater flows, evaporation rates and drainage (local topographic relief) interplaying with the tidal inundation regime and producing intricate vegetation patterns.

Saltmarsh often exhibits distinct vegetation zonation (Figure 4.3). Four vegetation zones can be identified in the Circular Head region saltmarshes (see Conceptual diagram below). Zone 1 is inundated daily and has pioneer saltmarsh flora dominated by *Sarcocornia quinqueflora* and *Samolus repens*. Zone 2 is inundated less frequently and dominated mainly by the longer lived *Tecticornia arbuscula* and *Gahnia grandis*. Zone 3 is inundated rarely and dominated by grasses and rushes such as *Austrostipa stipoides* and *Juncus kraussii*. In many areas however, where enough freshwater inputs are available, *Juncus kraussii* occur in Zone 1 as a pioneer species. Zone 4 is the terrestrial zone which is predominantly dominated by *Melaleuca* swamp forests. The presence or absence of one or several of these zones within a given saltmarsh depends on the size of the marsh and the effect of localised environmental factors (Glasby, 1975). Apart from the structurally dominant higher plants of the saltmarsh, there is a vastly extensive benthic (bottom dwelling) algal community that live on the uppermost layers of the saltmarsh substrate, including the tidal channels and marsh pools (also called as edaphic algae). These microscopic algae are an important component of saltmarsh food-web and can equal or exceed the higher plants in terms of primary productivity (Sullivan and Moncrieff, 1990; Sullivan and Currin, 2000).

[12] *See*: Resource Planning and Development Commission, *Listed Threatened Vegetation Communities*, <http://soer.justice.tas.gov.au/2009/indicator/46/index.php>, accessed on 27 April 2010.

Saltmarsh plants are generally hardy (evolved to withstand the mechanical damage caused by waves) and have little nutritional value (Long and Mason, 1983). Hence they are largely ignored by herbivores, with the exception of cattle and sheep that can feed extensively on saltmarshes causing much detriment via removal and disturbance. In the absence of herbivores, detritivores become the primary consumers in the saltmarsh food-web breaking down the plant material and facilitating the flow of energy and organic nutrients (Adam, 1990; Deegan *et al*., 2000). These inconspicuous detritivores, including snails, amphipods, isopods and crabs, form the most abundant component of the invertebrate fauna of Tasmanian saltmarshes (Wong *et al*., 1993). Besides providing organic material that supports marine species (especially fish), they help to build the saltmarsh substrate and keep it aerated (thereby reducing anoxic conditions). They also support a range of birdlife which can directly feed on them, including the migratory shorebirds (Spencer *et al*., 2009).

Figure 4.3. A saltmarsh (in Kangaroo Island, Boullanger Bay) with two distinct vegetation zones, one dominated by low succulent herbs, and the other dominated by grasses and sedges. Also visible is the well developed sinuous tidal channel cutting through the marsh platform.

Under suitable growth conditions, saltmarshes function by trapping and binding mineral sediment, stabilising the soil by reducing wave energy (decreasing scour) and producing organic material which helps to further build up the marsh substrate (see Conceptual diagram below). As the building process continues, the saltmarsh expands and intricate drainage (tidal) channel networks develop. These channels play an important role in delivering and removing tidal water along with mineral and organic matter to and from the marsh platform (Lawrence *et al*., 2004). The growth and extent of saltmarshes within any particular location will be determined in part by the degree of protection afforded by adjacent coastal features, the nearshore seabed topography and the availability of fine sediments (Long and Mason, 1983). Within the study area, saltmarshes form extensively on shallow low energy shorelines (i.e. “protected” from high wave action by coastal barriers) of tide dominated environments, where they generally occur between the area below the mean high tide mark and the highest tide mark.

When suitable growth conditions change, such as associated with climate change and sea level rise, the abovementioned function of the saltmarsh is subjected to severe stress. Where the saltmarsh is not able to respond in time to these stresses, they start reducing in extent (through peripheral erosion) and vigour (vegetation loss and internal erosion). Recently, climate change and sea level rise has been related to changes in the extent and vegetation composition of south east Tasmanian saltmarshes (Prahalad, 2009). On the seaward boundary, increased sea level and storminess have been noted to cause widespread marsh edge erosion and the deposition of sand sheets and shell ridges over the marsh surface. On the landward boundary, the response to sea level rise is usually the gradual movement of halophytic (salt-loving) saltmarsh vegetation inland replacing either glycophytic (salt-intolerant) terrestrial vegetation or into agricultural land (Choi *et al*., 2001). Across the saltmarsh platform, the changes are usually associated with the replacement of the long lived high marsh vegetation by the pioneer low marsh vegetation which is more tolerant to waterlogging (Donnelly and Bertness, 2001). The marsh platform is subjected to a process known as “internal marsh erosion” where mud mounds (or vegetation hummocks) are formed, marsh accretion rates fall and there is an increase (or coalescence) of marsh pools reducing plant cover (Allen and Pye, 1992). Reduction of plant cover (biomass) and increased loading of water can cause autocompaction of the marsh sediment and provide as positive feedback for further saltmarsh erosion and deterioration with sea level rise.

Essentially, saltmarsh morphodynamics in the study area can be said to be governed by the environmental “forcing factors” (Allen, 2000) which include: the influence of the sea and wave energy; the amount and quality of sediment available; plant productivity; and autocompaction (Figure 4.4). In addition to these forcing factors, two other agents of change that can considerably affect saltmarsh morphodynamics are subsidence (e.g. tectonic) and direct anthropogenic influence. In some parts of the world, such as in south-east England, saltmarshes are being lost extensively due to the subsidence of the coast caused by tectonic movements (Boorman, 1999). Tasmania however, has been tectonically stable during the Holocene epoch (Murray-Wallace and Goede, 1991) and hence subsidence is not of consequence for shaping saltmarshes in the study area. Humans have been known to be one of the major causes of saltmarsh loss worldwide (Kennish, 2001; Doody, 2008), in Australia (Laegdsgaard *et al*., 2009) and in Tasmania (Prahalad, 2009). Human influences on saltmarshes are numerous and can be either direct or indirect (Adam, 2002) and can be summarised as follows: development (landfill, tidal restriction/manipulation), eutrophication, grazing, trampling, firing, use of off road vehicles, weeds, littering, removal of fringing vegetation, catchment modification, anthropogenic climate change and sea level rise and eliminating the landward buffers that would otherwise accommodate the natural saltmarsh response to sea level rise.

Melaleuca swamp forests occur extensively on waterlogged soils in the Circular Head region and are capable of growing under moderate levels of salinity (Salter *et al*., 2007). *Melaleuca ericifolia*, which is the structurally dominant plant of the vegetation community, is a colony-forming clonal tree species with extensive root networks (Robinson, 2007). These swamp forests are usually abutted on the seaward side by saltmarshes which occur on the higher intertidal areas, while extensive areas of seagrasses and intertidal flats occupy the lower portions of the intertidal area. As salinity increases with the more frequent inundation of sea water (with increased sea levels), *M. ericifolia* suffers die back giving way to the saltmarsh halophytes that occupy the newly created niche.

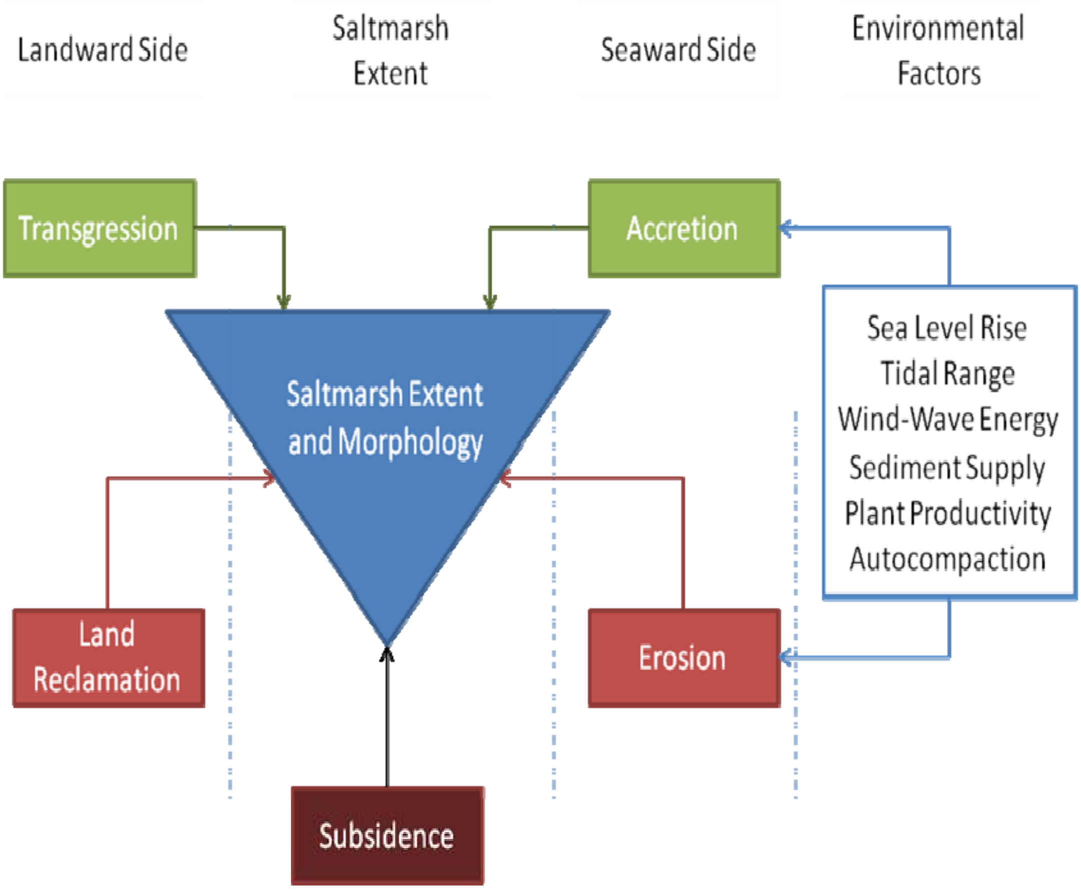


Figure 4.4. Factors determining the morphology and extent of Circular Head region saltmarshes. Environmental factors (forcing factors) are as described by Allen (2000).

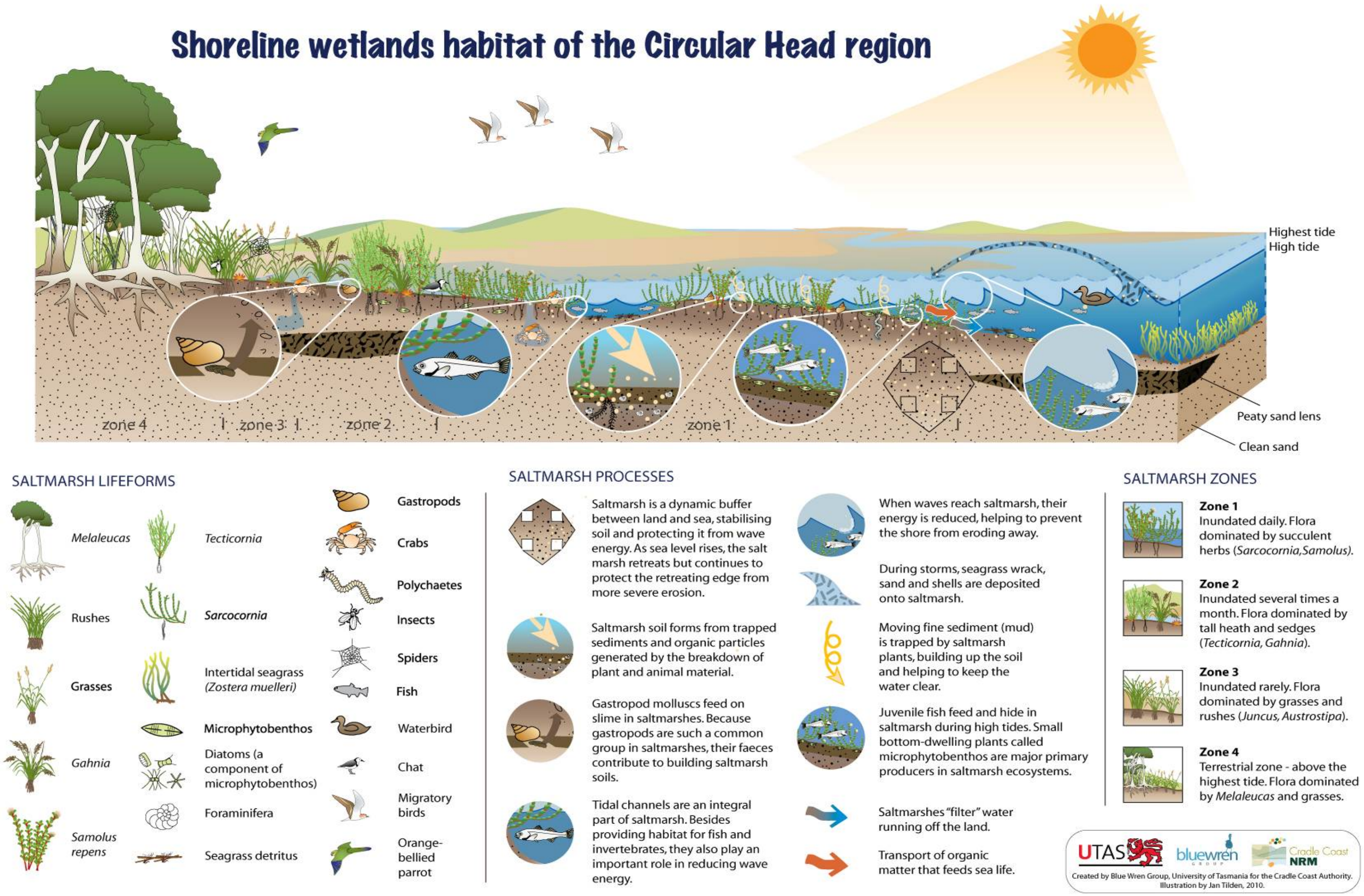


Figure 5 Conceptual diagram of Shoreline Wetlands ecological functioning

4.2.3. Ecosystems services (benefits) to people from Shoreline Wetlands

Eminent saltmarsh researchers Teal and Howes (2000) wrote that "saltmarshes contributed to estuarine food chains beyond their borders and had a greater ecological (and economic) value beyond just being there as open space." The role saltmarsh plays within the coastal areas has been studied extensively (e.g. detailed in Boorman, 1999; Weinstein and Kreeger, 2000; Doody, 2008; Saintilan, 2009) and can be summarised to include (also see Ecosystem Services Conceptual diagram below):

1. Producing and exporting organic material (detritus) to coastal waters through tides and improving their productivity (Merrill and Cornwell, 2000; Valiela *et al*., 2000).
2. Providing habitat for plants and animals that are consumed by commercially and recreationally important marine transient species (Deegan *et al*., 2000; Saintilan *et al*., 2007). Presence of high concentrations of crab and gastropod larvae in the saltmarshes provide food for fish species (Mazumder *et al*., 2009). Gut content analysis have indicated that fish fed predominantly on crab larvae in the saltmarsh (Mazumder *et al*., 2006).
3. Providing secure habitat for juvenile fish (at high tide) to evade predation risk in the open sea (Deegan *et al*., 2000; Figure 4.6). Studies reporting the use of saltmarshes by Australian fish species suggest that up to 56 species can be found within an area of 100 m^2 (summarised in Connolly, 2009).
4. Intercepting land driven nutrients (both from aboveground and belowground flows) and hence regulating the response of phytoplankton (algal blooms), macroalgae and seagrasses in the receiving coastal waters. Especially, the health of seagrass meadows has been directly linked to land driven nitrogen interception by saltmarshes (Valiela and Cole, 2002).
5. Intercepting and settling down suspended sediments in the water column which would otherwise make the coastal waters murky, less productive and aesthetically unpleasant. The ability of saltmarshes to intercept nutrients and sediments from the water is extremely important to maintain and enhance coastal water quality (Doody, 2008).
6. Building up soil and providing a buffer between the land and sea. Saltmarshes greatly reduce wave energy by channelling and diffusing it in their tidal creek systems. The dense and robust saltmarsh vegetation acts as a buffer attenuating wave energy. In the UK for instance, saltmarsh has been highly valued for its role in coastal defence as it can be more cost effective than raising and maintaining artificial coastal defences like sea walls or levees (Doody, 2008).
7. Providing crucial habitat for resident and migratory shorebirds which use saltmarshes as feeding, roosting and breeding habitats (Spencer *et al*., 2009; Figure 4.9). Many shorebirds are under increasing pressure globally and require undisturbed coastal habitats such as in the study area for their long term survival.
8. Providing habitat for a wide range of terrestrial birds including the critically endangered Orange-Bellied Parrot which feed on saltmarsh seeds during winter migration to mainland Australia (Commonwealth of Australia, 2005).
9. Providing habitat for vertebrates other than birds, such as macropods and water rats (Spencer *et al*., 2009).

10. Providing habitat to numerous invertebrates, especially the very large numbers of molluscs and crustaceans that play an important role in saltmarsh ecology especially through detritivory, soil aeration and soil building (Wong *et al*., 1993; Figure 4.7). These invertebrates provide important food for higher animals such as birds and fish. Many other smaller invertebrates are not sufficiently studied and their values are yet to be fully understood.
11. Providing habitat for rare saltmarsh flora such as *Limonium australe* (Schahinger, 2009; Figure 4.8). Importantly, they provide a seedbank for revegetating other areas.
12. Acting as highly efficient carbon sinks by sequestering and storing carbon in their soil profiles. It has been noted that saltmarsh soils store 210 g C $m^{-2}yr^{-1}$ and that the carbon stored in saltmarsh soils in USA constitutes 1-2% of its total yearly carbon sink (Chmura, 2009). Hence, there has been an international push recently to consider saltmarshes as “natural coastal carbon sinks” to reduce the potential risks of climate change while accruing their other ecosystem services (Laffoley and Grimsditch, 2009).
13. Providing several scientific opportunities. For example, saltmarshes can be used to reconstruct old sea levels as their sediments provide a record of sea level changes. Also, saltmarsh vegetation and geomorphology can be used to study the rate and effect of sea level rise (Prahalad, 2009).
14. Providing recreational and educational opportunities. The services that flow on from saltmarshes are important for maintaining the many recreational pursuits in the area, especially fishing, duck-hunting, bird watching, and other activities that require good water quality. The extensive and relatively undisturbed saltmarshes of the study area can also provide excellent opportunity for education and public awareness of coastal ecological values, ecosystem services and sea level rise.

Melaleuca swamp forests provide various ecosystem services on their own right besides contributing to considerably enhancing the quality and function of the adjacent wetlands. Research has indicated that the number and diversity of invertebrates, especially crustaceans and molluscs, is considerably increased within the saltmarshes where they have fringing vegetation such as the *Melaleuca* swamp forests (Wong *et al*., 1993). The presence of these forests also increases the vertebrate density and diversity. They provide habitat for birds such as the Orange-bellied parrots and Blue-winged parrots which use the saltmarshes in these areas. Apart from enhancing the biodiversity value, they also act in other less obvious ways to improve the quality of the coastal waters by acting as buffers for nutrients, invasive species and other direct human effects. They have extensive root systems that hold and build the soil together reducing erosional stress caused by high energy waves.

Figure 4.6. A school of juvenile fish taking refuge in a saltmarsh tidal channel. This particular channel was heavily degraded by stock trampling.

Figure 4.7. A crustacean in the flooded *Sarcocornia* zone (Zone 1) in a saltmarsh.

Figure 4.8. Figure to the left showing a narrow *Juncus* zone between the *Tecticornia* zone (in the foreground) and the fringing *Melaleuca* vegetation. Figure to the right shows a saltmarsh patch dominated by the listed (under State legislation) rare species *Limonium australe*.

Figure 4.9. Different species of migratory birds using the high saltmarsh as a roosting habitat at high tide when most of their intertidal feeding areas are inundated.

4.3. *Intertidal Flats and Shallow Subtidal areas (seagrass, channels, sand and mud)*

Primary Authorship: Richard Mount

4.3.1. Description of Intertidal Flats

Intertidal seagrass occupies the majority of the intertidal flats at 61 km^2 (56%), while the unvegetated areas (46 km^2, 43%) occupy the areas with more tidal, fluvial, wave and wind energy and consist mostly of sand and outcropping peat platforms with the exception of a few mud flats in the more sheltered estuaries and bays. Outcropping rock makes up the balance with a relatively miniscule 0.6 km^2 (0.6%).

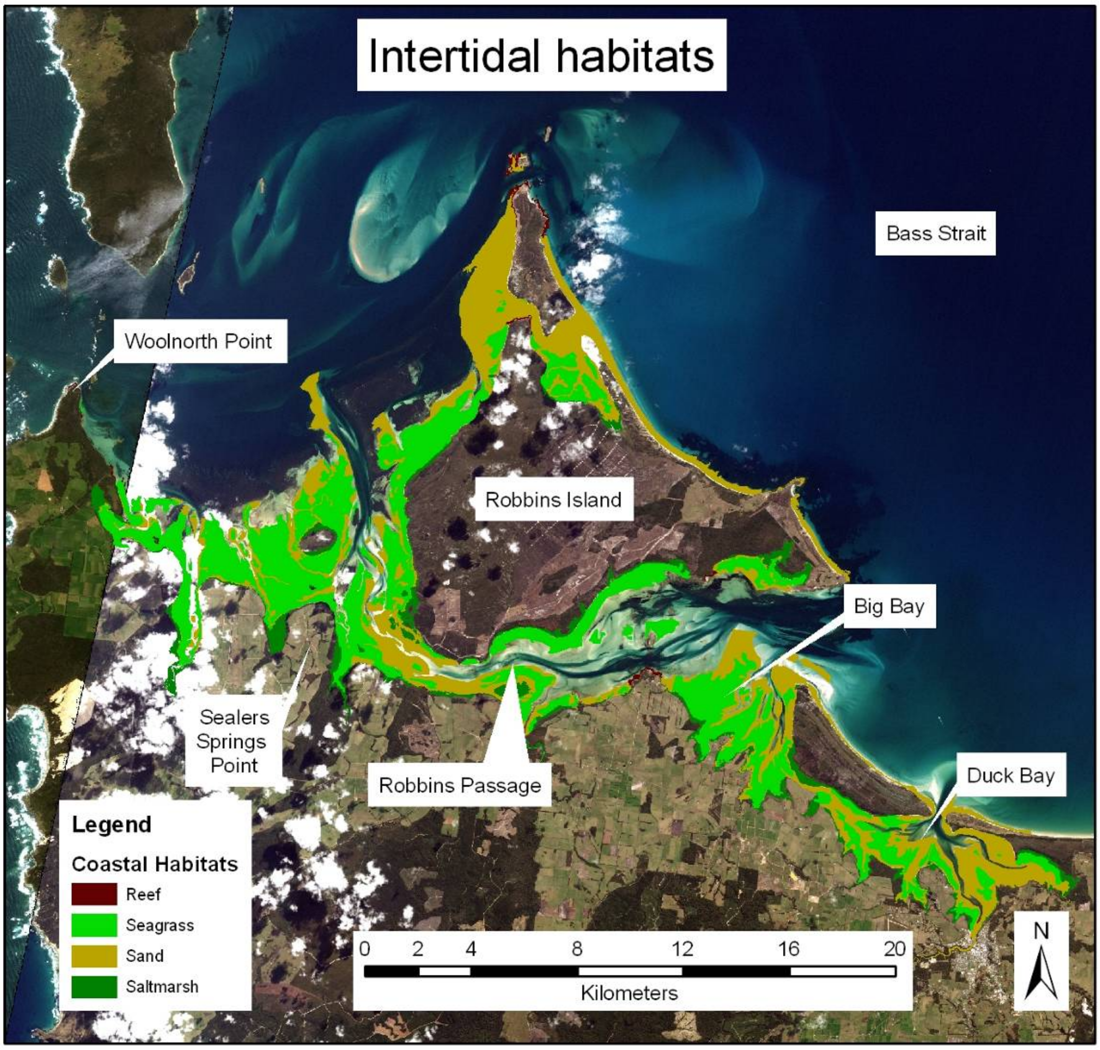


Figure 4.10 Intertidal habitats across the study area including saltmarsh (Note: saltmarsh are treated separately in the previous section).

The intertidal zone is simply defined as the area of land inundated at high water and drained/exposed at low water. The extent of exposure and frequency and length of inundation varies with the tidal regime and the elevation of the land. The tidal range within the study area varies between 2.8 m and 3.4 m with the maximum occurring at in the proximity of Robbins Crossing. The land is very gently sloping within the intertidal zone and this produces a huge area of intertidal flats of over 100 km^2, which is close to half of the entire study area (see Figure 4.1 and Figure 4.2). Close to one billion tonnes of water arrives and leaves this intertidal zone during each tide cycle (i.e. tidal prism).

The intertidal flats of the study area are structured by a variety of geomorphic land forms described by Ryan *et al*. (2003) including:

- small areas of mud flats in the areas with the lowest wave, tide and fluvial (river) energy;
- vast areas of tidal sand banks and flats where processes including tidal flows and wind waves produce higher energy water; and,
- a large network of tidal channels where the tidal and fluvial flows dominate the erosion and deposition processes across the surface of the intertidal flats.

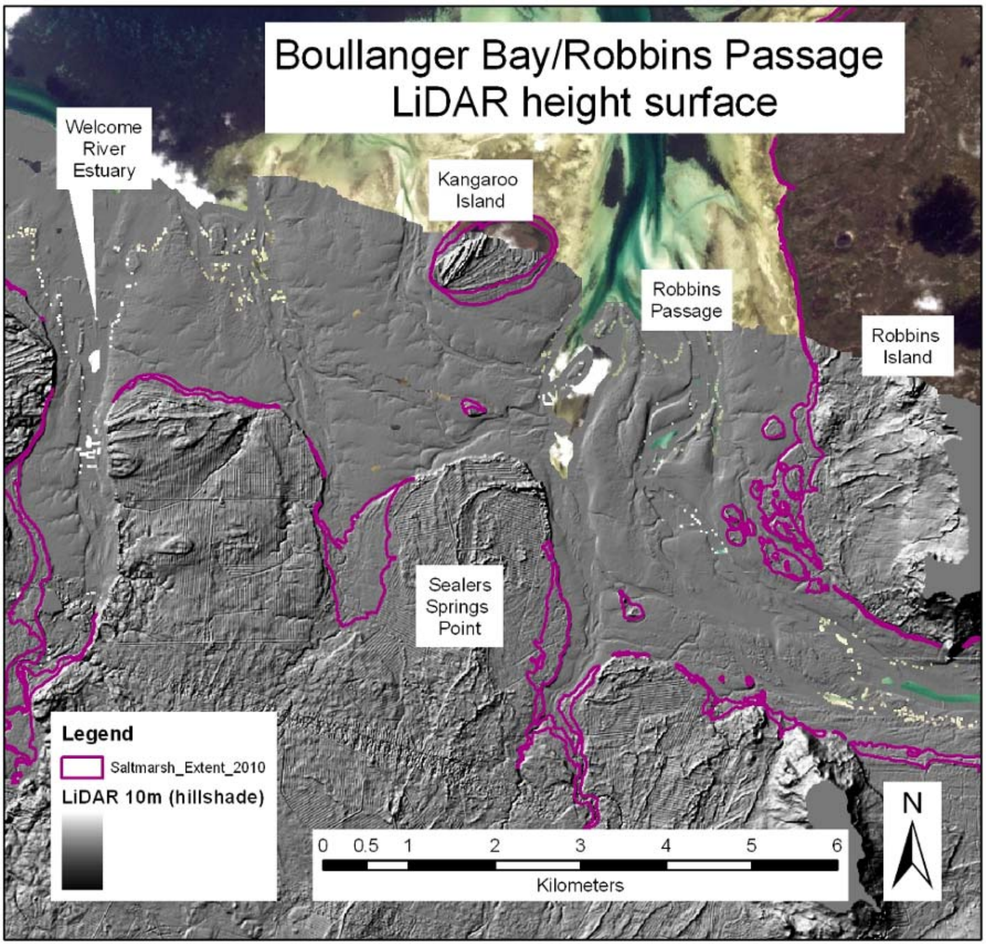


Figure 4.11 A surface elevation model (height map with vertical exaggeration x20) for the Boullanger Bay Case Study area illustrates the geomorphic features defined for the intertidal zone. There are longitudinal sand banks in the large channel structure of Robbins Passage. The area between Kangaroo Island and Sealers Springs are tidal flats intersected by tidal channels. The Welcome River estuarine area is a combination of fluvial (river) and tidal channels. The corduroy-like striations on the land are extensive pasture drainage channels.

Examples of these features can be seen in Figure 4.11. These land forms result from the environmental conditions acting on them and provide the substrate for the intertidal habitats. These same environmental conditions also shape the ecology of the intertidal habitats. The geomorphology of the flats is thus integral to understanding the habitats themselves. The following definitions of these geomorphic landforms are adapted slightly from Ryan *et al*. (2003).

"**Intertidal Flats** are generally low gradient and low energy environments, consisting of poorly- to moderately-sorted sandy mud, muddy sand and sand. Carbonate concentrations are moderate (reflecting shelly material in the sediments) and the concentration of organic material is variable, but generally high. Surfaces tend to occur from mean low water spring to mean high water spring elevations and are usually flat, but may be dissected by shallow drainage channels. In the study area they are often, but not always, vegetated by saltmarsh species or seagrass. Biological activity consists of both high and low tide visitors, as well as permanent inhabitants. Burrowing infauna, crustaceans, molluscs, fish and birds are generally abundant."

"**Tidal Sand Banks** are sedimentary features commonly found within tide-dominated estuaries, deltas and tidal creeks. Tidal sand banks are typically subtidal to intertidal in elevation, and consist of elongate linear to sinuous sand bars; though in the study area's expansive intertidal zone they may also be broad, probably due to the influence of wind generated fetch waves redistributing sediments. They comprise moderate- to well-sorted fine muds to sands. Sediments may fine towards the head of the estuary. Concentrations of carbonate material are generally high; whereas concentrations of organic material are generally low. Strong tidal shear stresses and highly variable bottom morphology result in turbulent, well oxygenated, and turbid waters. Tidal Sand Banks may be vegetated by extensive seagrass beds such as in the study area, however high turbidity may limit primary productivity where the water energy is highest."

"**Channels** are environments of frequent high energy, in terms of tidal movement (e.g. tidal channels) or fluvial flow (e.g. river channels). Thus, salinity, water quality and sediment types are variable, however, coarser grained sand to gravel (lag) deposits are common on the Channel floor. Channels are often found in association with Fluvial (Bayhead) Deltas, Flood and Ebb Tidal Deltas, Tidal Sand Banks, and intersecting Intertidal Flats in macrotidal environments. Channels may be intermittent, and may also be abandoned when river or tidal flows change course. Concentrations of carbonate and organic material vary. Channels are often non-depositional environments and are sometimes erosional. Channels are typically subtidal, however in macrotidal regions entire channel networks may be exposed at low tide. Channels are important environments for a wide range of marine and estuarine organisms (depending on salinity and turbidity), and provide shelter and access for larger estuarine predators, as well as potential seagrass habitat."

A fourth geomorphic landform of **Peat Platform** is also recognised for the purposes of this report. This landform is characterised by a very flat surface often pocked with 3-20 m sized shallow pools (Figure 4.13). These pools are distributed across the platform surface on a drainage network often in a semi-regular pattern which suggests that some kind of repeating process formed them. Speculatively, they could be the weakened substrate formed by tree root penetration in the original Pleistocene peat swamps as the spacing is suggestive of tree spacing. Alternatively, they could be formed and maintained by some kind of physical or biogenic process, for example, perhaps similar to that forming alpine string bogs.

The platforms consist of a peat deposit as described in detail in Section 3.1.2 and in the Stratigraphy report (see Appendix 4 Stratigraphy analysis – Technical Report). The peat platforms appear to be distributed extensively along the tidal channels throughout Boullanger Bay and into the western end of Robbins Passage around Harcus Island and Brick Islands (see Figure 4.14). They are also apparent to the east of Stony Point in Big Bay and some peat outcrops in the western end of Duck Bay. Given the dating evidence outlined in the stratigraphy report (Appendix 4), these are of Pleistocene origin and are in the order of 20,000 to 40,000 years old. It is surprising that they are still surviving given their exposure to water currents and waves and how soft they are, yet they are cohesive enough to resist the action of the water and seem to provide a solid underlying structure to the intertidal flats.

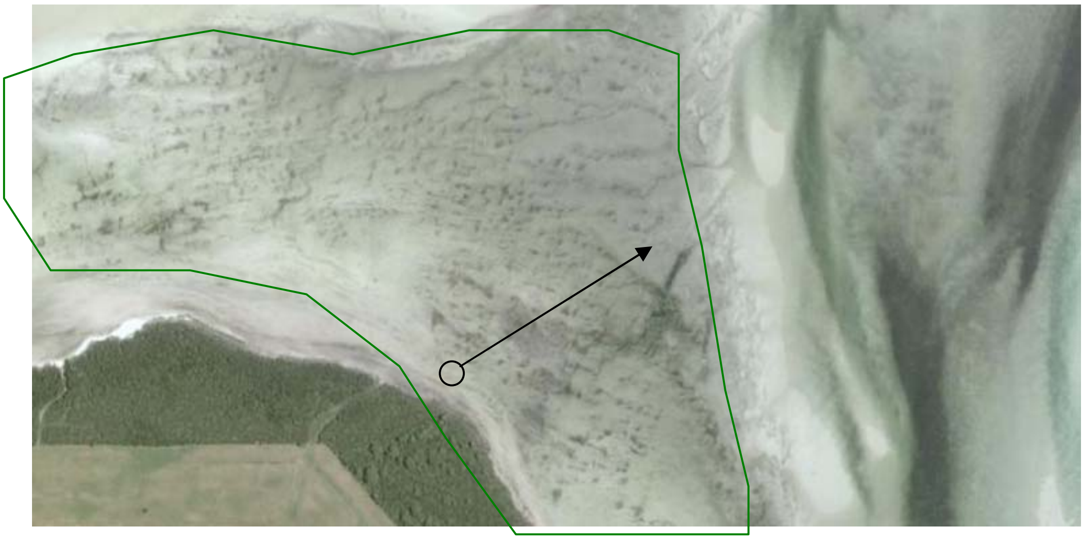


Figure 4.12 "Peat platform" geomorphic landform (indicated by green area) at Sealers Springs Point beside the Robbins Passage tidal channel to the east (right). Circle and arrow indicate photo position and direction for Figure 4.13 below.

Figure 4.13 View of the "Peat platform" with exposed peat in the foreground, a thin sheet of sand over peat with pools and seagrass (*Z. muelleri*) in the middle ground and Robbins Passage tidal channel and Robbins Island in the background.

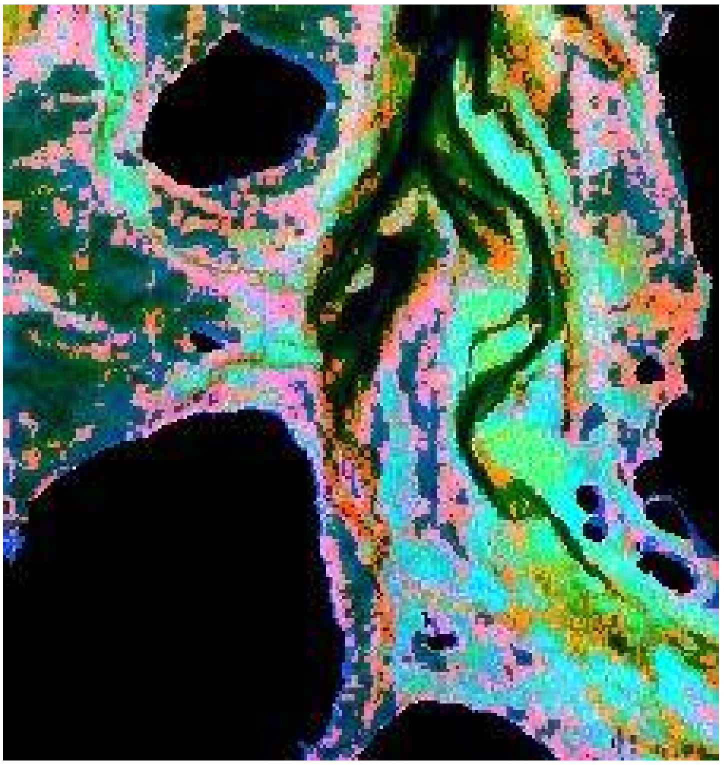


Figure 4.14 A highly processed Landsat satellite image from 2007 over the Boullanger Bay Case Study area between Robbins Island and Sealers Springs Point showing the extent of the peat platforms in pink. The mid-blue and blue/green areas are intertidal seagrass beds of *Z. muelleri* many of which are overlying the peat platforms. The very dark green, pale green and orange indicate channels. North is up and the image shows an area about 600 m across. Image courtesy Kan Otera, 2010.

Figure 4.15 *Posidonia australis* in Boullanger Bay

Box 4.1 Seagrasses

Seagrasses dominate the intertidal and subtidal habitats and are key "environmental engineers".

Across the intertidal flats, the dominant seagrass species found forming vast single-species beds (approx 60 km^2) is *Zostera muelleri* (Rees 1993) which is commonly known as eelgrass. It is very similar in form to *Heterozostera tasmanica* and has some similarities to *Heterozostera nigricaulis* to the casual observer. The key differentiating characteristic is that neither of the *Heterozostera spp.* are found in the intertidal zone (Edgar, 2008) and *Z. muelleri* occupies lower energy environments and besides sand can live on substrates with particle sizes dominated by mud and silt (Rees, 1993) as well as on sand. The seagrass beds provide habitat for many fish and invertebrates species and are major primary producers at the base of a food chain that supports many larger animals including swans and dolphins (Edgar, 2008). The seagrass blades themselves provide a suitable substrate for macroalgae, microphytobenthos and smaller invertebrates to grow on and among. Reduced water flow at the sediment surface generated by the baffling effect of the leaves creates a protected micro environment, a habitat for microphytobenthos such as diatoms, to form mats. This protection is also extended when the tide is out as the leaves form a protective shield to the desiccating forces of wind and sun.

In the subtidal areas, the dominant seagrass species (approx 60 km^2) are *Posidonia australis* and *Amphibolis antarctica*. *Posidonia angustifolia* may also be present (Rees, 1993). These are larger seagrasses and have substantial primary production rates and biomass. They are long lived and, in the study area, form very extensive single-species beds. They may have been present in the area from the start of the Holocene following the stabilisation of the sea level. For example, *Posidonia spp.* are known to have colonised the new shallow water subtidal areas around Australia that were created when the seas inundated the land at the start of the Holocene about 6,600 yrs BP. Evidence is available from Shark Bay (Larkum *et al*., 1989) and Spencer Gulf (Belperio *et al*., 1984).

Amphibolis produces viviparous seedlings that break off the parent plant and then use hook-like combs to secure themselves to the sea floor (Larkum *et al*., 1989).

4.3.2. Description of Shallow Subtidal areas

The shallow subtidal habitat covers 47% of the total study area and consists of extensive seagrass beds (~60 km^2 or 57%), very large areas of sand (~43 km^2 or 40%) and a small area (~1.9 km^2 or 1.8%) of outcropping rock (i.e. reef). The very large *Posidonia* beds in Boullanger Bay occupy the subtidal areas immediately below approximately Lowest Astronomical Tide (LAT) (i.e. the base of the plants are almost always submerged) down to about 5-7 m depth. On the outer northern edges of the Boullanger Bay seagrass bed, in areas more exposed to wave energy and tidal currents along Walker Channel, the dominant seagrass is *Amphibolis antarctica*. In places, the *Posidonia* beds have a distinct edge and drop off into an *Amphibolis* filled gutter running along the Walker Channel.

Figure 4.16 *Posidonia australis* has a very large below ground biomass consisting of roots and rhizomes.

Figure 4.17 Much of the large *Posidonia* bed in Boullanger Bay emerges form the water at low tide. It stretches into the distance towards Walker Channel. Trefoil Island is in the background.

There are large subtidal channels between 0.5 to 3 km wide cutting across the sea floor including at both ends of Robbins Passage and at the entrance to Duck Bay. These channels are mostly formed by the tides as they move in and out of the area, but several of them also drain the main rivers entering the area including the Welcome, Montagu and Duck Rivers. Large networks of smaller tidal channels drain to the main channels and link the subtidal areas with the intertidal areas including in Boullanger Bay, Robbins Passage, Big Bay and Duck Bay. In general, the floor of these channels is harder and more resistant to erosion than the surrounding seabed due to the higher velocities of water in the channels. In places, the channel floor consists of cobbles, for example, in the eastern end of Robbins Passage and the entrance to Duck Bay. These harder substrates usually have macroalgae (seaweed) and *Amphibolis antarctica* growing on them while other channels bottoms and banks have open sand and, in places, *Posidonia australis* and *Heterozostera spp* growing on them. At the mouth of Duck Bay and either end of Robbins Passage (near Perkins Island in the east and on the edge of Walker Channel in the northwest) there are large ebb tide deltas of open mobile sand. The location and orientation of these changes through time with variation in the dominant direction of sediment movement, probably due to changes in wind speed and direction.

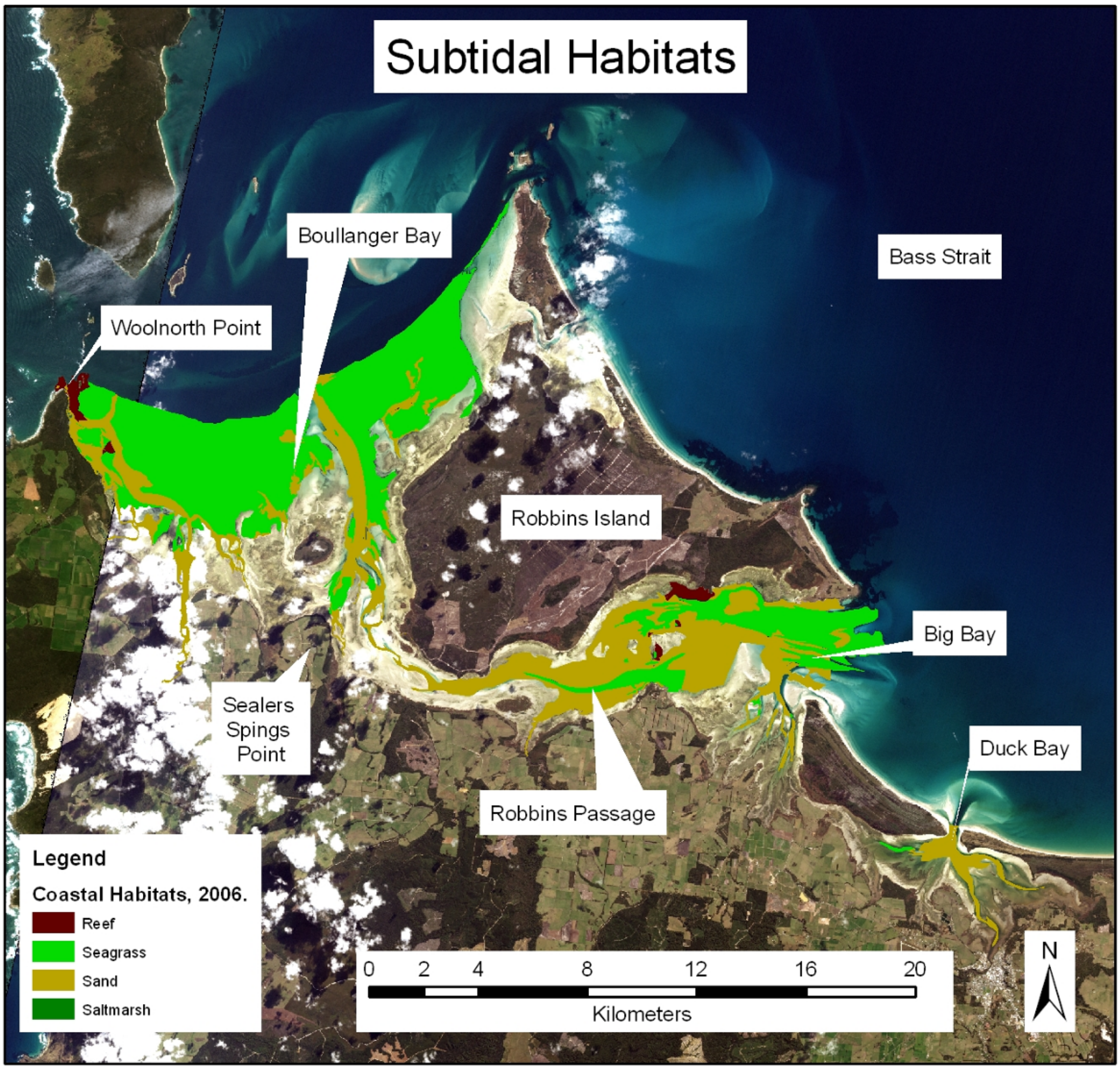


Figure 4.18 Shallow subtidal habitats across the study area – primarily consisting of large seagrasses (*Posidonia* and Amphibolis) and sandy substrates.

A time series of Robbins Crossing made with Landsat satellite imagery (Otera, unpub data; see Figure 4.19; image listing Appendix 1) shows that the net flow of sediments through Robbins Crossing within the main channel is from east to west. This direction of flow may change over longer periods than the time series study but has been consistent in direction during the 19 years of the study. This flow direction indicates that there are geomorphic processes delivering mobile sediment to the Robbins Crossing area. Conceivably, a chain of processes could be identified as follows:

1. Marine sediment is delivered into the eastern entrance of Robbins Passage. The source of such sediment is currently unknown, though could be from Bass Strait or from the eastern end of Walker Channel. Evidence includes the extension of the western end of Perkins Island since the 1950s by more than 200 m (determined from aerial photography; see Section 5.2.4. Aerial photography time series analysis).
2. Fluvial sediment may also be delivered into the Robbins Passage from the Montagu River; note however that present day natural sediment supply from rivers in the study area is thought to be minor, although some contribution from land clearance may be occurring. However no evidence bearing on this issue was obtained during this study (see also Section 3.1.2).
3. The net tidal flows may support the westerly progress of the sediment in the channel due to a differential in the tidal wave at either end of Robbins Passage.
4. Periodic strong easterly winds could also drive processes that either retain or increase the sediment volume at Robbins Crossing. Within Robbins Passage, the westerly wind fetch is smaller than the easterly winds. This mechanism could be enhanced by the “funnel” shape of Robbins Passage.
5. The shores of Robbins Passage may supply significant amounts of sediment, though no clear evidence supports this view.

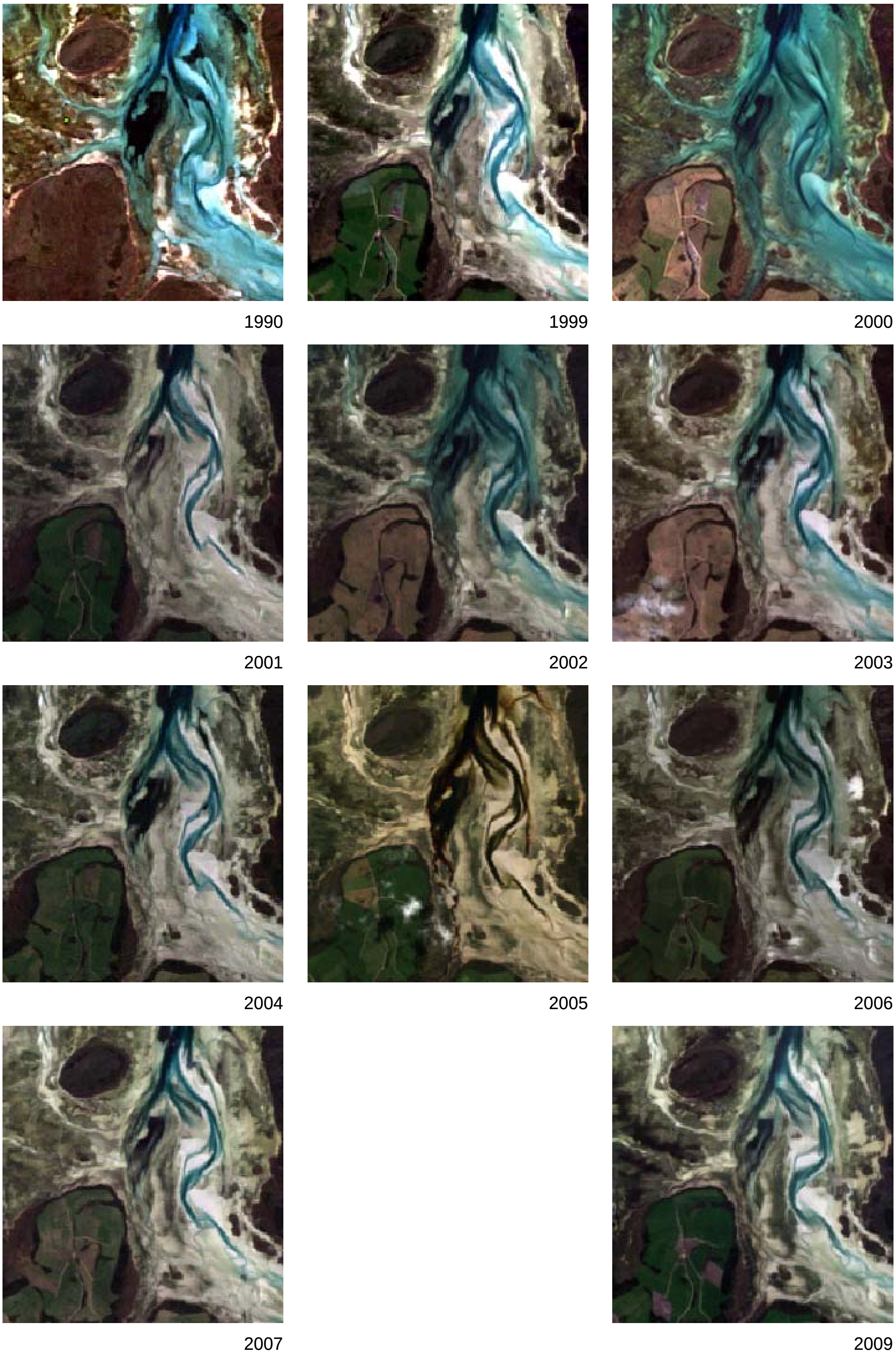


Figure 4.19 A time series of Landsat images (image listing Appendix 1). The images show a migration of the meanders and sand banks in the Robbins Passage channel from within Robbins Crossing (the lower right (SE)) into Boullanger Bay in a northerly direction. This indicates that the net sand movement is from east to west through the Passage during these two decades.

4.3.3. How Intertidal Flats and Subtidal Habitats function

The functioning of seagrasses have been summarised into six “axioms” by Larkum *et al*. (1989). They are as follows:

1. Stability of structure (stabilisation of the sea floor);
2. Provision of food and shelter for many organisms (habitat);
3. High productivity (primary productivity);
4. Recycling of nutrients (nutrient “filtering”);
5. Stabilising effects on shorelines (sediment trapping and water “baffling”); and
6. Provision of nursery ground for commercial fish (base of the food web).

Since the development of these axioms, much interest has arisen in the carbon cycle, particularly atmospheric carbon levels. Therefore, we add the concept that seagrasses are highly efficient at carbon sequestration and storage (Kennedy and Bjork, 2009).

For the purposes of this report we have recombined these axioms and reorientated them as ecosystem services for the entire intertidal flats including unvegetated habitats with the seagrass and also for the shallow subtidal habitats, as follows:

1. Seafloor and shoreline stabilisation
2. Nutrient cycling and filtering
3. Primary productivity and the associated food web
4. Carbon sequestration
5. Maintaining options for the future by supporting high levels of biodiversity

Each of these will be dealt with in the following sections.

Seafloor and shoreline stabilisation

The dominant seagrass species in the study area’s intertidal flats is *Zostera muelleri* (See Box 4.1 Seagrasses). It plays a key role in the geomorphology of this zone primarily by trapping sediments. The sediment will settle out of the water column when the water turbulence can no longer hold it in suspension. Water turbulence is reduced (baffled) among seagrass leaves compared to the water passing above the leaves. In this way sediments gather on the sea floor at the base of the seagrass leaves. As the level of the sea floor rises, the seagrass rhizomes will grow up through the sediment to ensure their leaves are produced above the surface to enable photosynthesis to take place. Generally, the seagrasses occupy higher mounds on the tidal flats and sand banks. Figure 4.20 shows mounds with seagrass on top and Figure 4.21 shows a height profile across the flats between Kangaroo Island and Sealers Springs that illustrates this relative height.

Seagrasses have a number of mechanisms for colonising the intertidal zone. These include reproduction and growth including via seeds, viviparous seedlings, rhizome elongation, striking of broken and transported rhizomes, adventitious roots, and distribution of clonal plantlets. In the intertidal zone of the study area, *Z. muelleri* produces seeds. In samples of sediment in Port Phillip Bay[13] up to 1,400 seeds m^{-2} were found (Parry, 2007). In Westernport Bay in 2003/2004, "the mean density of seeds on plants was 540-840 m^{-2} (maximum density in a 0.019 m^2 sample was ~4700 seeds m^{-2}), and the mean density of *Z. muelleri* seeds in sediments was 280 m^{-2} (maximum density in a 0.019 m^2 core was ~2100 seeds m^{-2})" (Parry *et al*., 2005). The energetic cost of producing so much seed suggests that this is a successful reproductive strategy. It may indicate the recolonisation by seed rather than rhizome elongation in areas subject to higher levels of sediment disturbance (Parry, pers. comm., 2010).

In the shallow subtidal areas in the study area the sea floor has remained relatively stable. The evidence is from two sources, firstly, a comparison of the two most detailed seagrass maps of the area and, secondly, a Landsat satellite time series over the past 18 years (image listing Appendix 1). The map comparison consists of the mapping completed for this project with satellite and aerial photographic imagery from circa 2006 with that of Chris Rees conducted using circa 1985 aerial photography (Rees, 1993). The most striking observation is the extraordinary stability of the large subtidal beds of the large seagrasses of *Posidonia* and *Amphibolis*. Some of the intertidal beds are also stable over this time period, particularly those around Sealers Springs and Kangaroo Island. The main Robbins Passage channel appears to be very stable where it passes through the subtidal seagrass beds. There is noticeable change apparent in the intertidal zone along the low water mark. There are also areas of change where the Welcome River crosses the intertidal flats and along the western shore of Robbins Island adjacent to Robbins Passage channel. Note that some visible differences are due to differences in the mapping methods, for example, the more recent mapping used orthophotos, whereas the first effort did not. Also, it is reasonable to expect that some patches of seagrass along channels will be missed due to poor illumination and water column turbidity.

Figure 4.20 Intertidal seagrass showing the sediment trapping capability of seagrass on the tops of mounds while the open sand is generally lower. The seagrass patch in the foreground also has a very low erosion scarp, illustrating the dynamic nature of these environments.

[13] Both Port Phillip Bay and Westernport Bay share many similar geomorphological and environmental characteristics with the study area.

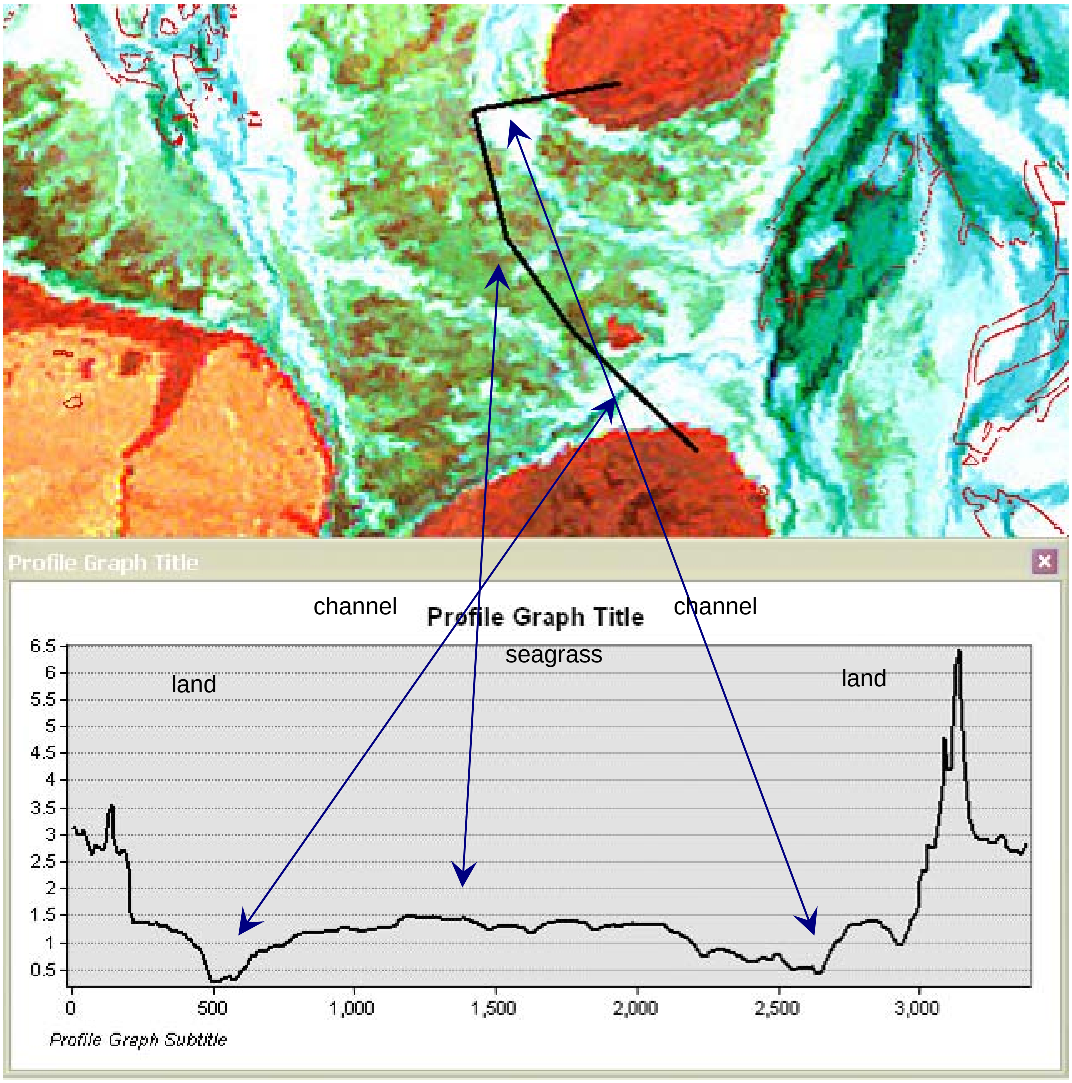


Figure 4.21 Height profile across the intertidal flats (black line). The intertidal seagrass *Z. muelleri* generally forms mounds in between the tidal channels by trapping passing sediments. The background image is a Landsat satellite image that highlights terrestrial vegetation in bright red (using near infrared light). The seagrasses are the red tinged greenish patches between the land and the white and blue tidal channels.

A second time series assessment was conducted by Otera (unpub. data). For example, a series of "gaps" or sand patches between 10 and 40 m across within the main *Posidonia* beds in Boullanger Bay have remained the same size and in the same location since 1990 (see Figure 4.23 and Figure 4.24). See also the evidence showing the rapidly changing habitats where the Welcome River crosses the intertidal flats in the next section.

Rates of sediment accretion in subtidal seagrass beds are higher than coral reef largely due to the high turnover of leaves with a calcareous epiphyte load. Over long periods of time this process is known to produce large stable sedimentary banks (e.g. Belperio, Hails et al., 1984). Walker and Woelkerling (1988) found in Shark Bay under *Amphibolis antarctica* that calcareous algae skeletal remains can contribute to sediment depths by 0.5 mm m^{-2} yr^{-1}.

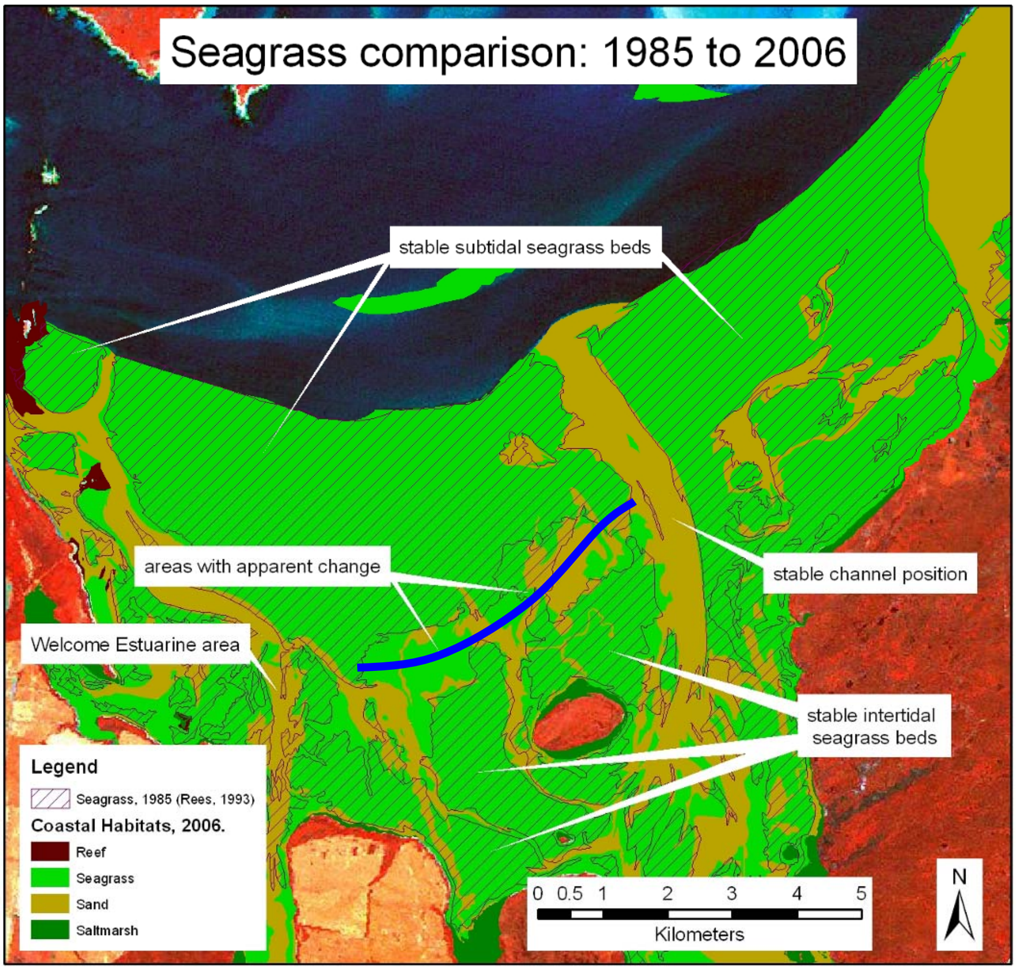


Figure 4.22 Seagrass areal comparison in Boullanger Bay 1985 to 2006. Note the extremely stable boundaries of most of the subtidal seagrasses and many of the intertidal beds. A zone of relative instability is apparent along the low water mark (approx indicated by blue line) and on the banks of some of the main channels, particularly the Welcome and Robbins Passage near Robbins Island. Sources: 1985 mapping from aerial photography and ground truthing by Rees (1993) and the 2006 mapping by TAFI, 2009 and this project using aerial photography, satellite imagery and ground truthing. Background image is an infrared Landsat image that shows vegetation in reddish hues.

Figure 4.23 Unexplained “gaps” (approx 10-50 m across) in *Posidonia* beds in Boullanger Bay.

Instability of seagrasses

While the seagrasses can stabilise the sea floor and have excellent sediment trapping capabilities, it is important to note that they are typically more dynamic in their coverage of the landscape than terrestrial vegetation. Large scale changes are recorded for many species of seagrasses including the species in the study area (Larkum and Hartog in Larkum *et al*., 1989). Within the study area where the Welcome River channel crosses the intertidal flats, a Landsat imagery time series study was recently conducted covering a period of 18 years (1999 to 2007; image listing Appendix 1). It identified areas that were extremely unstable in that they shifted from sand to seagrass and back again almost every year of the study (see Figure 4.25) yet adjacent areas were stable throughout (Otera, unpub. data).

The unstable areas shown in Figure 4.25 are on the more mobile sand of the estuarine channels and the stable areas are on the more sheltered higher banks.

There are a variety of ways that seagrasses protect shorelines from erosion, in particular by slowing the movement of water and by absorbing wave energy. Seagrasses slow the passage of water in a number of ways. The first mechanism is where the water closest to the surface is slowed as it passes through the seagrass leaves. Slower water has less energy and can carry less sediment, therefore it has less erosive power. The amount of water velocity attenuation varies with the type of water movement; tidal flows are more attenuated than wave action. The second mechanism is where the entire seagrass bed accretes vertically over a large area and the entire bank reduces the volume of the water column above the bank. Well-researched examples of this occur in Shark Bay, WA where the water flow, salinity, geomorphology and even the geology are influenced by the seagrasses.

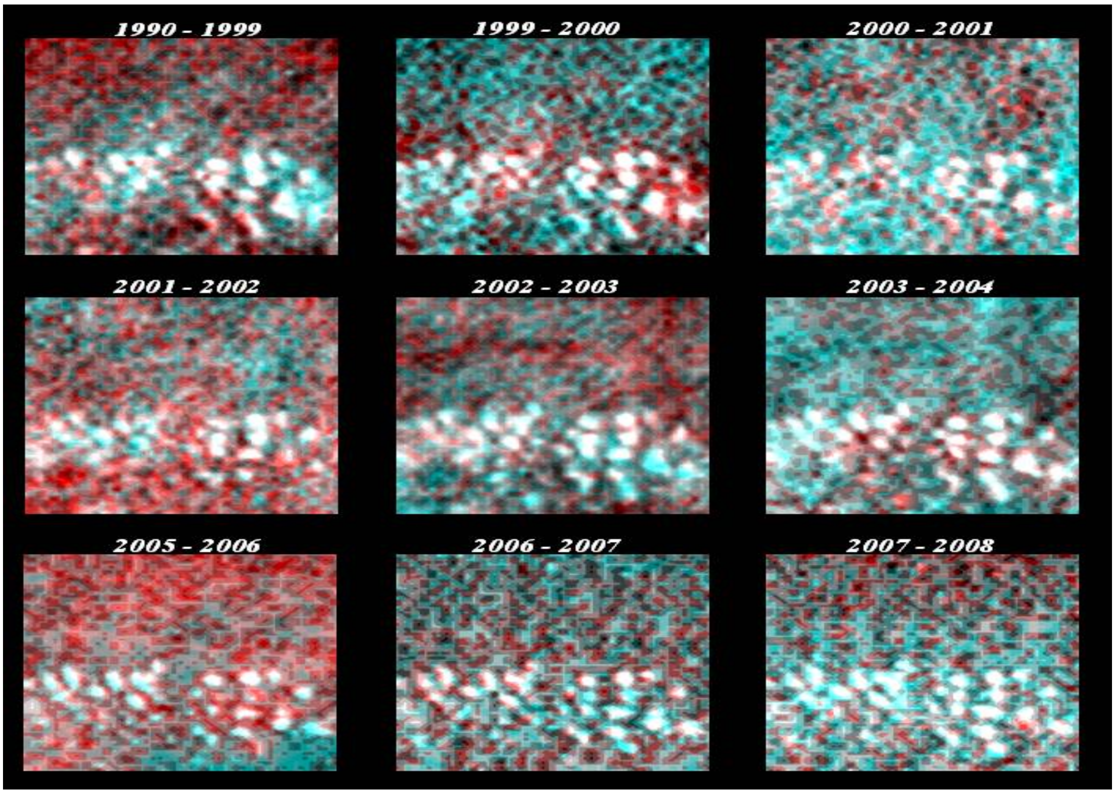


Figure 4.24 A time series of a portion of the dense seagrass beds in Boullanger Bay drawn from the Landsat satellite image archive (Appendix 1). The white patches across the bottom third of the image indicate locations with little or no change and these are the sand patches or "gaps". Otera, unpub. data)

Box 4.2 Intertidal seagrass change detection methods

Change detection in satellite remote sensing is a process of identifying non-change and actual change in the geometry or status of the proposed object by observation through multi-temporal images. The intertidal submerged aquatic vegetation (SAV) in the area of the Welcome Inlet, Boullanger Bay was subject to the change detection analysis. Intertidal area of this estuary contains large SAV meadows, consisting of intertidal seagrass and macro algae habitats. Information on the SAV distribution, especially the seagrass community at the local area is now regarded as significant information for an environmental management system.

Ten multi-spectral Landsat TM and ETM+ satellite images collected over 18 years (Appendix 1) were used for a Multiple-date Composite Image (MCI) change detection approach to produce the time series of change detection results. The change detection results of SAV meadows in the Welcome Inlet show areas of SAV meadows with both high stability (low rates of change) and high instability (high rates of change).

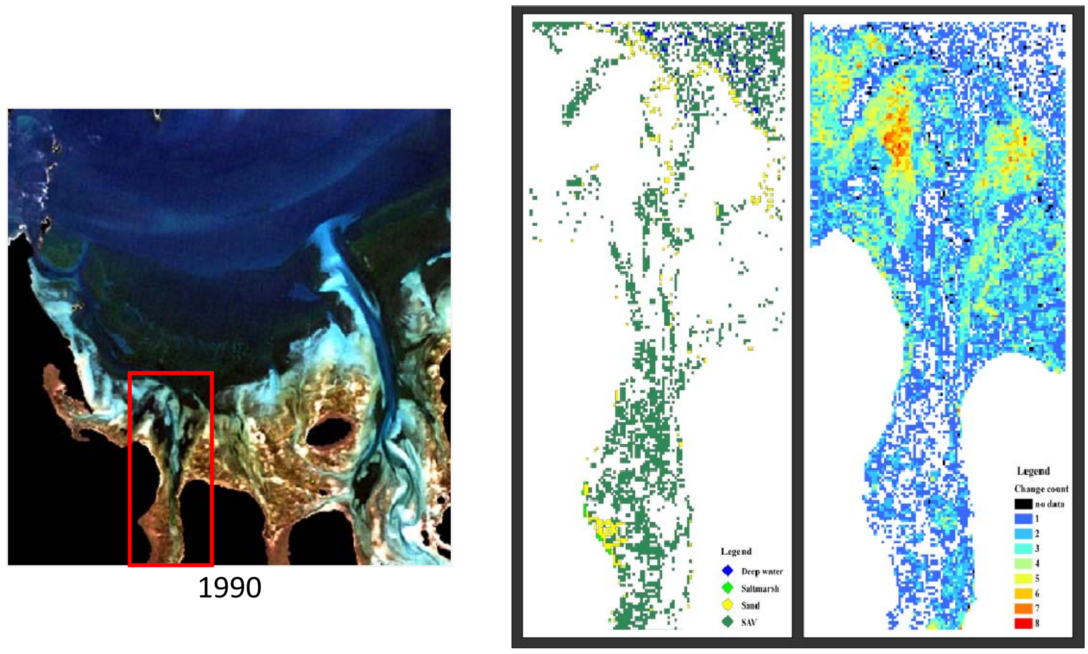


Figure 4.25 Seagrass stability changes at the mouth of the Welcome River using 18 years of Landsat imagery (1990-2007; listed Appendix 1). The left image shows the area of the study in a red box and the middle image shows stable areas of habitat while the right image represents the count of times the habitat has changed over the 18 years. Note the red and yellow areas show up to eights changes, most of which are in the last 10 years.

Nutrient cycling and filtering

Coastal foreshore habitats such as seagrasses and microphytobenthos have high rates of primary productivity which infers a high nutrient demand for nutrients such as nitrogen, phosphorus and carbon (e.g. Mateo et al., in Larkum et al., 2006; also see the following section on primary productivity). Typically, nitrogen and phosphorus are the limiting nutrients for seagrass (Larkum et al., 1989; Larkum et al., 2006). Given the high levels of these nutrients entering the study area from the rivers (see Section 6.4 Nitrogen and phosphorus), these nutrients have the potential to drive changes in production rates. While coastal and estuarine areas are vulnerable to eutrophication (i.e. pollution with excess nutrients), the high productivity rates infer that the ecosystems are sustainably capturing and recycling substantial amounts of nutrients. For example, seagrasses can take in nutrients from both the water column and the sediments while growing. As leaves are shed (up to 2 to 5 times a year) the dead plant matter is decomposed and nutrients are released that support further growth. However, the fluxes of nutrients can take many pathways, most of which are not documented within the study area.

Drawing on studies and understanding from other areas, it is straightforward to suggest that given the large biomass and productivity rates the biota in the intertidal flats and shallow subtidal areas are both a large sink and a source of nutrients in the area. This means they are capturing, processing and releasing nutrients in a relatively controlled and regulated way. This provides stability in nutrient fluxes and helps to reduce the likelihood of spikes of nutrients in the system including those that may cause unwanted effects such as algal blooms. The inorganic (mineral) sediments themselves also contribute to the nutrient fluxes. For example, phosphorus is known to readily adsorb to mineral particles. In this way the sediments may capture excess phosphorus from the water column. Under other environmental conditions nutrients and heavy metals may be released from the sediments. Almost all of the intertidal and subtidal habitats (~220 km^2) can be considered to regulate nutrients by capturing, transforming and filtering them.

Most marine plants interact with nutrients via the water column and therefore the concentration of key nutrients in the water is a driving factor in the ecological responses of the habitats of interest. For example, it is water column nutrient concentrations that are one of the determinants of the degree of eutrophication (nutrient pollution). Given that, the relatively high water concentrations of nutrients in the water delivered by the Montagu and Duck rivers is of concern, particularly for areas in the upper estuary of those rivers (John Gibson, pers. comm.). The Landscape Logic project is addressing those issues and is soon to deliver its findings, so further analysis by this project is premature. However, previous work by Hirst *et al.*, 2007) suggests that there is a protective effect provided by the high flushing rates of the estuaries in the region as a result of the meso-tidal exchange diluting nutrient concentrations. In other works, the 3 to 3.5 m tides strongly dilute the nutrient concentrations in the water, both within, and it must be assumed, outside of each estuary.

Primary productivity and the associated food web

Coastal foreshore habitats including intertidal and subtidal habitats are highly productive (Underwood and Chapman, 1995) with seagrasses producing up to 800 gC m^{-2} yr^{-1} compared to macroalgae at 375 gC m^{-2} yr^{-1}; forests at 400 gC m^{-2} yr^{-1}; and crops at 300 gC m^{-2} yr^{-1} (Mateo et al., in Larkum et al., 2006). It is important to note that these rates are simplified averages and may be very different in the study area. While coastal phytoplankton and microphytobenthos (sea floor, or benthic, microalgae) have lower productivity rates (167 gC m^{-2} yr^{-1} and 50 gC m^{-2} yr^{-1} respectively), they occupy a very large area and therefore make a significant contribution to primary productivity. For example, a series of studies have found that algal epiphytes can contribute between 20 and 60 percent of total primary productivity in seagrass beds (Borowitzka et al., in Larkum et al., 2006). In a study by Kaldy et al. (in Larkum et al., 2006) the benthic macroalgae accounted for 33-42% of net primary production, while seagrasses contributed 33-38% and microalgae 23-56%. The key concept here is that while seagrasses are the most obviously observable component in the study area’s intertidal and subtidal habitats, they may not be the main primary producer. Having established that, we do not have access to observations of productivity by any of the primary producers in the study area. In lieu of actual observations, we have applied some reported productivity rates for seagrasses in similar circumstances to those found in the current study area.

Carbon production is an accepted proxy for net primary production and is also relevant for calculating carbon sequestration potential (see the section on carbon sequestration). Carbon production by *Posidonia australis* and *Amphibolis antarctica* in Shark Bay, Australia was measured at 310 and 445 g C m^2 yr^{-1} respectively (Walker in Larkum et al., 1989), which is considerably higher than the global average of 83 g C m^2 yr^{-1} mentioned above. A summary of research into productivity reveals that there is little difference in maximum productivity rates for seagrasses whether tropical or temperate, estuarine or marine, or subtidal or intertidal (Hillman et al., in Larkum et al., 1989). Rates of 250 gC m^2 yr^{-1} for smaller seagrasses and 300-550 gC m^2 yr^{-1} for larger seagrasses are reported. There is reason to think that the seagrasses of Boullanger Bay and Robbins Passage are producing more than the Shark Bay as seagrasses are generally phosphorus and nitrogen limited and probably have access to more phosphorus delivered via the rivers in the study area (see the section on nutrients) compared with the available phosphorus in Shark bay.

In an effort to identify the magnitude of gross carbon production, the production rates were multiplied by the mapped area of the two dominant subtidal seagrasses in the study area. The resulting estimate is circa 36,000 tonnes C yr^{-1}. This figure is very approximate, though conservative, and should be used with caveats and caution, but it does give a sense of the magnitude of the carbon production. An estimate for the intertidal seagrasses (~60 km^2) is circa 21,000 tonnes C yr^{-1} giving a total for the study area of circa 57,000 tonnes C yr^{-1}. Note that this figure does not include the amount of production by the phyto-planktons either benthic or pelagic.

The same calculations were conducted for total biomass (“standing crop”) and productivity rates per year i.e. for the entire plant not only carbon. Intertidal seagrass estimates are based on McKenzie (1994) and subtidal estimates on Walker, in Larkum et al., 1989). Below ground production may be 2-5 times above ground production (Mateo et al., in Larkum et al., 2006) and the lower estimate was used here. The units are dried weight (DW) tonnes.

Table 4.1 Standing crop of seagrass biomass estimated with published figures (rounded to nearest ‘000). The units are dried weight (DW) tonnes. Intertidal estimates based on McKenzie (1994) and subtidal estimates on Walker, in Larkum et al., 1989)

Habitat	Above ground biomass	Below ground biomass	Total biomass (“Standing Crop”)
Intertidal seagrass	6,000	11,000	16,000
Subtidal seagrass	51,000	102,000	153,000
Total	56,000	113,000	**169,000**

The results show that the total standing crop of seagrass for the entire study area may be in the order of 169,000 DW tonnes though it is important to note that this is not based on biomass observations made in the study area. The annual leaf production rates were only able to be calculated for the larger subtidal seagrasses, i.e. *Posidonia* and *Amphibolis*. This was done in a very conservative manner using observed rates from Shark Bay where there are negligible anthropogenic nutrient inputs (Walker, in Larkum at al., 1989). This calculation delivered a combined figure for leaf production of approximately 75,000 DW tonnes yr^{-1}. Given that this figure does not include any other primary producers including intertidal seagrass, benthic microalgae, macroalgae or phytoplankton, this figure could underestimate primary production by up to an order of magnitude (i.e. ten times). A crude cross check can be conducted as there is a robust relationship for seagrasses where the annual seagrass leaf production rate is between 2.2 to 5.5 times seagrass leaf standing crop (Hillman et al., in Larkum et al., 1989). The above ground biomass for the subtidal seagrasses is estimated to be ~51,000 DW tonnes (see Table 4.1) which, if multiplied by the most conservative rate of 2.2, gives 112,200 DW tonnes. Though this is higher than the 75,000 DW tonnes it has the same order of magnitude and this lends some support to the range of values produced.

A comparison was made with rates of grass production (Tony Norton, TIAR pers. comm.) within the adjacent catchments, Montagu, Welcome and Duck in kilograms per hectare. Figure 4.26 shows that even with a very conservative calculation the primary productivity of seagrass leaf is comparable with pasture in this rich dairy farming area. Further, there is likely to be at least as much biomass again produced by the below ground seagrass, macroalgae, microalgae and phytoplankton in the study area.

This level of primary productivity underpins a large food web which also includes people. The wild and recreational fishery and the aquaculture production depend on the primary productivity of the area. While a detailed study of the complex trophic pathways have not been conducted in the study area, based on the evidence produced in other places including Bass Strait (e.g. Davenport and Bax, 2002), it is reasonable to assume that this level of primary productivity is supporting a large food web including commercially important species.

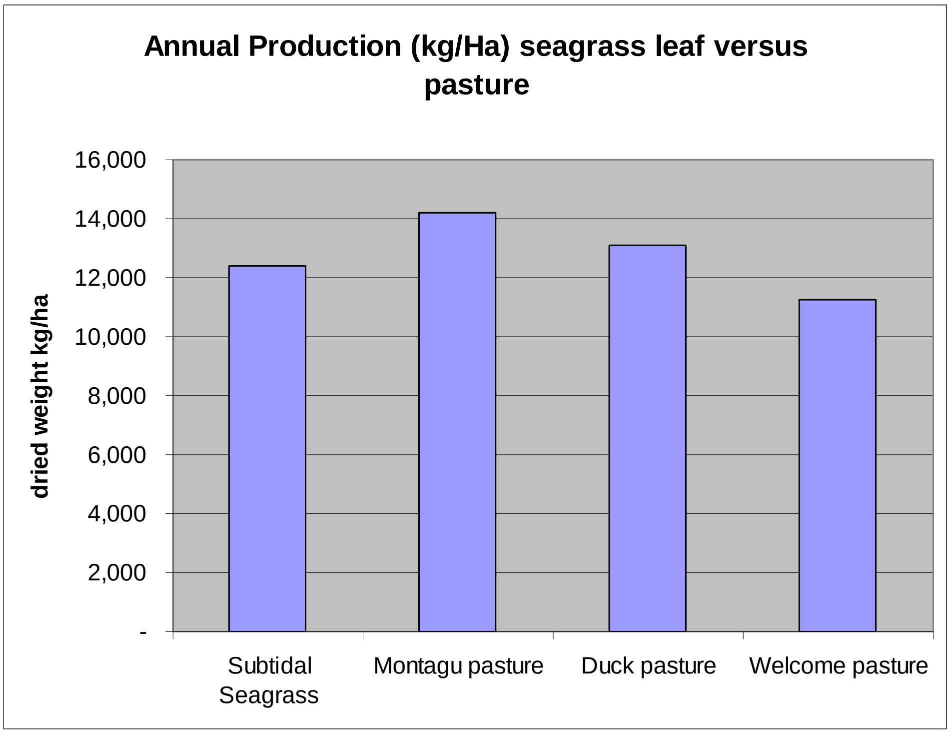


Figure 4.26 Comparison of primary productivity rates by subtidal seagrass and pasture in three adjacent catchments. Seagrass rates from published data and pasture rates provided by Tony Norton, TIAR.

Carbon sequestration

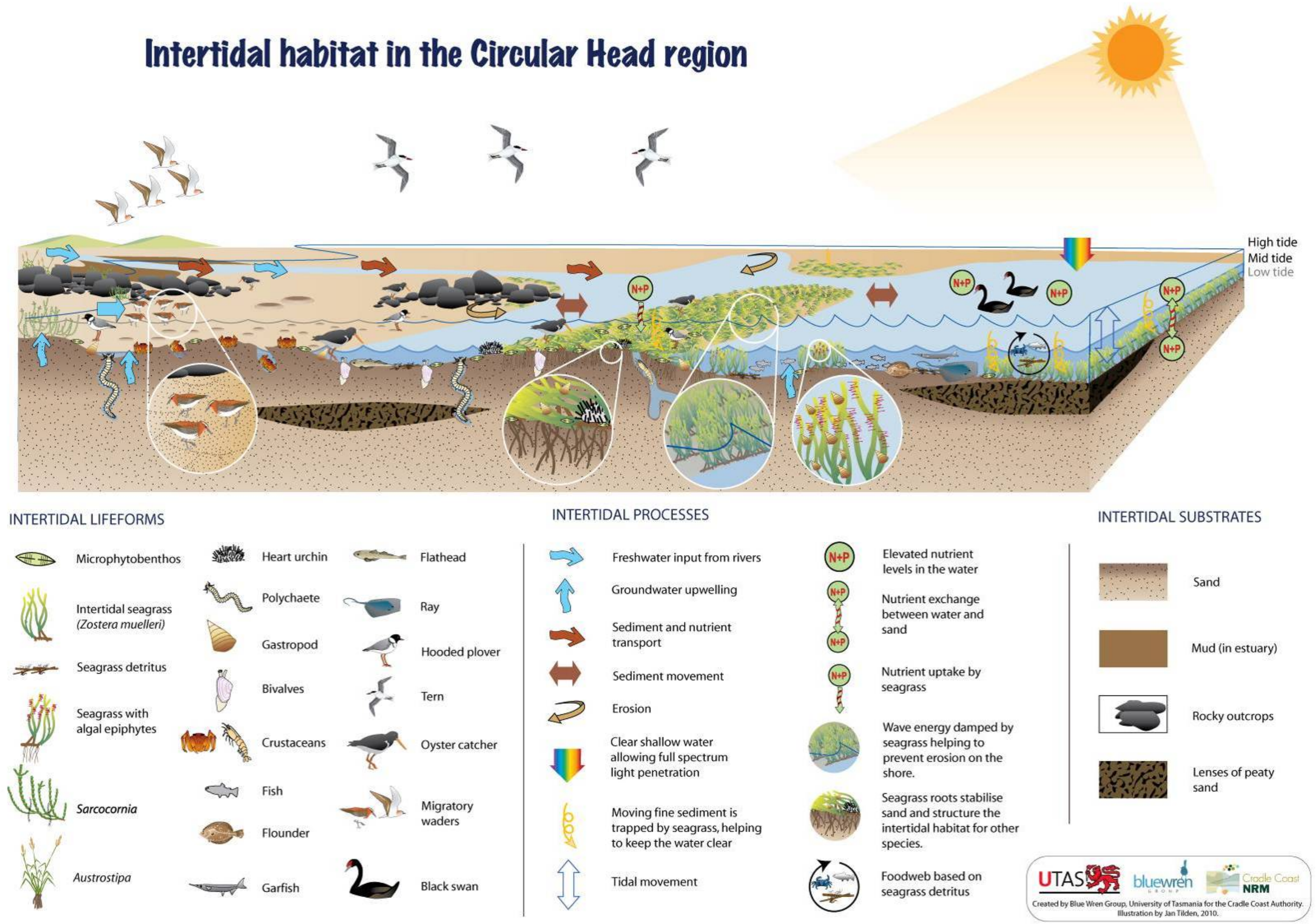
Natural coastal wetlands have, hectare for hectare, similar or higher rates of carbon sequestration and carbon storage compared with terrestrial ecosystems, such as forests and generally are more efficient than coral reefs (Laffoley and Grimsditch, 2009). This is partially explained by the lower potential for methane emissions. For example, a global average rate of carbon sequestration for seagrasses is 83 g C m^2 yr^{-1} with a total amount of C sequestered being 27-40 Tg C yr^{-1} (assuming a global coverage of 0.3 million km^2). This means that about 15% of total marine carbon sequestration is provided by a habitat covering about 1% of the ocean area. Vegetated coastal habitats (saltmarsh, mangroves and seagrasses) sequester carbon on average at between 10 to 50 times faster than forests. Partially for this reason, the loss of 110 km^2 yr^{-1} of seagrass (the current global estimate) is equivalent to the loss of about 770 km^2 yr^{-1} of temperate forest and up to 3,600 km^2 yr^{-1} of tropical forest (Waycott et al., 2009 in Laffoley and Grimsditch, 2009).

For the study area, total carbon production was estimated using published rates and the seagrass alone generates circa 57,000 tonnes C yr^{-1} (see primary productivity section for details). Much of this carbon recycles through the food chain including back through the seagrass, though some of it becomes refractory carbon and is sequestered (Mateo et al., in Larkum et al., 2006). There are a number of ways seagrass beds can deliver carbon storage including directly via the seagrasses themselves and indirectly by providing a greatly increased area of habitat for epibionts (epiphytic plants and associated animals) particularly calcareous epiphytic algae. Evidence for these pathways follows.

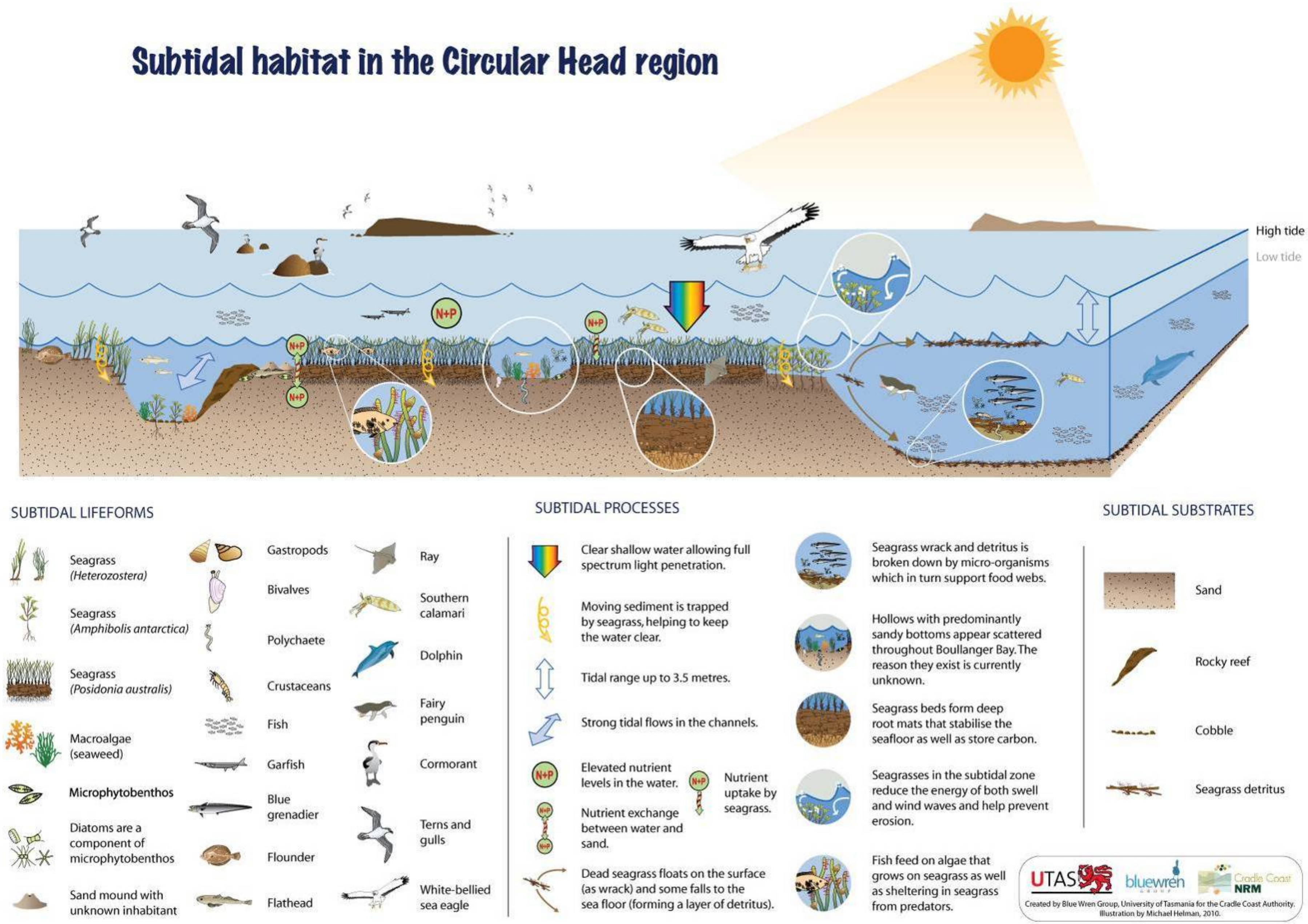
Seagrasses (and saltmarshes) use carbon directly to build their plant structures including their roots, rhizomes, stems, leaves and leaf sheaths. Over time many species of seagrass, including *Posidonia australis* and *Amphibolis antarctica*, shed leaves and leaf sheaths and these are either incorporated into the seabed under the seagrasses or exported into the surrounding waters. The larger slower growing species, such as *Posidonia*, may have very large below ground biomass; this plant material is less subject to herbivory (browsing/grazing) and much of it may be stored as carbon rich (up to 40% carbon) detritus. In the Mediterranean Sea, *Posidonia oceanica* "mattes" (accumulations of old seagrass detritus) have been dated at over 3,000 yrs old with most of their nutrient content intact though time (Romero *et al.*, 1997). *Posidonia* seagrass matte can accumulate vertically at 1-2 mm yr^{-1} (Clarke and Kirkman in Larkum et al., 1989). *Posidonia* is also reported to be able to increase vertical accretion rates up to 52 mm yr^{-1} when covered by sand waves (Bourdouresque and de Grissac, 1983 in Larkum et al., 2006).

The export of shed leaves and leaf sheaths to surrounding beaches and marine areas can be a significant sink for carbon. For example, the floor of the Gulf St Vincent and Spencer Gulf, South Australia hold vast quantities of *Posidonia australis* leaf sheath (Read and Smith, 1919). The movement of large rafts of *Posidonia* leaves generated by storms out past Woolnorth Point to the Tasmanian west coast has been indicated by a fisheries study that found evidence of Boullanger Bay *Posidonia* nitrogen in Blue Grenadier in Macquarie Harbour (Thresher, 1992). A pathway that included juvenile Blue Grenadier feeding on the storm generated detrital rafts was posited. A "tidal pump" mechanism is also likely, where the regular movement of the water with the tides carries detritus away from the seagrass beds to adjacent areas where it may become part of a detrital food chain. If the detritus consists of large amounts of relatively refractory carbon it may not decompose for long periods of time (Jahnke, 2008 in Laffoley and Grimsditch, 2009; Pidgeon, 2009 in Laffoley and Grimsditch, 2009).

A second pathway for carbon sequestration is via the accumulation of the remains of calcareous life forms that grow on the seagrass leaf blades (Walker and Woelkerling, 1988 in Larkum *et al*., 1989). The carbon rich remains are deposited locally (Belperio *et al*., 1984) or may be exported to nearby beaches or the floor of the adjacent marine areas. The magnitude of these deposits in the study area is unknown but could be substantial, particularly under the current position of the large subtidal seagrass beds.



Intertidal habitat in the Circular Head region
High tide
Mid tide
Low tide
N+P
INTERTIDAL LIFEFORMS
Microphytobenthos
Intertidal seagrass (Zostera muelleri)
Seagrass detritus
Seagrass with algal epiphytes
Sarcocornia
Austrostipa
Heart urchin
Polychaete
Gastropod
Bivalves
Crustaceans
Fish
Flounder
Garfish
Flathead
Ray
Hooded plover
Tern
Oyster catcher
Migratory waders
Black swan
INTERTIDAL PROCESSES
Freshwater input from rivers
Groundwater upwelling
Sediment and nutrient transport
Sediment movement
Erosion
Clear shallow water allowing full spectrum light penetration
Moving fine sediment is trapped by seagrass, helping to keep the water clear
Tidal movement
Elevated nutrient levels in the water
Nutrient exchange between water and sand
Nutrient uptake by seagrass
Wave energy damped by seagrass helping to prevent erosion on the shore.
Seagrass roots stabilise sand and structure the intertidal habitat for other species.
Foodweb based on seagrass detritus
INTERTIDAL SUBSTRATES
Sand
Mud (in estuary)
Rocky outcrops
Lenses of peaty sand
UTAS
bluewren GROUP
Cradle Coast NRM
Created by Blue Wren Group, University of Tasmania for the Cradle Coast Authority. Illustration by Jan Tilden, 2010.


Subtidal habitat in the Circular Head region
High tide
Low tide
N+P
SUBTIDAL LIFEFORMS
Seagrass (Heterozostera)
Seagrass (Amphibolis antarctica)
Seagrass (Posidonia australis)
Macroalgae (seaweed)
Microphytobenthos
Diatoms are a component of microphytobenthos
Sand mound with unknown inhabitant
Gastropods
Bivalves
Polychaete
Crustaceans
Fish
Garfish
Blue grenadier
Flounder
Flathead
Ray
Southern calamari
Dolphin
Fairy penguin
Cormorant
Terns and gulls
White-bellied sea eagle
SUBTIDAL PROCESSES
Clear shallow water allowing full spectrum light penetration.
Moving sediment is trapped by seagrass, helping to keep the water clear.
Tidal range up to 3.5 metres.
Strong tidal flows in the channels.
Elevated nutrient levels in the water.
Nutrient uptake by seagrass.
Nutrient exchange between water and sand.
Dead seagrass floats on the surface (as wrack) and some falls to the sea floor (forming a layer of detritus).
Seagrass wrack and detritus is broken down by micro-organisms which in turn support food webs.
Hollows with predominantly sandy bottoms appear scattered throughout Boullanger Bay. The reason they exist is currently unknown.
Seagrass beds form deep root mats that stabilise the seafloor as well as store carbon.
Seagrasses in the subtidal zone reduce the energy of both swell and wind waves and help prevent erosion.
Fish feed on algae that grows on seagrass as well as sheltering in seagrass from predators.
SUBTIDAL SUBSTRATES
Sand
Rocky reef
Cobble
Seagrass detritus
UTAS
bluewren
Cradle Coast NRM
Created by Blue Wren Group, University of Tasmania for the Cradle Coast Authority. Illustration by Michael Helman, 2010.

4.4. Ecosystems services (benefits) to people from coastal foreshore habitats

Primary Authorship: Richard Mount

There are many ways to define benefits that flow from ecosystems to people; one is to adopt an ecosystem services approach. That approach was taken here to enable an assessment that is explicitly focussed on the value of the ecosystems to people. This report is not a conservation report; rather it places people squarely in the picture and seeks to understand the beneficial linkages between people, coastal ecosystems and sea level rise. There is a lot of activity in the ecosystem services arena and a burgeoning literature with many new ideas developing rapidly. A useful summary is provided in the recent Ecosystem Services Mapping Stage 1 report to Cradle Coast NRM (Williams, 2009) and given that both reports are dealing with the Cradle Coast NRM region, interested readers are referred to that report. The approach taken in this report is designed to be complementary and is easily translated to the approach and the categories (Table 4.2) outlined in Williams (2009).

Table 4.2 Broad themes encompassing the benefits associated with ecosystems (Williams, 2009).

• Biodiversity conservation	• Food production & security
• Water security	• Coastal stability
• Carbon	• Resilience to climate change
• Tourism & recreation	• Quality of life

To illustrate the concept of ecosystem services, the following conceptual diagram (Figure 4.27) shows that the natural assets, such as coastal foreshore habitats, provide some services and goods directly to people (in blue) and also maintain themselves through regulating processes (green).

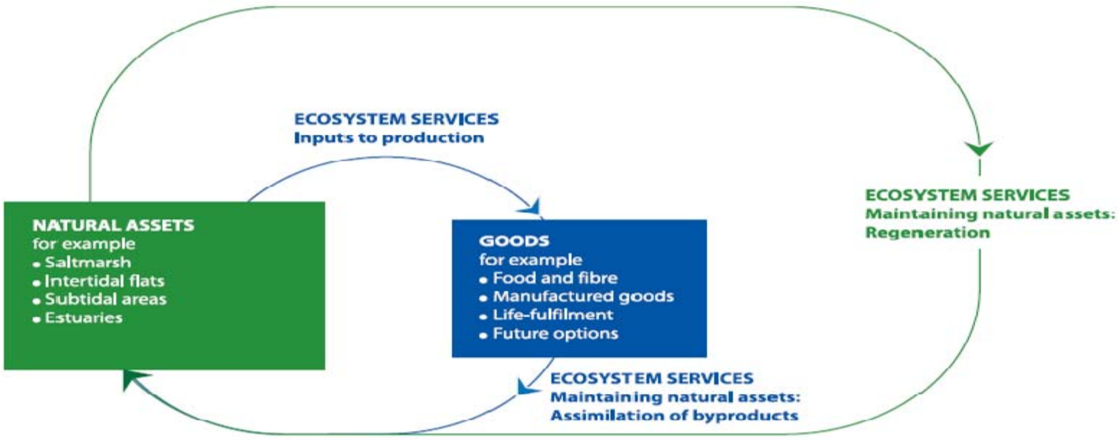


Figure 4.27 Ecosystem Services conceptual diagram (Adapted from Cork,)

The full set of defined ecosystem services is presented in Table 4.3. The process adopted is to identify the linkage between the habitats and specific human activities and values. Table 4.4 lists the set of human activities considered for assessment and Table 4.5 sets out the linkages between a selection of those activities and the three habitats.

Table 4.3 Ecosystem Services (Adapted from Daily, 1999 by Cork and Sheldon, 2000. Also informed by Wallace, 2007 - processes and elements vs services and values). Note that this list is not exhaustive and more services are likely to be identified as more becomes known about these systems.

A	**Production of Goods**		
		1	Food
		2	Energy
		3	Durables
		4	Genetic resources
		5	…
B	**Life-fulfilling Services**		
		1	Aesthetic beauty
		2	Cultural activities
		3	Intellectual challenges
		4	Spiritual inspiration
		5	Existence value
		6	Scientific discovery
		7	Serenity
		8	…
C	**Regeneration Processes**		
		1	Nutrient cycling
		2	Nutrient filtration
		3	Sediment cycling
		4	Sediment filtration
		5	Pollination, seed\propagule production
		6	Maintaining biodiversity
		7	Primary production
		8	Soil building
		9	Food chain services
		10	Sediment production
		11	Translocation of propagules and nutrients
		12	…
D	**Stabilising Processes**		
		1	Seabed stability
		2	Shoreline stability and protection
		3	Carbon sequestration
		4	Stabilising hydrodynamics (e.g. wave power)
		5	Pest control
		6	Stabilising water quality (e.g. clarity)
		7	Maintaining geodiversity
		8	…
E	**Preservation of Options**		
		1	Maintenance of ecological components and systems needed for the future
		2	Supply of goods and services awaiting discovery
		3	…

Table 4.4 Human activities and values for which ecosystem services provided by coastal foreshore habitats could be assessed (Drawn from management plans and policy documents)(See Section 2 on Management Objectives and Values).

Activity Category	**Activity (or Value)**
Land Food Production	Cattle and sheep
Land Food Production	Dairying
Land Food Production	Intensive grazing
Sea Food Production	Abalone and Rock Lobster harvest
Sea Food Production	Oyster lease
Sea Food Production	Shark fishery
Environmental	Water quality
Protected Ecosystem Values (PEVs)	Recreational water activities
Conservation	Threatened species
Conservation	Biodiversity values
Conservation	Shorebird
Conservation	Climate change refuge
Conservation	Foreshore reserves
Energy	Wind farms
Aboriginal Values	Traditional food gathering
Aboriginal Values	Cultural camp
Recreational	Recreational fishing
Recreational	Tourism
Recreational	Ecotourism
Recreational	SCUBA diving
Recreational	Duck hunt
Recreational	Beach fishing
Recreational	Recreational boating
Recreational	Sight seeing
Recreational	4x4 driving
Recreational	Beach walking
Recreational	Horse riding
Recreational	Safe anchor
Recreational	Mutton birding
Historical	Indigenous
Historical	European

Table 4.5 A few key examples of human activities and values that receive benefits (ecosystem services) from the coastal foreshore habitats. The codes (e.g. "C2") refers back to the ecosystem services list in Table 4.3

Value, Industry, or Land Use?	Specifically	Comment	Shoreline wetlands (saltmarsh)	Intertidal flats	Subtidal habitats
Land Food Production	Farming in low lying coastal location	The growth of pasture is affected by salinity. Coastal erosion can remove pasture from production therefore stable foreshores are valuable. Carbon sequestration opportunities are of interest to this industry.	C8, C10, D1, D2, D3, D4, E1, E2	C10, D1, D2, D3, D4, E1, E2	C10, D1, D2, D3, D4, E1, E2
Aquaculture	Oyster growing	Oyster production needs intertidal areas with plankton for the oysters to eat, clean water and a stable substrate to support the racks	C1, C2, C4, C5, C6, C9, C10, C11 D2, D6, D7	A1, A4, C1, C2, C4, C7, C9, C10, D1, D2, D3, D4	C1, C2, C4, C5, C6, C9, C10, C11, D2, D6, D7
Recreational Water Activities	Protected Ecosystem Values (PEVs)	Takes place in intertidal and subtidal areas. Needs good water quality with limited pathogens. Aesthetics are important.	B1, B2, B7, C2, C4, D2, D6	B1, B2, B7, C2, C4, D1, D6	B1, B2, B7, C2, C4, D1, D6
Conservation	Threatened vegetation species and communities	Threatened vegetation species need large enough places to maintain their populations and a great number of ecosystem services to maintain their ecological envelope.	A4, B1, B2, B5, B6, C5, C6, C8, C9, C10, C11, D2, D4, D6, D7, E1, E2	A4, B1, B2, B5, B6, C5, C6, C8, C9, C10, C11, D1, D4, D6, D7, E1, E2	A4, B1, B2, B5, B6, C5, C6, C8, C9, C10, C11, D1, D4, D6, D7, E1, E2
Tourism	Coastal ecotourism	Snorkel Tours need clear water in intertidal and subtidal areas with a variety of interesting things to see	C2, C4, C5, C6, C9, C10, D2, D6	B1, B2, B3, B4, B5, B6, B7, C2, C4, C5, C6, C7, C9, C10, C11, D1, D2, D4, D6, D7, E2	B1, B2, B3, B4, B5, B6, B7, C2, C4, C5, C6, C7, C9, C10, C11, D1, D4, D6, D7, E2

4.4.1. Synthesis of key ecosystem services as conceptual diagrams

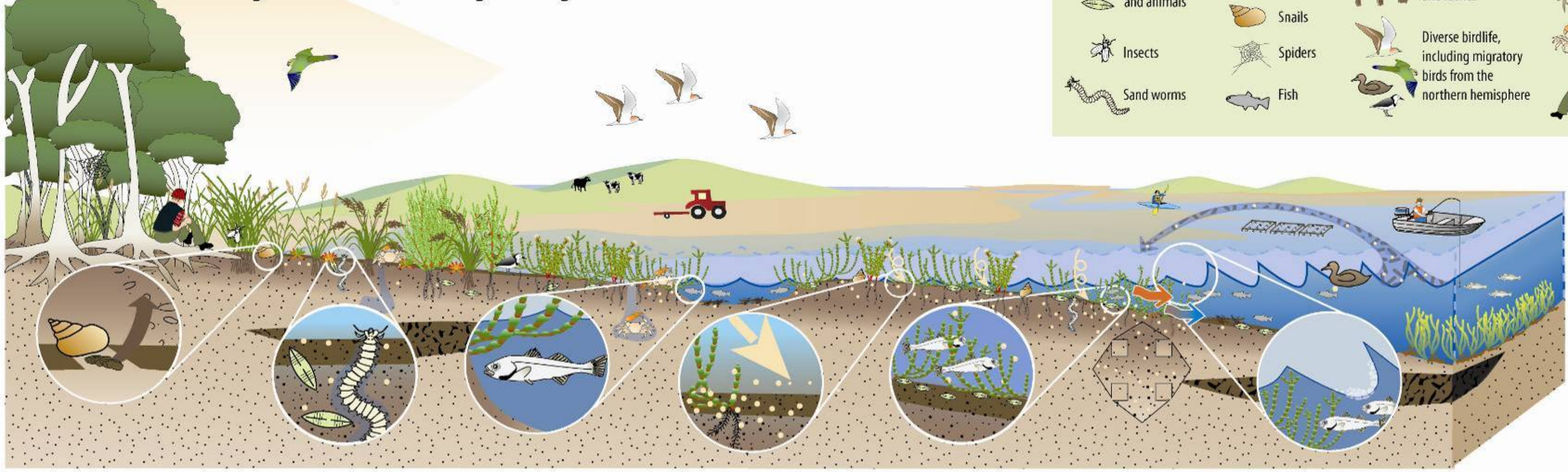
Following extensive discussions during a series of four Synthesis Workshops with ecosystem experts, the ecosystem services most at risk were identified and are summarised by the following diagrams – one for each of the main habitat types. Note that the terms ecosystem services has been translated into "benefits" for the purposes of the diagrams.

Shoreline wetlands - what's the good of them?

Healthy shoreline wetlands provide many benefits to those who visit, work and live in the Circular Head region of Tasmania, including buffering coastal lands from the effects of sea level rise.

Who lives there?

- Minute bottom-dwelling plants and animals
- Insects
- Sand worms
- Seagrasses
- Snails
- Spiders
- Fish
- Succulent herbs and shrubs
- Grasses, sedges and rushes
- Diverse birdlife, including migratory birds from the northern hemisphere
- *Melaleucas*
- Crabs
- People



What are the benefits of healthy saltmarsh?

1. Saltmarsh builds the land and holds and protects it from erosion

Saltmarsh is a dynamic buffer between land and sea, clinging to soil and protecting it from wave energy. As sea level rises, saltmarsh retreats but continues to protect the retreating edge from more severe erosion.

Snails feed on slime in saltmarshes. Because there are so many snails in saltmarshes, their faeces contribute to building saltmarsh soils.

Tidal channels are an integral part of saltmarsh. They play an important role in reducing wave energy as well as providing living places for sea life.

Saltmarsh soil is formed from trapped sand and mud, and from small pieces of broken-down plant matter.

When waves reach saltmarsh, their energy is reduced, helping to prevent erosion.

Broken off seagrass, sand and shells are deposited onto saltmarshes during storms.

2. Saltmarsh helps to keep the water clean and clear

Saltmarsh helps to keep the water clear by trapping fine particles of mud. These particles also help to build up the soil.

Saltmarsh "filters" water running off the land. It traps dirt, making the water less murky. It also removes excess nutrients & chemicals that would pollute the sea.

3. Saltmarsh is productive in ways that benefit people as well as the environment

Saltmarsh is a primary producer of plant material that feeds sea life.

Saltmarsh is an importnt habitat for resident and migratory birds.

Saltmarsh provides a living place for many plants and animals that are in turn eaten by others including commercial species.

Juvenile fish feed and hide in saltmarsh. Small bottom-dwelling plants called microphytobenthos are major primary producers in saltmarsh ecosystems.

Saltmarsh acts as a "seedbank" for the saltmarsh plant species. Along with other uses beneficial to people, these seeds may be needed to reseed areas where saltmarshes have been lost.

4. Saltmarsh provides a variety of other services from which we benefit, directly or indirectly

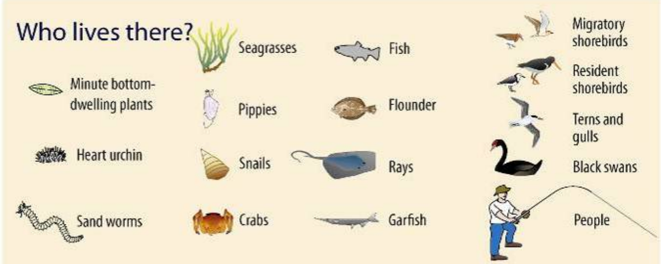
As saltmarsh builds soil partly by accumulating organic matter from the breakdown of plants, carbon is captured and stored.

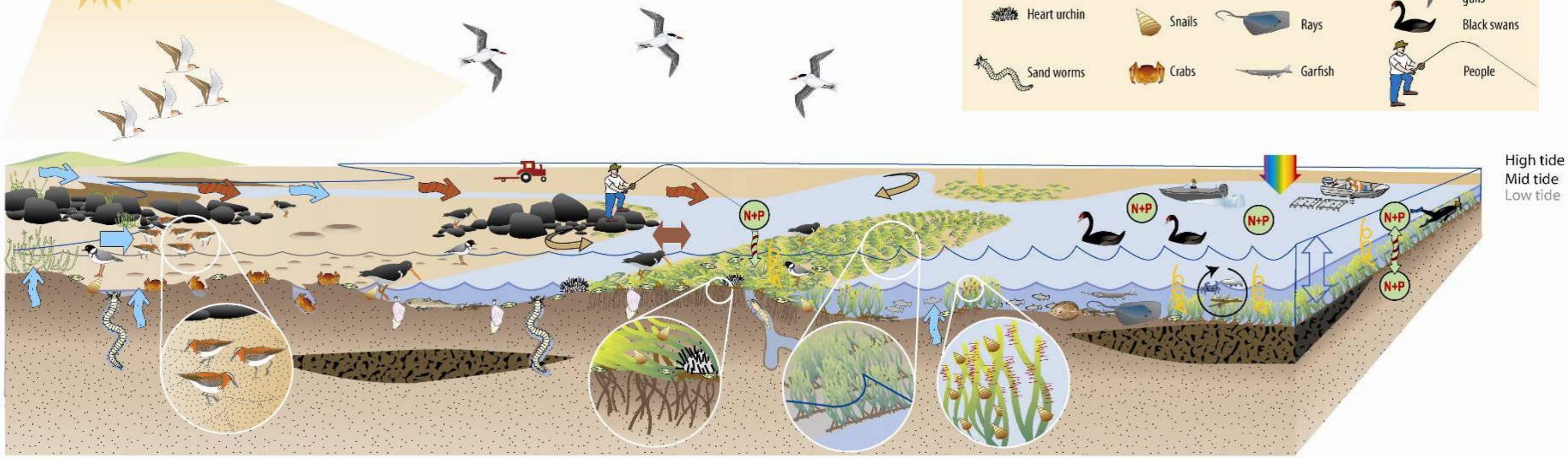
Healthy, productive saltmarshes support human recreational uses such as fishing and tourism.

Created by Blue Wren Group, University of Tasmania for the Cradle Coast Authority. Illustration by Jan Tilden, 2010.

Intertidal seagrass & sand - what do we value?

Healthy intertidal flats are more than just beautiful places to cast a line or go for a stroll.
They are productive areas, providing benefits to people, industry and the environment.





What are the benefits of healthy intertidal flats?

1. Seagrass stabilises the vast areas of intertidal sand and helps prevent erosion

Seagrass roots anchor sand and reduce its tendency to move around with water movement. Areas stabilised by seagrass provide safe living places for other wildlife such as snails and urchins that are part of the food chain of the intertidal flats.

As the tide rises, beds of seagrass in the intertidal zone reduce the energy of wind waves and help prevent erosion.

Predictable water movements and stable sea beds support aquaculture. They also help prevent erosion, benefiting coastal landholders.

2. Seagrass and small bottom dwelling plants are the basis of intertidal foodwebs

Some animals (e.g. snails) feed directly on seagrass. Seagrass also provides a base for other plants (epiphytes) that contribute to intertidal primary production.

Seagrass breaks down to form detritus. This is easier to digest and supports many more animals than direct grazing on seagrass.

Resident and migratory shorebirds forage on wildlife supported by seagrass food webs.

Intertidal foodwebs support human food species along with the plants and animals that these species rely on for their food.

3. Seagrass and sandflats helps to keep the water clean and clear

Seagrass and sandflats remove nutrients from the water and process them in various ways, helping to prevent algal blooms and keeping water clean and clear.

Clear water lets the full spectrum of sunlight to reach the seabed, allowing the growth of bottom-dwelling species that contribute to intertidal foodwebs.

Seagrass traps and filters sediment and absorbs nutrients from land-based activities, helping keep water clean and clear.

Clean clear water supports aquaculture and fisheries.

4. The intertidal flats of Robbins Passage and Boullanger Bay sequester and store carbon

The vast seagrass beds of the intertidal zone continually take in carbon dioxide from the air and the sea and store it by converting it to living plant matter.

Within the sands of far NW Tasmania are peaty deposits that may be remnants of swamps from 20-40 000 years ago. These peaty deposits are storing fossil carbon.

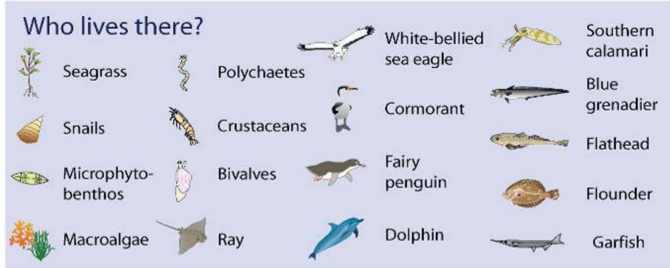
5. The intertidal flats provide social and cultural benefits

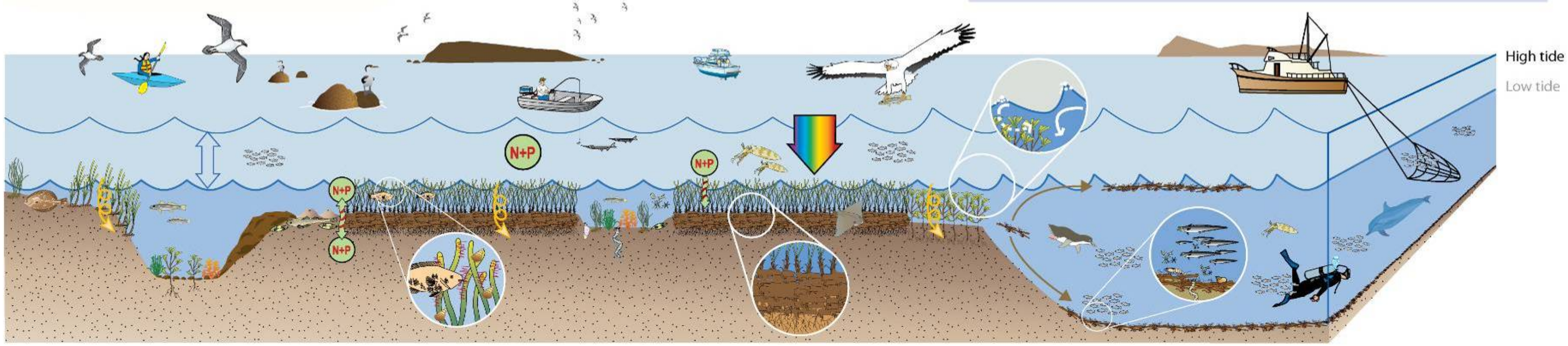
The intertidal flats of Robbins Passage and Boullanger Bay give both locals and tourists a place for recreation, educational opportunities and communing with nature. Thus, these sandy expanses contribute to the region's growing ecotourism industry while supporting local culture and ways of life.

Created by Blue Wren Group, University of Tasmania for the Cradle Coast Authority.
Illustration by Jan Tilden, 2010.
UTAS bluewren Cradle Coast NRM

Subtidal seagrass beds - how they work for us

The healthy seagrass beds of Boullanger Bay have been stabilising the seabed, producing enormous quantities of food, locking away carbon and benefiting people in many ways, probably for over 5000 to 6000 years.





What are the benefits of subtidal seagrass beds?

1. Seagrass stabilises the seabed sand and helps prevent erosion by damping wave energy and responding to sea level rise

Seagrass roots anchor sand and reduce its tendency to move around with water movement. Areas stabilised by seagrass provide safe living places for animals such as fish, worms and crabs.

Seagrasses in the subtidal zone reduce the energy of both swell and wind waves and help prevent erosion.

Seagrasses create and trap sediment and the beds can efficiently adjust upwards with sea level rise.

2. Seagrass and small bottom dwelling plants are the foundation of subtidal foodwebs

A few animals like snails graze directly on seagrass. Most of the grazers, such as fish, feed on algae and phytoplankton that grow on the seagrass.

The massive productivity of the subtidal seagrasses of the perhaps 100,000 tonnes per year or more supports the growth of thousands of tonnes of fish.

Seagrasses shed thousands of tonnes of leaves which bacteria break down into detritus. This makes it easier for animals to digest and is the base of a large food web.

Subtidal foodwebs produce food for people that is important both economically and socially. Catching fish is an important part of the local people's identity.

3. Seagrass helps to keep the water clean and clear

Seagrasses remove nutrients from the water and process them in various ways, helping to prevent algal blooms and keeping water clean and clear.

Clear water allows the full spectrum of sunlight to reach the seabed, allowing the growth of bottom-dwelling species that contribute to subtidal foodwebs.

Moving sediment is trapped by seagrass, helping to keep the water clear.

Clean clear water supports aquaculture and fisheries and recreational pursuits like diving.

4. The vast subtidal seagrass beds of Boullanger Bay sequester and store carbon

Subtidal seagrasses form vast deep root mats where carbon is stored. The seagrasses in Boullanger Bay may have been locking up and storing carbon for over 5000 years.

Rafts of seagrass leaves (wrack) transport thousands of tonnes of carbon to beaches and the surrounding sea floor each year. This contributes to existing carbon reservoirs.

5. A sense of identity

The seagrass, sea, the islands, the channels and the tides are all an important part of what it means to live in this region.

Created by Blue Wren Group, University of Tasmania for the Cradle Coast Authority.
Illustration by Michael Helman, 2010.
UTAS bluewren Cradle Coast NRM

5. Sea level rise effects: mechanisms, evidence and models

This section summarises, firstly, the key concepts and mechanisms used to assess the hazards of sea level rise and, secondly, on-ground observations and synthesis of the same and, thirdly, inundation (coastal flooding) models of sea level rise given current knowledge of future sea levels (i.e. scenarios).

There are many approaches to estimating and predicting sea levels and their rate of change. It is generally accepted that sea levels have changed by hundreds of metres through geological time. There is also strong evidence that there was a "recent" rise in sea level that ended about 6,000 years ago, which inundated formerly dry land and stabilised at the current shoreline. It is fairly obvious that specialist shoreline plants and animals have moved/adapted with those sea level changes. This means that, in general terms, the habitats are fairly robust to sea level changes. However, the current circumstances are different to those previous times of change as there are broad scale human alterations to the land, including along the coast, and a set of people with a mix of values and objectives that may be impacted by sea level changes.

Note: Hazards other than sea level rise are being dealt with elsewhere, firstly, in each section about how habitats function (e.g. nutrient cycling and filtering) and, secondly, within the section summarising other threats and stressors to the coastal habitats (e.g. nutrient enrichment) (see Section 6 Other threats and stressors).

5.1. Sea level rise concepts and mechanisms

Primary Authorship: Chris Sharples

The following concepts and mechanisms have currency in the literature and in the scientific community and have formed key parts of the lens through which the hazard of sea level rise has been assessed for this project.

This section broadly outlines the expected physical changes in coastal landforms that can be expected as a response to sea level rise. Note that additional impacts of sea level rise on coasts – including increased flooding and saline groundwater intrusion – are not discussed here but are outlined in other sections of this report as appropriate.

A considerable body of scientific literature exists on the physical effects of sea level rise on coastal landforms. With the recognition that after over 6000 years of relative stability, eustatic (i.e., global) sea levels have been rising at an accelerating rate through the Twentieth Century (Church and White, 2006), and that this rise is detectable on Tasmanian coasts (Hunter *et al*., 2003), there has been an intensification of research into this issue. Although (as discussed further below) there has as yet been little unequivocal demonstration of coastal landform changes directly attributable to recent global eustatic sea level rise, the processes and impacts of sea-level rise on coastal landforms are well understood. Good evidence of the physical effects of rising sea levels on coastal landforms comes from observations of shorelines where a rise of sea level *relative* to the land has been occurring for millennia due to land subsidence resulting from post-glacial isostatic crustal adjustment (e.g. eastern USA: Zhang *et al.*, 2004). The geological and geomorphic record also provides good evidence of coastal landform changes that occurred during past phases of sea level rise, such as the Last Interglacial phase (circa 125,000 years ago) when global sea levels stood higher than at present, and produced receded shoreline profiles and shoreline erosion scarps that are today observable well above and inland of present sea level in many locations globally, including in the Circular Head district (van de Geer, 1981).

5.1.1. Physical effects of sea-level rise on coastal landforms

The best known formulation of the landform changes to be expected on shores subject to sea level rise is known as "The Bruun Rule" (Bruun, 1954; 1988). In essence this "rule" states that – in the absence of countervailing processes – a shore subject to sea level rise will respond through increased wave erosion of the upper shoreface, and deposition of the eroded debris on the lower shoreface, so as to maintain an equilibrium profile relative to the new (rising) sea level. This occurs because a rise in sea level allows more frequent wave attack on the upper shoreface than previously, resulting in accelerated erosion and landwards recession there, while the rise in sea level also raises the wave base, creating extra accommodation space on the lower shoreface into which the eroded material can settle out.

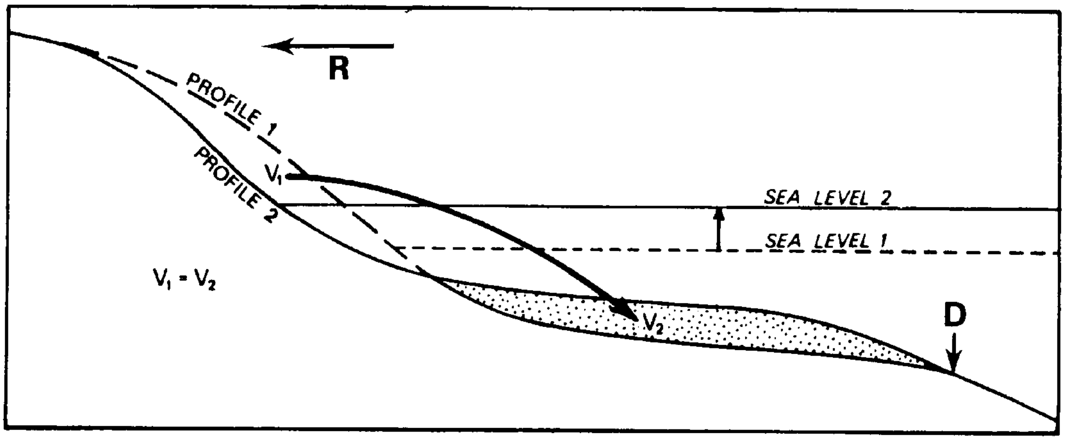


Figure 5.1: The Bruun Rule in its simplest form. From Bird (1993, p.57, Figure 29), whose original caption to this figure reads: "The Bruun Rule states that a sea-level rise will lead to erosion of the beach and removal of a volume of sand (v1) seaward to be deposited (v2) in such a way as to restore the initial transverse profile landward of D, the outer boundary of near-shore sand deposits. The coastline will retreat (R) until stability is restored after the sea-level rise comes to an end. The coastline thus recedes further than it would if submergence were not accompanied by erosion."

This principle has been subject to considerable criticism (e.g., Cooper and Pilkey, 2004), much of which relates to the fact that other coastal processes occurring simultaneously with sea level rise (such as those relating to longshore drift and sediment supply) may over-ride this "Bruun process" and result in quite different outcomes. Indeed, the progradation (seawards growth) of Perkins Island as a result of the post-glacial marine transgression bringing large quantities of sand onshore is a good example of this (see Section 3.1.2). Other critiques of the Bruun Rule relate to its formulation as an equation commonly used by coastal engineers to quantify the degree of erosional shoreline retreat expected to occur as a result of sea level rise. This equation, which is often paraphrased as suggesting that shorelines will most commonly retreat (erode) landwards by a horizontal distance between 50 and 100 times the amount of vertical sea level rise (Bird, 1993), does not by itself model the other coastal processes and landform conditions which may (and usually do) cause greater or lesser amounts of retreat. In addition it is important to note that this formulation of the Bruun Rule is based on the behaviour of open-coast (swell-exposed) sandy shores, and is arguably not applicable to more sheltered or non-sandy shores, such as those which are the subject of this study.

Despite these critiques however, the Bruun Rule embodies an underlying principle which is broadly applicable to a wide range of coastal landform types, on both exposed and sheltered coasts. This is the principle that shorelines will tend towards a profile (shape) which is in equilibrium with the sea level – and other processes including the wave climate and sediment supply – to which it is exposed. It can therefore be expected that, as a general rule, shorelines will tend to erode and retreat landwards as sea level rises, in order to maintain their equilibrium profile. Although some shores will not respond to sea level rise in this way, in such cases it will be because some other process (for example an increased sediment supply) is counter-acting the tendency towards recession.[14] However existing observations of subsiding shores subject to relative sea level rise and interpretation of the geological record of past sea level changes (as noted above), indicates that shoreline recession is generally the dominant response to sea level rise. This has been observed not only on sandy coasts subject to a relative rise in sea level, but also other shoreline types including subsiding saltmarsh shores in eastern USA (e.g., Schwimmer, 2001) and subsiding "soft-rock" (gravelly – clay) coasts in eastern England (Pye and Blott, 2006).

Although the shores of the study area (Boullanger Bay to Duck Bay) have not historically been subsiding (see Section 3.1.1) they have been subject to gradually accelerating eustatic sea level rise over the Twentieth Century (see above and further discussion in Section 5.2 following). There are no processes or conditions known to prevail in the study area that would be likely to significantly counter-act the general tendency towards shoreline retreat with sea level rise that is implied by the Bruun Rule. Indeed, one of the most common processes inhibiting shoreline retreat – an excess sediment supply to the shore – has been demonstrated by this project not to be the case for the study area. Far from being an abundant source of sediment as might superficially appear to be the case, this work has shown the tidal flats of Boullanger to Duck Bay to be mainly an eroded "peat platform" surface of older (Pleistocene) sands and peats, with only superficial tidal reworking of sand stripped from those older deposits. Whilst abundant marine sands transported landwards during the last post-glacial marine transgression piled up to build prograded coastal barriers on Robbins and Perkins Islands, the tidal flats of the study area behind these barriers were essentially starved of this additional sand (see Section 3.1.2) and hence do not now have an excess sediment supply which could counter-act a tendency towards shoreline retreat with sea level rise.

5.1.2. Where are the physical effects of recent sea level rise on coastal landforms evident to date?

Although renewed global eustatic sea level rise has now been in progress for over a century (Church and White, 2006), most open coast swell-exposed sandy

[14] To state – as is sometimes done – that the Bruun Rule is "wrong" because some shores do not behave in strict accordance with the rule (where they are dominated by other processes) is rather like claiming that the Law of Gravity is false because aeroplanes fly in apparent defiance of gravity. Actually, gravity is still operating; its just that in this case other processes (thrust and aerodynamic lift) are dominant.

beaches in south-eastern Australia have yet to show the sort of progressive recession in response to sea level rise that the Bruun Rule predicts. This is attributed to a combination of a significant sand supply from the lower shore face and exposure to a constructive swell wave climate following storms which is still sufficient to return sand to beaches and fully rebuild dune-fronts following erosive storms, thereby masking any underlying effect of sea level rise (Church *et al.*, 2008). It is anticipated that these beaches will only begin receding progressively and irreversibly in response to sea level rise once additional sea level rise has reached a threshold at which storm waves (reaching further landwards on that higher sea level) are eroding beaches and dunes too extensively and too frequently for the constructive swell to fully rebuild them in-between storms. The amount of additional sea level rise required to cross this threshold is as yet unknown.

That said there are arguably some indicators of the physical effects of renewed eustatic sea level rise visible on a few south-east Australian open coast beaches. For example, some beach erosion events have begun to expose old buried palaeosols (fossil soil horizons) and middens in foredune fronts. Even though many of these are later reburied as constructive swell pushes sand back to rebuild the beaches and dunes (as on North Beach, Perkins Island for example), their temporary exposure during storms is indicative of a degree of landwards erosion of the shoreface during storms that has not been seen previously for centuries at the least (i.e., since the original burial of the palaeosols), and hence is suggestive that higher sea levels are allowing storms to more frequently erode dunes further to landwards than has previously been the case. Evidence of progressive (non-rebuilding) sandy shore erosion is also becoming apparent on some open coast beaches exposed to extremely high-energy wave climates (for example, many south-west Tasmanian beaches have now been in a continually erosive state without significant rebuilding for some decades at least: Cullen, 1998), although further study of the causes of this erosion is needed. Some beaches exposed to locally-unusual conditions are also showing signs of responding to sea level rise, as at Roches Beach in south-east Tasmanian which appears to have entered a new progressively-eroding state in recent decades that is likely to be due to the initiation of a sand budget deficit owing to a combination of sea level rise and a strong local longshore drift process (Sharples, 2010).

Despite these examples however, as a generalisation it remains true that most south-east Australian open coast beaches are not yet showing a progressive recession trend that can be clearly attributed to sea level rise. On the other hand, recent field observations in a wide variety of swell-sheltered coastal re-entrants (such as tidal lagoons and estuaries) indicate that recently active fresh progressive erosion scarps are very common in many such places (C. Sharples, personal observations). The widespread occurrence of recent active shoreline erosion in re-entrants (in contrast to the apparent stability of open coast beaches) is suggestive that re-entrant shorelines generally have relatively recently entered a new erosion-dominated phase, for which the most likely apparent explanation is that the physical impacts of sea level rise are indeed affecting re-entrants earlier than is the case on the open coast.

There are good theoretical reasons to expect that swell-sheltered coastal re-entrants should show progressive shoreline recession in response to sea level rise earlier than the open coast does. Such reasons include:

- Tidal re-entrants are connected to the sea (permanently or intermittently), and hence their shores are affected directly by sea level rise;

- Owing to their swell-sheltered locations, re-entrant shores expose many soft erodible substrates including sandy, muddy, clayey, “soft rock”, gravel and peaty types which are susceptible to erosion by even moderate wave action, and hence can be expected to be exposed to more frequent wave-driven erosion as sea-level rises;
- Re-entrants may have considerable fetches of several kilometres or more, across which local wind waves with considerable erosive power may be generated in stormy (windy) weather. However in fair weather re-entrants experience mostly calm conditions with little wave action capable of returning eroded sediment to the shore, in contrast to open coasts which are exposed to constructive swell waves which can return sand to rebuild open coast sandy shores even in very calm weather conditions;
- As a consequence, eroded sandy shores in re-entrants rebuild only very slowly – if at all – after erosion events, since there is generally insufficient fair-weather wave power to return eroded sand to the shore;
- Some re-entrant shores are composed of substrates such as “soft rock” and clayey-gravels which – in contrast to sand – cannot in any case be returned to rebuild the shore after erosion has occurred. These shores do not oscillate around a “dynamic equilibrium” position as may shores capable of rebuilding, but rather they erode progressively and irreversibly. Most such shorelines have already been undergoing slow progressive recession for several millennia under stable sea level conditions, and such recession can be expected to accelerate with sea level rise, which permits local wind-waves to more frequently impact higher on the shore profile;
- Despite the above there are some re-entrant shoreline types that are capable of rapid rebuilding – notably saltmarsh, mangrove and “marsupial lawn” types – and which do so because plant growth in the intertidal zone captures and accretes sediment. Under stable conditions these shores oscillate around a “dynamic equilibrium” position in response to alternating storm erosion and calm weather accretion periods; however with sea level rise the dynamic equilibrium position can be expected to recede landwards;
- Most tidal re-entrants contain large sediment deposits – such as flood-tide deltas and tidal flats – whose morphology (including their lateral extent and depth below water of their upper surfaces) is determined by tidal current flows and wind-wave base depths. As sea level – and hence wave base – rises additional accommodation space is created on top of and around these deposits, which thereby provide a new sink into which additional sediment can be permanently accommodated. That is, sea level rise effectively creates a demand for additional sediment accumulation within the re-entrant which – if sediment supply from rivers or the open coast is inadequate – will be satisfied from erosion of the re-entrant shores. This process – described by the *Flood Tide Delta Aggradation* and *Translation* models - has been extensively studied in the Dutch Wadden Sea and has been described in an Australian context by Hennecke and Cowell (2000);
- Coastal re-entrants typically experience significant tidal current action capable of re-distributing sediment around the re-entrant. This mechanism means that sediment eroded from re-entrant shorelines may be efficiently transported to

sediment sinks (such as those described above), even during calm weather following erosion events. This further reduces the potential for eroded sediment to be returned to eroded shorelines, and instead feeds the sediment demand created in sediment sinks within the re-entrant by sea level rise. With its large tidal range, tidal current transport of eroded sediment can be expected to be a significant process within the study area environment.

Since the study area comprises such swell-sheltered coastal re-entrants, where extensive recently active erosion has been observed, a key aim of this study was to test the hypothesis that sea level rise may be the underlying driver of the observed erosion. If the evidence supports this hypothesis for the study area then this will provide support for the broader hypothesis that swell-sheltered coastal re-entrants are indeed beginning to physically respond to sea level rise earlier and more extensively than open coast shores. The evidence which tests this hypothesis in the study area is described in following sections.

5.1.3. Potential for shoreline recession with recent sea level rise in Boullanger to Duck Bays

Based on the discussions above, there is good reason to expect that the swell-sheltered re-entrant shores of the study area, behind the barriers of Robbins and Perkins Islands, are an environment in which the erosion and retreat of shorelines in response to recent sea level rise might be expected to become apparent earlier than on open coast shorelines. In particular the study area shores do not have an excess sediment supply which could counter-act the general shoreline retreat tendency resulting from sea level rise that is implied by the Bruun Rule, nor are they exposed to swell wave activity that might result in rapid shore rebuilding following erosion events. On the other hand, the study area shores are subject to locally-generated wind waves quite capable of progressively eroding the shores, and any eroded material is exposed to strong tidal currents capable of efficiently removing and depositing them in the increased accommodation space made available in the tidal flats and channels by the rising sea-level.

Significant shoreline erosion was evident in the study area prior to this work. Given that the above factors appear to pre-dispose the study area shores to responding to sea level rise by means of an overall shoreline recession tendency, a key aim of this project was to identify evidence as to the causes of the observed shoreline erosion so as to test the hypothesis that this erosion was indeed a response to sea level rise, or to determine whether other factors were more likely the dominant cause. In order to achieve this it was necessary to identify other factors actually or potentially causing shoreline erosion in the study area, and to determine what sort of evidence might "finger-print" sea level rise as an underlying cause of erosion in the area as opposed to other possible causes. The following sections describe the evidence that has been obtained by this study, which identifies multiple shoreline erosion mechanisms in the study area, but also "fingerprints" sea level rise as the most likely underlying driver of the observed erosion which is facilitated by these other mechanisms.

5.2. *Evidence about sea level changes and their effects in the Circular Head region*

Information on sea levels in the Circular Head region has been drawn from a range of sources. This includes tide gauge, aerial photography, satellite and other sources, with available data becoming sparser on moving back through time. Tide gauge data became available from 1966 onwards and the aerial photography beginning in the 1950s. Higher frequency, although coarser, satellite data became available from the mid 1970s, though more readily from 1990 onwards. Data has also been directly collected during early 2010 by the project team. There is also some dating evidence from the area that extends back circa 30,000 years before present. The evidence is sifted through a series of criteria.

Here, we first present the evidence for sea level rise and then, at the end of this subsection, assess it in the light of earlier parts of the report which describe and document the current understanding of the geomorphic and geological history as well as the environmental history of the individual ecosystems and habitats. Later in this report this evidence will be used in later sections of the report to evaluate the vulnerability of key ecosystem services (benefits) and management objectives and values, also identified in the earlier sections of the report.

5.2.1. Tide gauge measurements at Burnie

The tide gauge station at Burnie, situated 70 kms east of Stanley, provides the most reliable and long term sea level data pertinent to the study area. Records of sea levels at Burnie were obtained for the period between 1966 and 2006 from the National Tidal Facility (NTC) and John Hunter, Antarctic Climate & Ecosystems Cooperative Research Centre (ACECRC) based at the University of Tasmania, Hobart. TasPorts and Burnie Harbour Board are acknowledged for making available these data. The data were analysed to extract the rate and net amount of sea level rise experienced at Burnie. The data indicated a net rise in mean sea level since 1966 by 5.4 cm at a rate of 1.4 mm y^{-1} (Figure 5.1). This rate is consistent with the "Australian average" for the period 1920-2000, estimated to be 1.2 mm y^{-1} (Church *et al*., 2006). The rate is also consistent with a global average 20th century rate of sea-level rise of 1.7 ± 0.3 mm yr^{-1} (Church and White, 2006). Note that the latter rate is estimated to be accelerating at 0.013 ± 0.006 mm yr^{-1}. Additional features of interest in the tidal record are clear annual peaks in winter in most years, and that there are also longer term trends with, for example, sustained higher sea levels through the early 1990s. These episodic or cyclic features are normal and not due to global sea level rise (Pugh, 2004), which is however an additional underlying long term trend evident in the data.

5.2.2. Shoreline mapping: types and erosion status

Primary Authorship: Chris Sharples

Shoreline mapping was undertaken for about 130 km of shore within the study area. The mapping recorded, firstly, the shoreline type and substrate and, secondly, current and recent erosion status. There is a summary of the results at the end of each of the following sections.

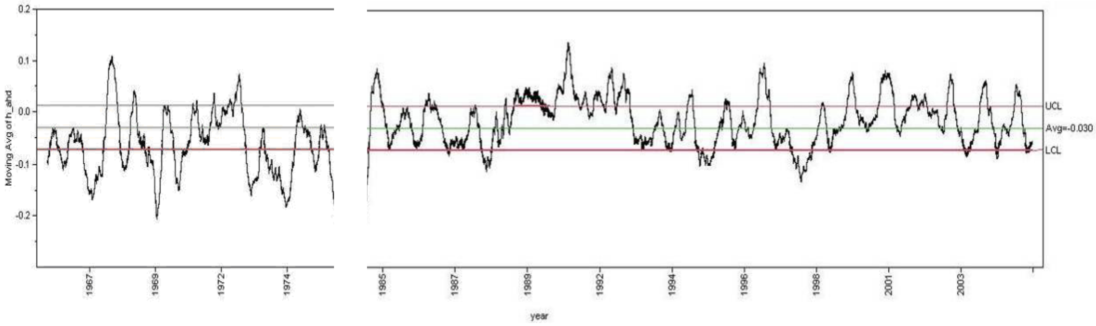


Figure 5.1. Smoothed (moving average) hourly Burnie tide gauge readings **from 1966 to 2006**. There are some gaps on the data record that are not apparent here, the main one between 1976 and 1985.

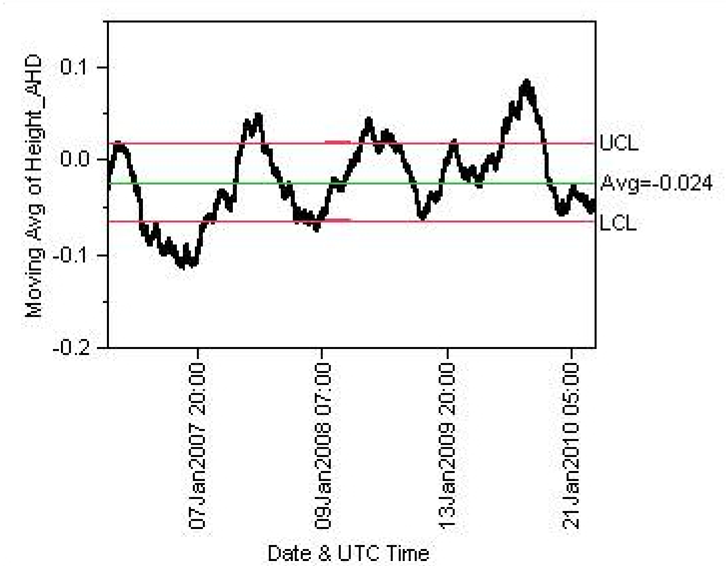


Figure 5.2. Smoothed (moving average) hourly Burnie tide gauge readings **since 2006**, including the time when field work was carried out for this project (January 2010). Note the approximately annual peaks of measured sea level in winter.

Shoreline substrate types

Shoreline mapping (GIS data) accompanying this study classifies the coastal landforms of the study area in two differing but complementary ways, namely:

- **Landform types** and assemblages present were mapped and classified using a multi-attribute system developed for the "Smartline" coastal geomorphic map of Australia (Sharples *et al.*, 2009), which classifies coastal landforms as assemblages of subtidal, intertidal and backshore landform types (A description, data model and data dictionary for this landform classification is fully described in Sharples *et al.*, 2009, copies of which can be downloaded from the Smartline pages at http://www.ozcoasts.org.au). Section 3.1.2 of this report synthesises a description of the landform types mapped in this way for the study area.
- **Shoreline substrate types** were classified by the shoreline features and substrates into which any erosion scarp present is developed, or in the case of stable or accreting shores, into which an erosion scarp would develop if erosion were occurring. This method of characterising shoreline types focuses on only one element of the landform assemblage forming a coast; however it is the element of most interest in studies of coastal erosion and landform change,

and describes that shoreline element in more detail than do the Smartline shoreline type attributes. This section (below) describes the shoreline substrate types mapped in this way for the study area.

Based on field observations throughout the entire study area (excluding Robbins Island, Wallaby Islands and other small offshore islands; see Figure 5.20), shorelines were grouped into mappable substrate type units broadly defined on simple criteria that were readily observable in the field (grainsize, composition and degree of consolidation, podzolisation or lithification). It is important to note that this is a classification of physical substrate types and not a classification of vegetation communities, albeit some substrates strongly correlate with vegetation types (especially in the case of soft clayey-sand marsh soils which are characteristically formed by sediment capture in saltmarshes).

The purpose of the substrate type classification was primarily to group together shoreline types having similar responses to drivers of erosion. Although the differing groups (classes) commonly relate to different origins, this is not necessarily the case – for example podzolised aeolian (wind-blown) sands and podzolised beach ridge sands are lumped together because they constitute shoreline types of similar erodibility despite their differing origins.

The shoreline substrates defined and mapped for this work are briefly described below with some combining of related categories; a complete listing of all the mapped substrate categories is provided in the mapping Data Dictionary (Appendix 2); numerical *erosfeat_n* codes given in the descriptions below refer to the equivalent types listed in the Data Dictionary that were actually mapped in this study.

Note that although significant lengths of the study area shoreline have artificial structures including tyres, concrete-coated wooden poles and sand levees, these are not recorded as the shoreline substrate type except in one case ("soft rock" shore *erosfeat_n* = 200) where the erosion scarp is actually developed in the artificial material. In most other cases[15] where artificial coastal structures are present erosion is occurring in front of (or behind) the structures, in essentially natural substrates which are therefore recorded as the shoreline substrate.

As noted above, the shoreline substrates described here do not represent the whole coastal landform assemblage associated with each shoreline segment, but rather are the substrates generally found at or just above the High Water Mark, where any shoreline erosion that may be occurring will be focused. Throughout most (but not completely all) of the study area, the widely differing shoreline substrate classes described here are typically fronted to sea-wards by extensive tidal sand-flats, and are backed to landwards by a mixture of marshy low-lying ground and slightly higher plains or low hills of Pleistocene wind-blown sand mantling bedrock above sea-level, or extending in depth to below present sea-level. These broader landform assemblages were also mapped and recorded in the "Smartline" geomorphic attributes of the accompanying digital mapping.

[15] Exceptions include some sand levees that have been partly breached by erosion, where the substrate type recorded is still that in front of the levee.

Hard stable bedrock shores

Mapped classes: *erosfeat_n* = 110

A "hard" bedrock shore is here considered to be a dominantly rocky shoreline which is sufficiently hard and erosion-resistant that it is unlikely to exhibit readily apparent erosional change, such as shoreline recession, within a human lifetime (see Figure 5.3). Rocky shores classified as "hard stable bedrock" are also generally characterised by a shoreline slope rising at a moderate angle above the High Water Mark (HWM), such that little if any soil above the HWM is exposed to wave attack during most high-water events. Where hard rocky shores have very low flat profiles such that any saltmarsh or other soils developed over the bedrock platform are exposed to occasional wave attack, then these shores are instead classed as "soft erodible substrates over hard bedrock" (see further below).

Figure 5.3: A hard bedrock shoreline near Cape Woolnorth (*erosfeat_n* = 110).

"Soft rock" shores

Mapped classes: *erosfeat_n* = 120, 200

A "soft" bedrock shore is here considered to be a bedrock shoreline where the bedrock is sufficiently soft (by reason of lithological type, relatively young age or sufficient weathering) that it is likely to exhibit apparent erosional change within a human lifetime, although it will generally exhibit more resistance to erosion than (for example) sand. This difference in erosion resistance is clearly evident in Figure 5.4, which shows a shore of eroding "soft rock" shore overlain by even more erodible sands.

Although “soft rock” shores such as Tertiary-age gravelly clays are common in some Tasmanian coastal re-entrants, no shores have been mapped as a pure “soft rock” (*erosfeat_n* = 120) type within the study area. However some shores on the eastern side of Welcome Inlet were mapped as “Podzolic sands over soft bedrock” (*erosfeat_n* = 122; see Figure 5.4). In these locations, the presence of a soft-rock substrate exposed to shoreline erosion probably reduces the rate at which the overlying sands would otherwise be eroded.

The general category of “soft rock” was also used in this mapping as a convenient category in which to place a few shores composed of artificial “sediments”, in other words, artificial fill. This classification has only been used in a few places where artificial fill comprises a shoreline feature that is currently being eroded, as at just east of the mouth of Scopus Creek (see Figure 5.5) where a gravelly artificial fill forms the shoreline and is responding to wave attack in a similar way to some Tertiary-age gravelly shores elsewhere in Tasmania.

Figure 5.4: At this site on the eastern shore of Welcome inlet, podzolic sands (interpreted as Pleistocene-age wind-blown sands) overlie a soft clayey substrate classified for the purposes of this study as a type of “soft bedrock” substrate (*erosfeat_n* = 120, 122). Van de Geer (1981, p. 98) has interpreted this clayey “soft bedrock” substrate as a Pleistocene-age palaeosol (fossil soil) which in turn overlies older Tertiary-age limestones.

Figure 5.5: Despite this example of creative coastal protection just east of the mouth of Scopus Creek, an active erosion scarp has formed behind the protection in gravelly artificial fill which is classified as a type of "soft rock" (pebble/cobble substrate undiff) for the purposes of this work (*erosfeat_n* = 200).

Erodible saltmarsh substrates

The following substrate classes are distinguished by their high erodibility and the fact they are generally associated with saltmarsh (albeit the peaty sands may also occur under podzolic sands without saltmarsh). These types are found only on swell-sheltered shores in the study area, and not on open coast sites such as Cape Woolnorth and Perkins Island North Beach, where they have either never been able to form (saltmarsh soils) or have long since been eroded away or buried by open coast beach and dune sands (Pleistocene peaty sands).

Despite their high erodibility, the association of these substrates with saltmarsh means that they are also capable of accretion when not exposed to actively erosive conditions, since saltmarsh may colonise to seawards and trap sediment, gradually accreting a saltmarsh soil (as described below) which may repair and ultimately cover earlier erosion scarps.

Clayey-sand saltmarsh soils

Mapped classes: *erosfeat_n* = 300

One of the most common shoreline types in the study area was a light-brownish clayey-sand soil (or sediment) characteristically associated with saltmarsh (see Figure 5.7). This class is a broad field-mapping unit which includes several sub-types described in more detail in Appendix 4 Stratigraphy analysis – Technical Report, where equivalent units include: "medium brown silt"; "silty sand"; and "saltmarsh peat".

This substrate is evidently of recent (Holocene) age and accumulates following saltmarsh colonisation of a site, both as a result of saltmarsh vegetation trapping sediment including sands and clays, and through accumulation of saltmarsh-derived organic debris. Being also easily erodible, this substrate is capable of a type of "cut-and-fill" shoreline behaviour, in that phases of shoreline erosion may be interspersed with non-erosional phases during which saltmarsh re-establishes to seawards of old erosion scarps, and accretes clayey-sand saltmarsh soils until significant rebuilding of the shoreline has occurred (see also Section on Current shoreline stability status classes).

Clayey-sand saltmarsh soils may overlie recent Holocene sands, older Pleistocene sands or peaty sands, or hard bedrock (see below & Figure 5.6). The exposed thickness of this substrate in shoreline erosion scarps within the study area was nearly everywhere less than 0.5 m, reflecting the tidal conditions along the study area shores. Saltmarsh soil is known to accumulate below the high tide mark up to the storm tide mark, which in the study area is about 0.55 m.

Peaty sands (semi-indurated)

Mapped classes: *erosfeat_n* = 400

Black semi-indurated (i.e. somewhat hardened) peaty sands outcrop widely along eroding shorelines in the study area (see Figure 5.8). In some cases this substrate directly supports saltmarsh, although in many cases the black peaty sands are overlain by podzolic sands or Holocene clayey-sand saltmarsh soils. Since saltmarsh tends to accrete sediments and form a soft clayey-sand soil (see above), where saltmarsh sits directly on the peaty sands without significant development of soft clayey-sand soils (as shown in Figure 5.8), it is implicit that such sites have only recently been colonised by saltmarsh so that there has not yet been enough time for a significant accumulation of a saltmarsh soil over the peaty sand (see also *erosfeat_n* = 401 below for cases where saltmarsh soils have indeed accreted over the peaty sands).

Brigid Morrison has undertaken detailed studies of these sediments at several sites during this project (see Appendix 4 Stratigraphy analysis – Technical Report), and has confirmed that they are freshwater (marsh or lake) peat deposits of Pleistocene age (two samples yielded radiocarbon dates circa 26,000 and 37,000 years BP), comparable to peaty Pleistocene freshwater deposits previously found elsewhere in the Smithton region (e.g., by Gill and Banks, 1956).

Although the peaty sands are progressively eroding around many parts of the study shoreline, they are nonetheless considerably more resilient than some other substrates such as sand and the Holocene clayey-sand saltmarsh soils. As a result the peaty sands also outcrop in many places across the tidal flats of the study area, where their semi-indurated nature has allowed them to resist wave action. It is likely that they have played a significant role in constraining the geomorphic evolution of both the tidal flats and the shoreline, and they provide insights into the geomorphic history of the region since the Last Glacial Phase maximum (see Section 3.1.2. Geomorphology).

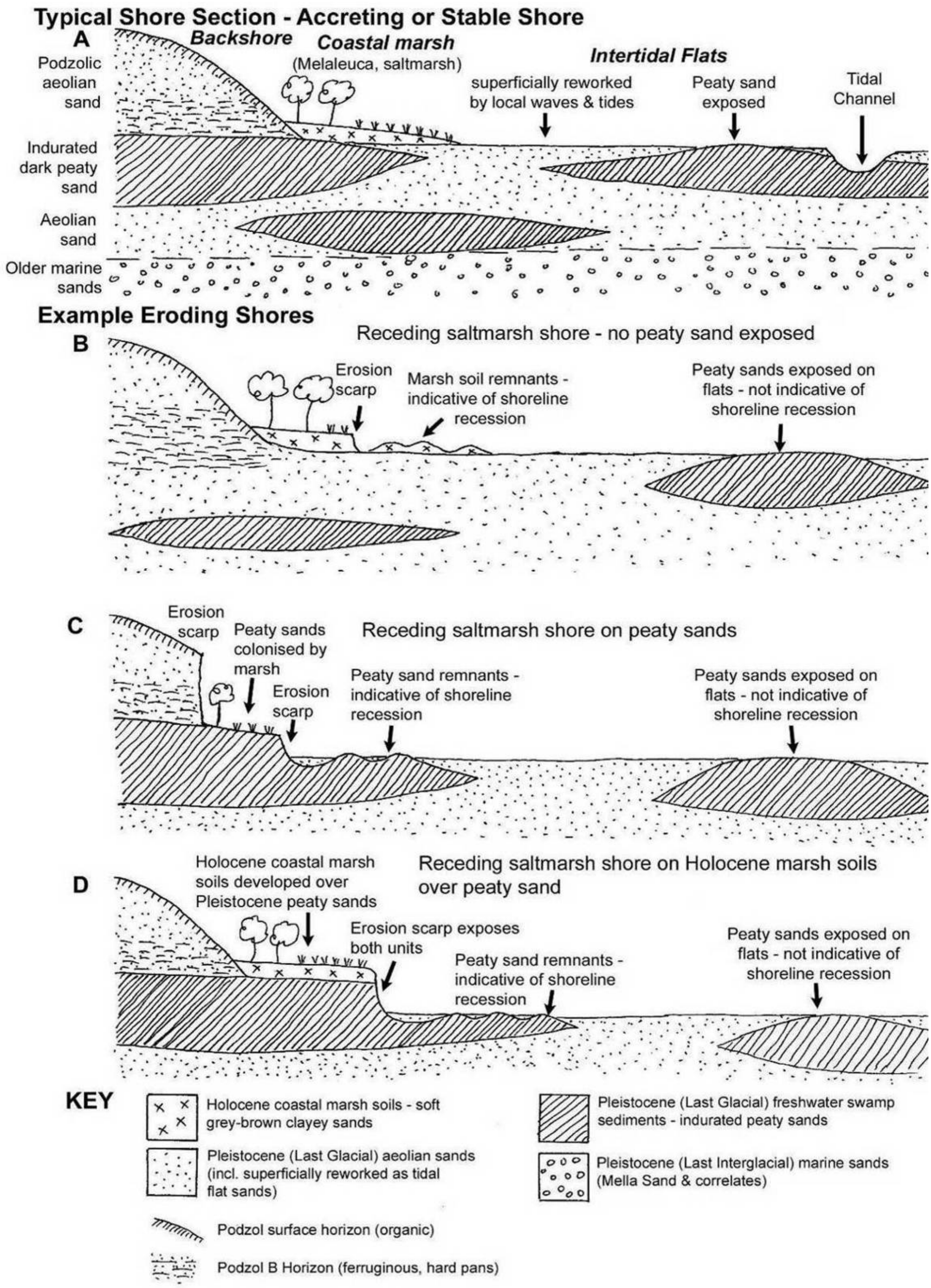


Figure 5.6: Representative examples of some Boullanger – Duck Bay shoreline types found where the present shore is formed in or over Pleistocene sediments, which is the case for many of the shores in the study area. Refer to associated text for further explanation of the illustrated substrates and stratigraphy. Note that these sections are schematic only; they are not drawn to scale and do not necessarily indicate the actual shapes, extents or inter-relationships of peaty sand lenses or beds which may in parts be more laterally extensive than suggested here.

Peaty marsh substrate undifferentiated

Mapped classes: *erosfeat_n* = 500

This minor substrate class is an artificial one that is used in a few places where the shoreline is occupied by saltmarsh over a substrate which is probably either brown clayey-sand (*erosfeat_n* = 300) or peaty sands (*erosfeat_n* = 400), but which has not been clearly differentiated as either.

Clayey-sand saltmarsh soils over semi-indurated peaty sand soils

Mapped classes: *erosfeat_n* = 401

This relatively common composite shoreline substrate type occurs where saltmarsh has been growing on semi-indurated Pleistocene-age peaty sands (*erosfeat_n* = 400) for sufficiently long as to have accreted a substantial thickness of soft clayey-sand saltmarsh soil (*erosfeat_n* = 300) over the peaty sand (see Figure 5.9). Where these shores are eroding, the recession of the softer overlying saltmarsh soil may leave remnants of the more resistant underlying peaty sand as pedestals and exposed platforms on the tidal flats (see Figure 5.9).

Figure 5.7: Soft brown Holocene-age (recent) clayey-sand saltmarsh soils exposed in an actively receding erosion scarp near Montagu Island (*erosfeat_n* = 300).

Figure 5.8: Saltmarsh growing directly on Pleistocene-age black peaty sands of freshwater (swamp or lake) origin (*erosfeat_n* = 400) just west of Sealers Springs. This shoreline is receding on an active erosion scarp; however remnant patches of the basal peaty sands remain exposed on the tidal flats owning to their semi-indurated texture which makes them moderately resistant to erosion.

Figure 5.9 a: Eroding saltmarsh shoreline in western Duck Bay (east end of "The Jam"), showing paler soft clayey-sand Holocene saltmarsh soil developed over dark semi-indurated peaty sands of Pleistocene (Last Glacial) age which the saltmarsh has colonised, but which considerably pre-date the saltmarsh. Figure 5.6 (D) provides an interpretative cross-section of this type of shoreline.

Figure 5.9 b: Soft brown Holocene-age clayey-sand soils (exposed in low erosion scarp at back) over older black semi-indurated Pleistocene-age peaty sands exposed on the tidal flats seawards of this eroding shoreline (*erosfeat_n* = 401). Both units are eroding however the soft overlying soils have receded faster here than the more erosion – resistant peaty sands beneath. The origin of the enigmatic circular structures in the peaty sand, evident here and at other sites in the region, is currently uncertain but may reward further investigations with insights into the Pleistocene environments in which the peaty sands formed.

Soft erodible substrates over hard bedrock

Where hard rocky swell-sheltered shores slope up at only a gentle gradient to landwards, saltmarsh and other vegetation communities have commonly colonised the rocky surfaces, allowing thin soils to accumulate over the bedrock within the range of occasional wave erosion. Many of these soils are exhibiting noticeable erosion now – even though their underlying bedrock platforms are not – and may be more frequently exposed to erosion as sea-level continues to rise in future. These substrates are therefore classed as a special case of erodible shorelines. Two classes of this sort have been recognised and mapped in the study area, as follows:

Soft clayey-sand saltmarsh soil over hard bedrock

Mapped classes: *erosfeat_n* = 111

Where saltmarsh has colonised low-profile hard rock surfaces, similar light brown clayey-sand saltmarsh soils to those found elsewhere in the region may accumulate as thin veneers over the bedrock (see Figure 5.10).

Undifferentiated soils over hard bedrock

Mapped classes: *erosfeat_n* = 119

Other sandy or loamy soil types may occur over bedrock beneath non-saltmarsh vegetation types, within sufficient proximity to the HWM as to be occasionally eroded by storm wave action. These have been mapped as a lumped "undifferentiated soils over hard bedrock" shoreline substrate class (see Figure 5.11).

Figure 5.10: At this location a short distance west of Robbins Island Crossing, soft brown clayey-sand saltmarsh soils have accumulated directly over a low-profile hard bedrock surface which repeatedly protrudes above sea-level along this shoreline, for example in the middle distance shown here (*erosfeat_n* = 111). Although the underlying hard rock platform is unlikely to erode significantly within the next century or so, the soft saltmarsh soils here are eroding, hence this is regarded as an "eroding" shore rather than a "stable" shore as would be the case if the bedrock surface rose more steeply.

Figure 5.11: This site at Stony Point has non-saltmarsh soils developed over a rocky platform (*erosfeat_n* = 119). Since some intermittent soil erosion is occurring on this shoreline (central part of visible vegetation margin) the erosion status of this site has been classified as intermittently eroding (see Section 5.2.2. Shoreline mapping: types and erosion status), rather than as a purely stable shoreline which would be the case if the hard bedrock exposed in the intertidal zone rose more steeply above the High Water Mark.

"Cut and fill" shoreline substrates (non-saltmarsh)

Apart from some saltmarsh shoreline substrates (as described above), this group of substrates are the other main group of shorelines that are characterised by a capacity for "cut-and-fill" behaviour, which is the capacity to rebuild their profiles following storm erosion events. In contrast to saltmarsh shores, which are a dominant type capable of shoreline rebuilding within sheltered coastal re-entrants such as the study area, the types described below are characteristically "active" landforms on open coast sandy or cobble shorelines, where storm waves quarry material from the upper shore face and dump it lower down, following which constructive fair-weather swell waves can return eroded material to the upper shore after storms. However in a few cases sandy shores exposed to large wind-wave fetches within the Duck Bay coastal re-entrant appear to also exhibit a limited scale of cut-and-fill behaviour.

Because these shoreline types occur mostly on open swell-exposed coasts, they have mostly been mapped in the present project only in a few places where the shoreline mapping was – for no particularly good reason – extended out of the swell-sheltered study area to adjacent open coasts at Cape Woolnorth and Perkins Island. Nevertheless as noted above minor examples do occur and were mapped on swell-sheltered shores within the study area proper at Duck Bay.

Sand foredunes

Mapped classes: *erosfeat_n* = 701

Sandy foredunes are shore-parallel sand ridges formed by accumulation of sand blown from a beach or tidal flat and trapped by vegetation above the High Water Mark (Hesp, 2002). Foredunes are recent (currently "active") landforms characteristic of open swell-exposed coasts.

They are subject to episodic storm wave erosion followed by swell-driven beach rebuilding which in turn supplies sand for dune rebuilding (the cut-and-fill cycle). Foredunes along North Beach (Perkins Island) exemplify such "classical" foredunes (see Figure 5.12).

However minor occurrences of sand foredunes occur in more unusual circumstances southeast of Cape Woolnorth (where sand foredunes back stony shingle beaches, but are assumed to capture sand blown from sandy tidal flats at low tide; see Figure 5.13) and in a few swell-sheltered locations in north-east Duck Bay where low "incipient" foredunes were mapped behind narrow sandy beaches fringing the sandy tidal flats.

Foredunes are composed of loose unpodzolised (and thus uncemented) sands reflecting their frequent active reworking in "cut-and-fill" cycles, hence are both highly susceptible to erosion yet capable of being rebuilt following storm erosion. Foredunes thus tend to maintain a dynamic equilibrium with the prevailing sea level and storm climate. As such, foredunes are expected to progressively migrate inland with sea-level rise, however such progressive migration may be at least partly masked by the episodic "noise" of the cut-and-fill cycle.

Beach ridges

Beach ridges are shore-parallel ridges formed by wave swash on the upper beach face, and may be composed of cobbles, pebbles, sand or shelly material. Examples of cobble-pebble (shingle) and shelly-sand beach ridges occur within the study area as described below:

Pebble-cobble (shingle) beach ridges

Mapped classes: *erosfeat_n* = 210

Basaltic shingle (pebble-cobble) beaches predominate in the swell-exposed stretch of coastline between Cape Woolnorth and Shoal Inlet, on the margins of the study area. These shores imply southwards swell-driven longshore transport of cobbles from offshore basalt islands, since the underlying bedrock types actually outcropping along the shingle beach shores are Precambrian metamorphosed sedimentary rocks, not basalt. Whereas some of these shingle beaches are backed by sandy foredunes (as noted above), others are backed by low wave-deposited shingle beach ridges (see Figure 5.14). These are susceptible to erosion in large storm surges but may also be rebuilt by slightly less energetic swell wave action. Although a minor feature of the study area, most shingle beach ridges north of Shoal Inlet were showing evidence of erosion when inspected in January 2010.

Sand & shelly beach ridges

Mapped classes: *erosfeat_n* = 702, 705

Although most of Perkins Island and the Anthony Beach coastal barrier are constructed of older ("fossil") Holocene-age beach ridges that prograded (accumulated) rapidly seawards after the post-glacial sea levels stabilised circa 6,500 years BP (see Section 3.1.2), currently active sandy beach ridges were only observed in one location within the study area, namely in the form of a shelly-sand beach ridge immediately north of Shell Pits Point in eastern Duck Bay. Although sheltered from open coast swells (which most commonly produce beach ridges), this shelly beach ridge is exposed to a very long westerly fetch across Duck Bay, which evidently produces local wind-waves sufficient to wash up a shelly sand beach ridge at this one location (see Figure 5.15). This beach ridge was in a partly eroded state when observed during January 2010, but can be expected to be rebuilt by moderate wave action.

Figure 5.12: This Holocene-age (recent) sand foredune (*erosfeat_n* = 701) backing North Beach on Perkins Island is typical for an open coast swell-exposed beach. The foredune shows evidence of the cut-and-fill cycle to which open coast foredunes are subject, in that a fresh incipient dune composed of sand blown off the beach face is starting to rebuild the base of large slumped erosion scarp which resulted from a recent major storm erosion event.

Figure 5.13: This sandy foredune (*erosfeat_n* = 701) is – apparently anomalously – situated at the back of a swell-exposed stony cobble (shingle) beach south-east of Cape Woolnorth. Although Pleistocene podzolic sands do occur further inland, the most likely source of sand to have built this foredune is probably the sandy tidal flats that are exposed below the cobble beach at low tide.

Figure 5.14: This pebble-cobble (shingle) beach ridge (*erosfeat_n* = 210) backing a swell-exposed cobble beach a few kilometres south-east of Cape Woolnorth is showing signs of recent erosion. Beach ridges such as this are built by storm wave action, and may rebuild after erosion; it is unclear whether sea-level rise has yet reached a threshold at which this shoreline will continue to progressively erode, or whether rebuilding of this beach ridge will occur.

Figure 5.15: A shelly sand beach ridge (*erosfeat_n* = 705) backing the shelly sand beach on the eastern side of Shell Pits Point (eastern Duck Bay) is an unusual shoreline substrate for a swell-sheltered re-entrant such as Duck Bay, however in this location a very long westwards fetch probably produces sufficient wind-wave exposure as to create this beach ridge.

Other sand shores

These shorelines comprise sandy shorelines which are not actively prograding or maintaining a dynamic equilibrium (like the foredune and beach ridge shores described above), but rather are composed of "inactive" or fossil sandy landforms, deposited in the past under different conditions, and today exposed along swell-sheltered coastal re-entrant shores subject to progressive erosional recession (at rates which may vary from negligible to rapid). These shores are highly erodible but are not capable of rebuilding after erosion as swell-exposed open coast foredunes and beach ridges may do; rather they are subject to unidirectional progressive erosional recession only, albeit the recession may occur more or less episodically.

Podzolic sands

Mapped classes: *erosfeat_n* = 600

Podzolic sands are those sand deposits which were deposited sufficiently long ago that they have a well-developed podzolic soil profile, typically comprising a well-developed dark surface organic (humus) horizon over a very pale leached A2 horizon which in turn overlies an iron-enriched B-horizon coloured and more or less cemented by brown ferruginous precipitates and other materials (see Figure 5.16 & Figure 5.17).

Podzolic sand shores are the most widespread eroding shoreline type in the study area after saltmarsh soils. At least two distinct types and ages of podzolic sands occur along the study area shorelines, but are lumped together into a single class for the purposes of shoreline erosion substrate mapping (based on their similar sedimentary character and response to coastal erosion processes). These are:

Holocene beach ridge deposits

Found on Perkins Island and the Anthony Beach barrier NE of Duck Bay, these are sand beach ridge deposits which accumulated as the shoreline rapidly prograded (grew) following the end of the post-glacial marine transgression circa 6,500 years BP (see Section 3.1.2). With an age no greater than 6,500 years BP, these show moderate podzolic profile development and only weak B-horizon cementation (see Figure 5.16).

Pleistocene windblown sand deposits

Exposed on many parts of the mainland shoreline from Duck Bay to Boullanger Bay, these are sand deposits interpreted as being very old wind-blown (aeolian) sands deposited around the coldest and most arid part of the Last Glacial climatic phase (see Section 3.1.2). The sands have not been dated directly but in some places overlie peaty sand freshwater deposits dated at circa 27,000 and 37,000 years BP (see Appendix 4), and hence were probably deposited sometime in the latter part of the Pleistocene between circa 25,000 to10,000 years ago. These sands are thus significantly older than the Holocene beach ridge podzolic sands (above), and they exhibit a correspondingly greater degree of podzolic profile development. This is expressed most notably as a very darkly coloured and strongly cemented ferruginous B-horizon (see Figure 5.17) which is likely to make these sands a little more resistant to coastal erosion than the Holocene podzols.

Podzolic sands over soft bedrock or semi-indurated peaty sands

Mapped classes: *erosfeat_n* = 122, 402

As noted above, the older (Pleistocene) podzolic sands commonly overlie Pleistocene freshwater peaty sand deposits. Where the peaty sands occur alone at the shoreline they are mapped as a simple type (*erosfeat_n* = 400), however where they are exposed at the shore but overlain by podzolic sands they are mapped as a combined type (*erosfeat_n* = 402) whose lower (peaty sand) component is significantly more indurated and resistant to shoreline erosion than is the overlying podzolic sand unity (see Figure 5.18).

A minor related type occurs on the eastern shores of Welcome Inlet, where Pleistocene podzolic sands overlie a soft clayey palaeosol classified for the purposes of this mapping as "soft bedrock" overlain by podzolic sands (*erosfeat_n = 122*; see Figure 5.4 & related description above). Despite being classified as "soft" bedrock, the underlying units – like the underlying peaty sands elsewhere – shows greater erosion resistance than the overlying podzolic sands.

Other sands undifferentiated

Mapped classes: *erosfeat_n* = 700

Another minor type within the study area, this mapping category comprises young (Holocene) sands previously mobilised in transgressive dunes from "blowouts" in older Holocene beach ridge deposits to seawards on the Anthony Beach Barrier. These mobilised sands have themselves subsequently stabilised in geologically-very recent times and are now exposed to shoreline erosion on the north-east shore of Duck Inlet (see Figure 5.19). These sands are differentiated as an erosion substrate by being loose highly-erodible recent sands without notable podzolic profile development (like foredunes), but by not being capable of rebuilding after wave erosion (unlike foredunes). Instead, like podzolic sand shores they are subject to progressive shoreline erosion (at rates which could vary from negligible to rapid) within a swell-sheltered coastal re-entrant environment.

Figure 5.16: A podzolic profile in Holocene-age beach-ridge sands just west of Shell Pits Point in Duck Bay (*erosfeat_n* = 600). Whilst this degree of podzolic profile development suggests at least several thousand years of stability and leaching prior to the current phase of active shoreline retreat, the degree of podzolisation (A2 leaching and B-horizon development) displayed here is significantly less than in the much older Pleistocene-age sands found exposed on some shorelines in the study area (see Figure 5.17), with weaker colouration and cementation of the B-horizon.

Figure 5.17: A good example of a well-developed podzolic profile in Pleistocene-age aeolian sands exposed in an erosion scarp on the eastern side of Welcome Inlet (*erosfeat_n* = 600). In contrast to the lesser degree of podzolic profile development in the younger Holocene sands illustrated above, this rather older Pleistocene podzolic sand exhibits a thick and strongly leached white A2 horizon over a dark well-developed B horizon with strong iron-cementation. Some peaty sand blocks in front of the erosion scarp suggest this profile sits on a peaty sand deposit; however this has not been confirmed at this site.

Figure 5.18: This well-podzolised Pleistocene-age aeolian sand at Sealers Springs is exposed in an active erosion scarp over a semi-indurated peaty sand horizon of freshwater (swamp or lacustrine)

origin (*erosfeat_n* = 402). The greater induration of the peaty sand results in remanent patches resisting wave erosion for longer as the softer podzolic sands recede further to landwards.

Figure 5.19: These recently-deposited Holocene-age (young) sands exposed in Duck Bay on the south side of the Anthony Beach barrier are not foredune sands nor do they yet show visible signs of podzolisation (leaching and iron - colouration and cementation of B-horizons). These currently-eroding sands are probably recently-deposited transgressive dune sands previously mobilised by wind-erosion of Holocene sand beach ridges, and are lumped as a "sands undifferentiated" substrate (*erosfeat_n* = 700) for the purposes of this study.

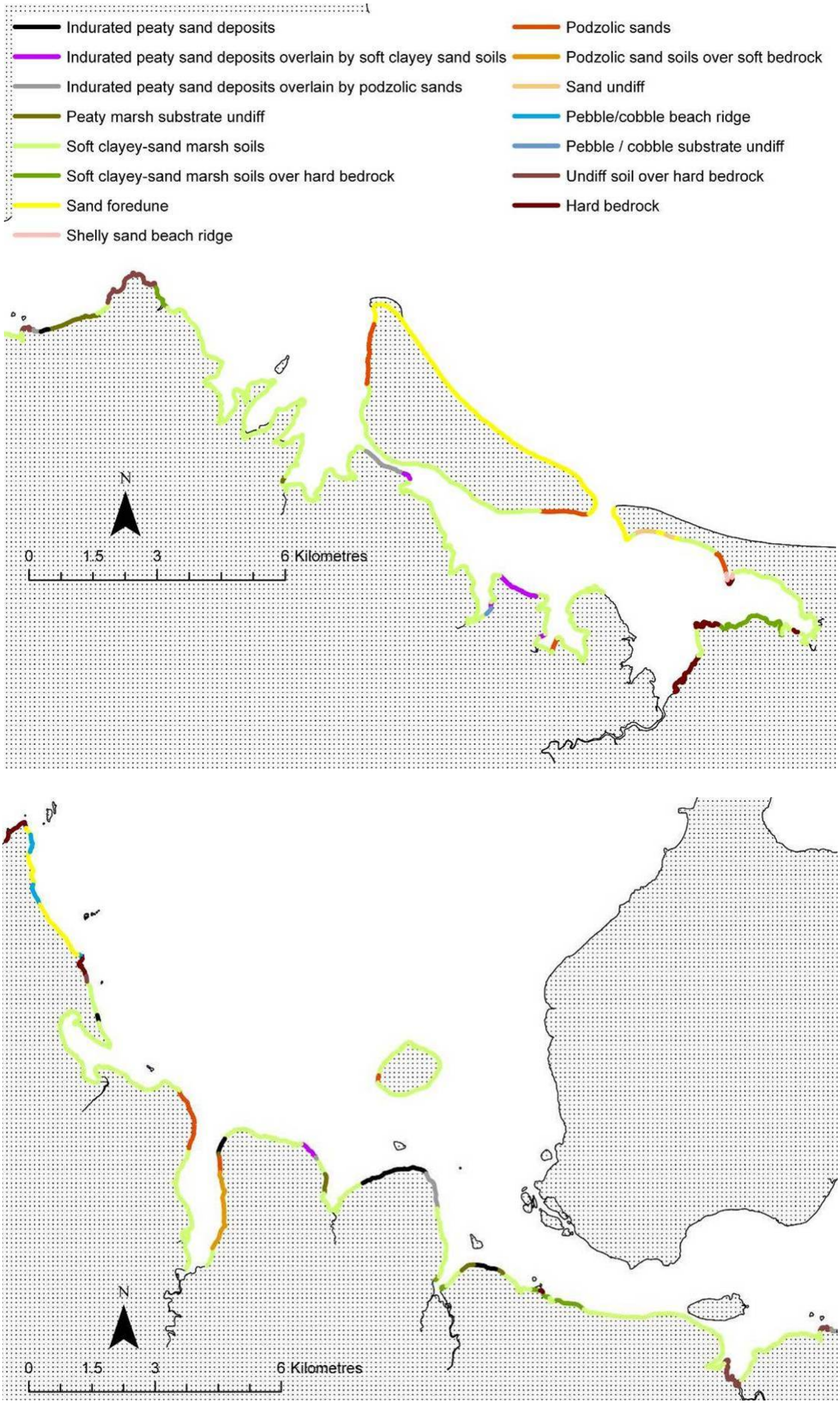


Figure 5.20. Shoreline substrate types mapping of the study area. Map above shows the Duck Bay and Big Bay areas while the map below shows the Boullanger Bay and Robbins Passage areas.

Shoreline type summary

About 129 km of shoreline within the study area, including Perkins Island and Kangaroo Island, excluding Robbins Island, Wallaby Islands and other small offshore islands were mapped (see Figure 5.20). Of these, a 7.3 km section from Pelican Point to Smithton was not mapped and thereby considered unclassified. The classification of the remaining sections of the shoreline, their respective length and relative dominance within the study area is provided in Table 5.1.

Table 5.1. Grouped shoreline substrate type classes with their respective *Erosfeat_n*, length and relative dominance within the study area (in terms of % of the total shoreline).

Shoreline Type Group	Numerical codes (*Erosfeat_n*)	Length (m)	% of the total shoreline
Dominantly erodible saltmarsh soil substrates	121 300 400 401 500	85,314	70.1%
Soft erodible substrates over hard bedrock	111 119	8,133	6.7%
"Cut and fill" shorelines – foredunes and beach ridges	210 701 702 705	13,182	10.8%
Other sands (including older podzolic beach ridge or aeolian sand sheet deposits)	112 122 402 600 700	10,655	8.7%
Dominantly soft rock shores	120 129 200	178	0.1%
Dominantly hard stable bedrock shores	100 110	4,240	3.5%

Current shoreline stability status classes

Comprehensive field mapping was used to classify and map shoreline stability status for almost all of the study area shoreline, with the exception of Shoal Inlet and a short section from Pelican Point to Smithton (excluding Robbins Island, Wallaby Islands and other small offshore islands; see Figure 5.34). "Shoreline Stability Status" or "Condition" here refers to whether a shoreline is physically stable or changing by means of erosion or accretion.[16]

A classification of shoreline stability status was developed for the study area, based on observations of patterns evident in the study area. As such it is not necessarily transferable to other regions or other shoreline types. This classification distinguishes shorelines according to both their spatial and temporal patterns of erosion insofar as these can be observed or confidently inferred. The *primary* aim is to record current erosion status without necessarily inferring whether erosion or accretion is progressive and non-reversing, or cyclic (e.g., a cut-and-fill cycle). However where clear evidence of cyclic erosion, accretion is visible (e.g., old erosion scarps behind current accretion) or can be confidently assumed (e.g., sandy foredunes on swell-exposed coasts), then these are classified as having "temporally intermittent erosion" status.

The shoreline stability status classes defined and mapped for this work are briefly described below with some combining of related categories; a complete listing of all the mapped status categories is provided in the mapping Data Dictionary (Appendix 2); numerical *status_n* codes given in the descriptions below refer to the equivalent types listed in the Data Dictionary that were actually mapped in this study.

Actively eroding shores, continuous (no accretion)

Mapped classes: *status_n* = 120

Substantial stretches of shoreline (several tens of metres length or more) with spatially continuous active erosion scarps and no notable intermittent stable or accreting sections. This class is indicative of ongoing progressive shoreline retreat with no current intermittent stability or accretion.

Active erosion scarps are indicated by fresh vertical scarp faces, under-cut scarp faces in soft substrates which are likely to collapse in the near future, recently collapsed scarp blocks and debris which are likely be broken up and removed by wave action, and by a lack of any signs of accretion or shoreface rebuilding (e.g., accreting secondary saltmarsh or incipient foredunes).

Continuous actively eroding shores were most commonly observed in saltmarsh substrates (Figure 5.21) and podzolic sand scarps (Figure 5.22).

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[16] *NOTE re "accretion'*: In this classification, 'accretion' refers to horizontal accretion (or progradation) only, not to vertical accretion. Whilst horizontally accreting shores are generally vertically accreting as well, there are also some horizontally receding saltmarsh shores in the study area that are vertically accreting too (overwash sediment is being deposited on the saltmarsh behind the erosion scarp).

Figure 5.21. A continuous actively eroding scarp in soft clayey-sand saltmarsh soil near Pelican Point (*status_n* = 120). A vertical scarp face and recently collapsed soil blocks not yet broken up by wave action are indicators of actively ongoing erosion. When photographed at close to high tide, near-shore turbidity at this site was indicating that the relatively small wind-waves seen in this photo were actively eroding the exposed saltmarsh soil.

Figure 5.22: Part of a long continuous actively eroding podzolic sand scarp on the south-eastern shore of Perkins Island (*status_n* = 120); indicators of active erosion include the fresh vertical face in soft friable sand, and the recently collapsed soil slabs which will be broken up by wave action but were still intact when inspected.

Dominantly actively eroding shores (with sub-ordinate stability or accretion)

Mapped classes: *status_n* = 211, 231

These classes describe substantial stretches of shoreline (tens of metres or more) dominated by actively eroding shores (as described above), but with minor accretion or stability exhibited either in a spatially intermittent distribution along the shore (*status_n* = 211, Figure 5.23), or in a temporally intermittent fashion indicated by minor accretion in front of recently active erosion scarps (*status_n* = 231, see example in Figure 5.24).

The spatially intermittent type (*status_n* = 211) may be indicative of predominantly ongoing progressive shoreline retreat but with less consistent exposure to drivers of erosion than is the case with continuous actively eroding shores. The temporally intermittent type (*status_n* = 231) may be indicative of episodic progressive shoreline retreat where it occurs in a swell-sheltered coastal re-entrant environment (e.g., Figure 5.24), but where found on open swell-exposed coasts (e.g., minor recent incipient dune accretion following foredune erosion) it may be merely a stage in a cyclic cut-and-fill shoreline process.

Figure 5.23: An example of dominant but spatially-intermittent erosion (*status_n* = 211). This shore on the southern side of Perkins Island has a low but mostly continuous active erosion scarp in soft saltmarsh soils, however a few short shoreline stretches – for example in the middle of this photo – are exhibiting current accretion.

Figure 5.24: An example of dominant but temporally-intermittent erosion (*status_n* = 231). This example, in podzolic Pleistocene aeolian sands on the south side of The Jam, shows a relatively fresh erosion scarp currently fronted by minor fresh vegetation growth indicative of recent accretion.

Intermittently eroding shores (with spatially or temporally intermittent accretion)

Mapped classes: *status_n* = 130, 210, 212, 220, 221, 230, 232, 235, 240

This group of shoreline status classes is characterised by indications of intermittent rather than continuous active shoreline erosion, implying that these shores are only marginally or intermittently exposed to drivers of erosion. In contrast to "dominantly actively eroding with sub-ordinate stability or accretion" (above) and "dominantly accreting shores with sub-ordinate erosion" (below), these classes are generally indicative of roughly comparable exposure to both erosion-driving and accretion-allowing conditions, interspersed either spatially or temporally. Several important sub-classes have been lumped into this broad category:

Spatially intermittent eroding shores are those exhibiting active or inactive erosion scarps interspersed alongshore with stable or accreting shoreline sections, on scales of the order of 10 metres or so alongshore. These types include classes *status_n* = 210, 212, 220, 221 & 240. An example is illustrated in Figure 5.25.

Temporally intermittent eroding shores are those exhibiting evidence of being subject to periods of active erosion interspersed with periods of stability or accretion. This is typical of the "cut-and-fill" process exhibited by open-coast swell-exposed sandy beaches and foredunes as a result of exposure to episodic erosional storms interspersed with long periods of swell-driven beach rebuilding and incipient dune accretion (Figure 5.26). A similar process can affect cobble beach ridges. However swell-sheltered saltmarshes can also rebuild following periods of erosion, since the saltmarsh plants both trap sediment and accumulate organic debris; this shoreline behaviour is indicated by the presence of old inactive erosion scarps fronted by accreting secondary saltmarsh (Figure 5.27). These styles of temporally intermittent erosion classes include *status_n* = 230, 232 and 235.

A further style of temporally intermittent erosion is that exhibited by spatially continuous or intermittent inactive erosion scarps (*status_n* = 130, 220, 221) without active indications of accretion. This indicates only occasional exposure to drivers of erosion, but without a strong tendency towards accretion during intervening stable periods. Indicators of inactive erosion scarps include slumped or rounded over scarps, typically with some degree of scarp revegetation (see Figure 5.28).

Some shores show a complex interplay of spatially and temporally intermittent erosion, for example the shoreline status classes' *status_n* = 220, 221 & 240 (see Figure 5.29).

Figure 5.25: An example of spatially intermittent erosion on the western shore of Acton Bay, showing low active erosion scarps in soft saltmarsh soil interspersed along-shore with actively accreting saltmarsh sections (*status_n* = 210, 212).

Figure 5.26: An example of temporally intermittent erosion on Perkins Island, illustrated by a large old foredune erosion scarp (rear of photo) fronted by an actively accreting incipient foredune (*status_n* = 230).

Figure 5.27: In this example of temporally intermittent saltmarsh erosion in Duck Bay, an old inactive erosion scarp in soft clayey-sand saltmarsh soil (over semi-indurated peaty sand) is fronted by currently – accreting secondary saltmarsh (*status_n* = 230).

Figure 5.28: This spatially continuous inactive erosion scarp (*status_n* = 130) in soft saltmarsh soil, located west of Welcome Inlet, is partly revegetated and not currently eroding, but is also not exhibiting current accretion. This is a style of temporally intermittent erosion characterised by episodic erosion without intervening phases of saltmarsh accretion.

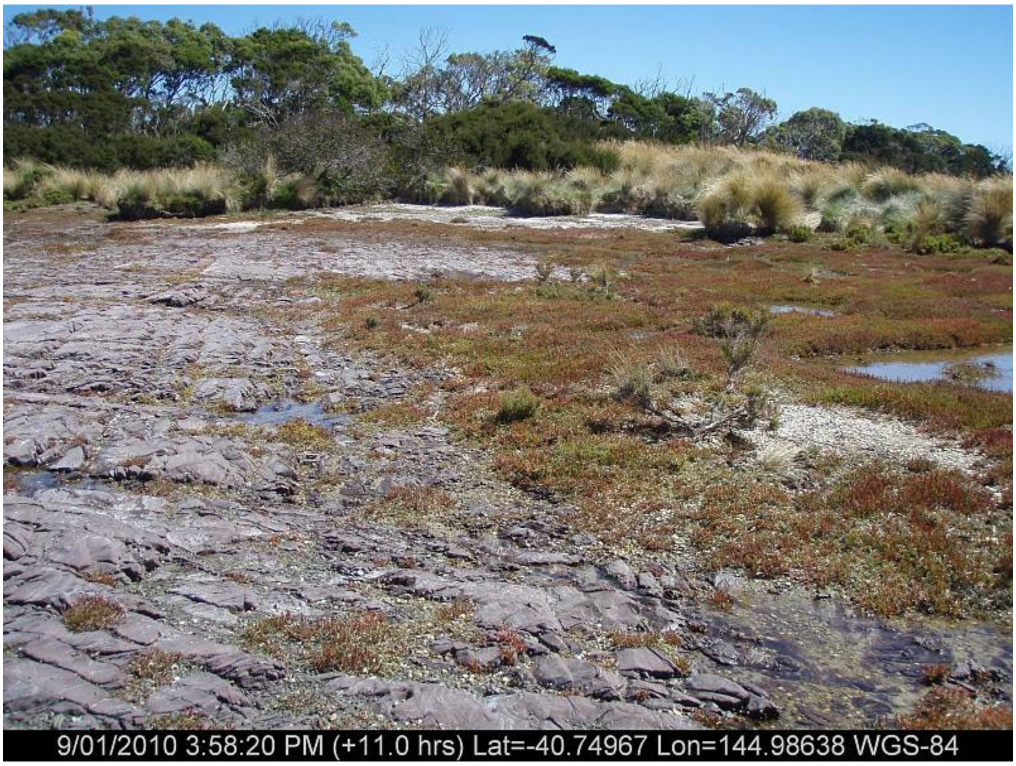

Figure 5.29: Spatially and temporally intermittent erosion (i.e., currently inactive spatially intermittent scarping, *status_n* = 220) of a thin veneer of saltmarsh soil at the back of a low profile hard rock platform with intermittent accreting saltmarsh is visible at this site on the eastern side of Stony Point.

Stable shores

Mapped classes: *status_n* = 300, 400

The class of stable shores is primarily intended to identify hard rock shores that are resistant to erosion and unlikely to show significant physical changes over human life-spans (class *status_n* = 400; see Figure 5.30). The immediate backshore behind many rocky shores typically rises above sea level at a moderate gradient so that only very limited erosion of coastal soils is likely with sea-level rise.

Note however that at some locations in the Circular Head region, rocky shore platforms are immediately backed by low gradient rocky terrain supporting patchy development of saltmarsh and associated soils above the High Water Mark; these shoreline environments are potentially susceptible to saltmarsh erosion with sea-level rise, and where this is occurring they are classified into an appropriate class of eroding shoreline (e.g., see Figure 5.29 above).

A class of "stable soft shore" has also been used in a very small number of cases where soft (sandy or saltmarsh) shores were not clearly showing any indicators of either erosion or accretion (*status_n* = 300)

Figure 5.30: This stable hard bedrock (Precambrian basalt) shoreline at Shell Pits Point (NE Duck Bay) is unlikely to exhibit noticeable shoreline recession within human lifetimes (*status_n* = 400). Since the backshore terrain rises significantly above sea-level, erodible saltmarsh soils are also not present over the bedrock on this shore.

Dominantly accreting shores (with sub-ordinate intermittent erosion)

Mapped classes: *status_n* = 213, 223, 233

These classes describe substantial stretches of shoreline (tens of metres or more) currently dominated by active accretion , but with minor erosion exhibited either in an active, spatially intermittent distribution along the shore (*status_n* = 213, see example Figure 5.31), or in a temporally intermittent fashion indicated by minor spatially intermittent inactive erosion scarps interspersed alongshore between dominantly accreting shores (*status_n* = 223) or by older inactive erosion scarps behind currently dominantly accreting shores (*status_n* = 233, see example in Figure 5.32).

These "dominantly accreting" shoreline status classes have mostly been used to describe dominantly accreting saltmarsh shores within the study area coastal re-entrants, however the "dominantly recently accreting with temporally intermittent sub-ordinate erosion" class (*status_n* = 233) has also been used to describe portions of the open coast foredune shore on Perkins Island North Beach which are currently in a dominantly accreting phase of the long-term cut-and-fill cycles to which they are subject.

Figure 5.31: This shore in Acton Bay has sub-ordinate stretches of spatially intermittent active erosion, but saltmarsh accretion is dominant along most of the shore (*status_n* = 213). Similar shores with spatially intermittent *inactive* erosion scarps and dominant accretion have also been mapped in a few parts of the study area but are not illustrated here (*status_n* = 223).

Figure 5.32: A low inactive erosion scarp (barely visible in this photo) is present at the rear of this dominantly accreting saltmarsh shore in Acton Bay, indicating that the shoreline stability status class here is "temporally intermittent erosion with recent accretion dominant" (*status_n* = 233). This same class has also been used for prograding sections of the sandy North Beach shore on Perkins Island where old foredune erosion scarps are fronted by strongly prograding (accreting) beach sections.

Accreting shores, continuous (no erosion)

Mapped classes: *status_n* = 500

The shoreline status class "continuous accreting shores" is characterised by substantial stretches of shoreline (several tens of metres length or more) with spatially continuous accretion of sediment and no evident spatially or temporally intermittent stable or eroding sections such as minor active or inactive scarps (see Figure 5.33).

This shoreline status class mostly comprises accreting saltmarsh shores within the study area, but also includes some rice grass-dominated shores in Duck Bay. Continuously accreting saltmarsh shores may occur over soft sediment substrates (e.g., sandy tidal flats) or may be found colonising low-profile rocky shore platforms (in which case the accreting saltmarsh defines the shoreline status rather than the stable rocky substrate beneath).

The assertion that these shores are actively accreting rather than merely stable is based on the fact that there is generally a visible mounding of sediment beneath the accreting saltmarsh margins which indicates active sediment capture; and further it is noted that widespread observations of saltmarsh elsewhere indicate that saltmarsh is rarely merely "stable"; it is generally either actively eroding or actively accreting with a tendency to trap sediment and accumulate organic debris as it grows (see Section 4.2 Shoreline Wetlands (saltmarshes, beaches, tidal channels and *Melaleuca* swamp forests)).

The prevalence of temporally intermittent saltmarsh erosion in the study area, with secondary saltmarsh rapidly colonising in front of inactive erosion scarps (e.g., Figure 5.27 above) is a testament to the vigour with which saltmarsh shores can accrete if not subject to erosive conditions. Indeed, historic air photo interpretation during this project (see Section 5.2.4.

Aerial photography time series analysis) indicates that most of the areas now classified as "continuously accreting" saltmarsh shores have in fact been subject to some intermittent erosion at times during the last 60 years; however accretion in these areas has been sufficiently vigorous as to have now entirely covered any old inactive erosion scarps.

Figure 5.33: A spatially-continuous accreting saltmarsh shore with no apparent signs of previous erosion, on the south-west side of Perkins Island (*status_n* = 500).

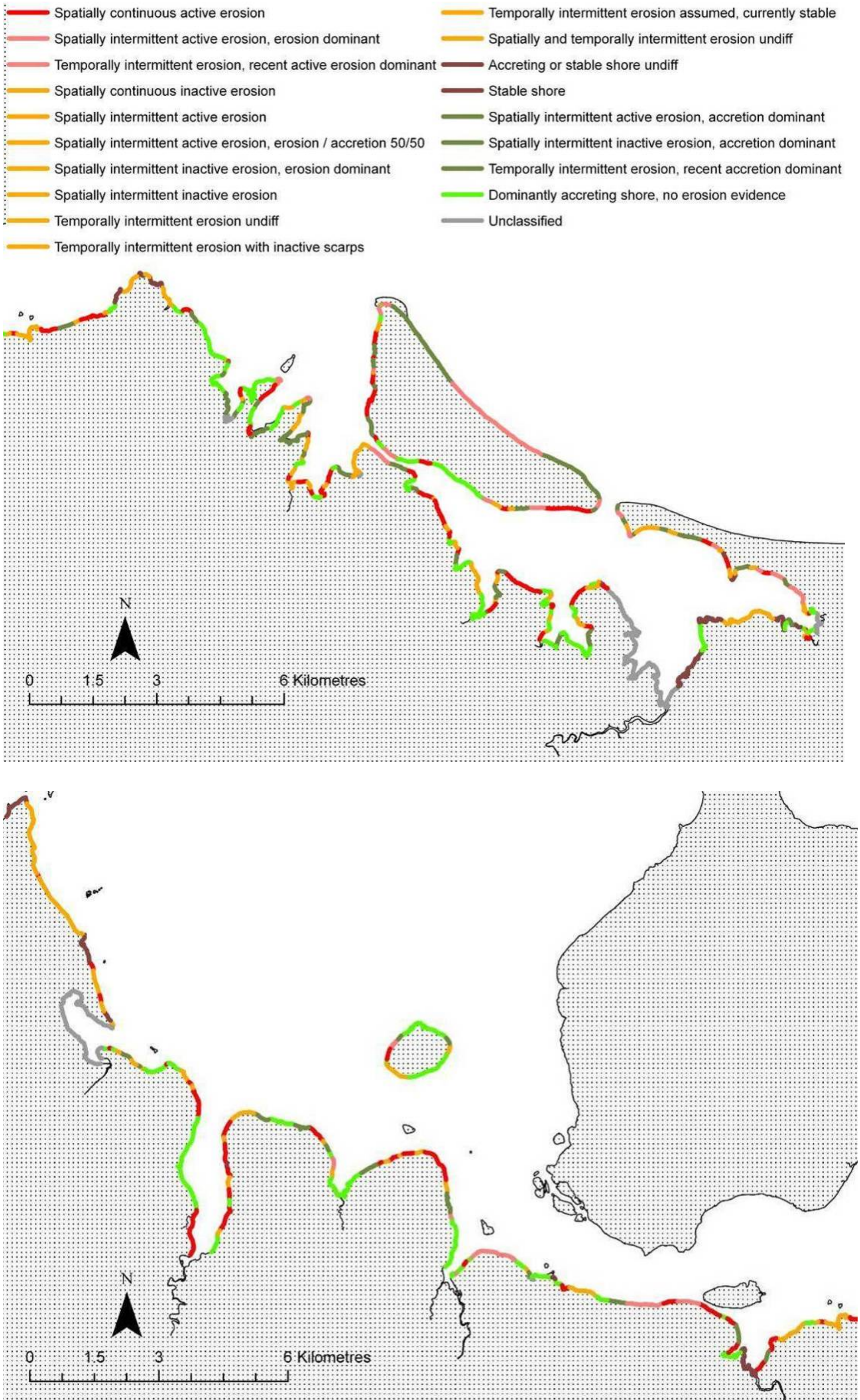

Figure 5.34. Shoreline erosion status mapping with grouped classes. Map above shows the Duck Bay and Big Bay areas while the map below shows the Boullanger Bay and Robbins Passage areas.

Shoreline erosion summary

About 129 km of shoreline within the study area, including Perkins Island and Kangaroo Island, excluding Robbins Island, Wallaby Islands and other small offshore islands were mapped (see Figure 5.34). Of these, about 13.6 km, including a 7.3 km section from Pelican Point to Smithton and a 4.4 km section in Shoal Inlet, were not mapped and thereby considered unclassified. The classification of the remaining sections of the shoreline, their respective length and relative dominance within the study area is provided in Table 5.2.

Table 5.2. Grouped shoreline erosion type classes with their respective *Status_n*, length and relative dominance within the study area (in terms of % of the total shoreline).

Erosion Group	Numerical codes (*Status_n*)	Length (m)	% of the total shoreline
Actively eroding shores, continuous	120	22,108	19.3%
Dominantly actively eroding shores (with some sub-ordinate intermittent stability or accretion)	100 201 211 231	10,586	9.2%
Intermittently eroding shores (some spatially or temporally intermittent accretion, but accretion not dominant)	130 200 202 210 212 220 221 222 230 232 235 240	23,414	20.4%
Stable shores (i.e., mainly hard bedrock, or soft shores with no indication of accretion or erosion)	300 400	7,958	6.9%
Dominantly accreting shores with some intermittent or prior erosion	203 213 223 233	19,564	17.1%
Accreting shores, no evidence of prior erosion	500	30,903	26%

5.2.3. Wind-wave exposure modelling

Primary Authorship: Vishnu Prahalad

Introduction

Within tide dominated environments, wave energy is considered to be one of the most important factors in shaping the shoreline (and saltmarsh) geomorphology (e.g. Allen, 2000; Harris *et al*., 2002). Wave energy is strongly correlated with wave exposure, which in the case of tide dominated environments is primarily a measure of aggregated fetch length (here, the sum of the distance of open water in a defined number of evenly spaced directions), near shore bathymetry, wind strength and wind direction. Recent changes in the climate have been associated with increased wind energy and a resultant rise in wave heights (Gulev and Hasse, 1999; Grevemeyer *et al*., 2000). Furthermore, a rise in sea level can increase the volume and area of water within tidal re-entrant environments thereby increasing fetch lengths and reducing the attenuation effect of shallow bathymetry on waves. The effect of increased wave energy will vary depending on the shoreline type. On soft sediment shorelines dominated by saltmarshes, increased wave energy is known to have caused considerable erosion and loss of marsh area on the seaward side (van der Wal and Pye, 2004; Prahalad, 2009). Hard bedrock shores however, are much less vulnerable to increased wave energy (Sharples, 2006).

The shoreline of the study area has been divided into six types known as "shoreline substrate classes" based on their form and substrate (see Section 5.2.2. Shoreline mapping: types and erosion status). Of these, the class **"Cut and fill" shorelines – foredunes and beach ridges** are mostly swell-wave dominated shorelines as opposed to wind-wave dominated shorelines. The remaining five classes belong to wind-wave dominated shorelines and are grouped into three types:

1. **Soft saltmarsh shorelines**, including:
    a. Dominantly eroding saltmarsh substrates
    b. Soft erodible substrates over hard bedrock
2. **Soft non-saltmarsh shorelines**, including:
    a. Other sands (including older podzolic beach ridge or aeolian sand sheet deposits)
    b. Dominantly soft rock shores
3. **Hard shorelines**, including:
    a. Dominantly hard stable bedrock shores

Of these three shoreline types, the effect of wind-wave exposure will be an important consideration for the soft saltmarsh and non-saltmarsh shorelines as their responses could be more pronounced within yearly or decadal timescales (van der Wal and Pye, 2004). The hard shorelines however, are less vulnerable and take longer to react, and hence will not be considered in this study for wave-exposure analysis.

Methods

Wind-wave exposure analysis was conducted using the GIS based cartographic wave exposure model developed by Pepper (2009) called Generic Relative Exposure Model (GREMO). The model is based on the Wave Exposure Model (WEMo) developed by Fonseca and Malhotra (2006) for estuarine (tide dominated) environments. The model has been built within the ESRI ArcMap software environment and can be readily customised to project needs. The data inputs for the models included:

1. A point file of 1031 points digitised at 100 m intervals on the shoreline vector file. This the standard data set developed for the Foreshore Condition Assessment project (Aquenal, in progress).
2. A polygon file, which is the digitised coastline of Tasmania, also a standard data set of the Foreshore Condition Assessment project (Aquenal, in progress) and supplied by The LIST in late 2009.
3. A 10 x 10 m digital bathymetric grid was compiled for the project to represent the bathymetry of the study area. The grid had three sources:
    a. The Climate Futures LiDAR digital elevation model (DEM) was captured during low tide and has the micro-relief of the intertidal flats and immediate nearshore area. In many locations the DEM includes areas below mean sea level (i.e. 0 m AHD). The original data have 1 x 1 m cells.
    b. Bathymetry data was available for Duck Bay from earlier sounding surveys conducted by TAFI for CCNRM.
    c. For areas not visited by TAFI or covered by the LiDAR DEM, points were digitised from low resolution bathymetric contours obtained from the Royal Australian Navy Hydrographers Chart (AUS00790 - Stokes Point to Circular Head - Oct 1971).
4. Wind speed/directional information, obtained for 16 compass directions for two Bureau of Meteorology weather stations:
    a. Cape Grim (at Woolnorth) - Station Number: 091245 · Opened: 1985 · Status: Open · Latitude: 40.68°S · Longitude: 144.69°E · Elevation: 94 m.
    b. Smithton - Station Number: 091292 · Opened: 1996 · Status: Open · Latitude: 40.83°S · Longitude: 145.08°E · Elevation: 8 m.

For each sampling point GREMO calculated the fetch length between the point (from the input point file) to the nearest potential wave blocking obstacle (input polygon file/coastline) for every 7.5 degrees around the point (i.e. 48 fetch lines radiating from every point) to a distance of 30 km to ensure differentiation between fetches open to Bass Strait and those more enclosed. The calculated fetch length was then weighted by overlaying the bathymetric grid data generated for the project. A distance of 2 km was set as the maximum distance for bathymetry interrogation, as it was assumed that sea floor elevation beyond that would not have a considerable effect on wind-wave attenuation. The resultant fetch-bathymetry values were weighted by the wind speed and direction information (for 16 compass directions) to calculate the relative wave exposure for each sampling point along the shoreline. The Cape Grim wind data was used for Boullanger Bay area while Smithton wind data was used for Robbins Passage, Big Bay and Duck Bay. This split was arbitrary and necessitated by the lack of finer scale wind data in the area. The relative wave exposure is a dimensionless value and is referred to as the Wind-Fetch Index (WFI).

WFI generated for each point on the shoreline for every 100m was compared with the shoreline mapping data - **erosion status** and **scarp height** (see Section 5.2.2.

Shoreline mapping: types and erosion status) - for the two types of soft sediment shores: soft saltmarsh shorelines and soft non-saltmarsh shores. Within the soft sediment shores, not all parts of the shoreline were able to be subjected to wave-exposure analysis as other environmental factors may render the energy of wind waves negligible in determining shoreline geomorphology and position. Six such factors were identified and the points associated with these factors (potential noise data) were excluded from the wave-exposure analysis:

1. Tidal barriers such as levees are known to amplify the erosional loss on soft sediment shorelines by increasing wave scouring (e.g. Hood, 2004) and can potentially provide an exaggerated erosion status for a given fetch. Tidal barriers have been mapped as a part of the project and 173 points in front of these barriers were excluded.
2. Tidal channels that occur between shorelines separated by narrow intertidal flats channel the rising and falling tides and generally have significant turbulence and thus erosive power unrelated of fetch length. The only place within the study area that this occurs is the narrow Perkins Passage, and 34 points falling in this passage were excluded.
3. Estuary mouths are often highly dynamic environments shaped by varying levels of river discharge (especially during floods). Hence, the net position of the shoreline in estuary mouths will be to an equal or greater amount be determined by river discharges along with wind-wave exposure. For this reason, 73 points were excluded.
4. The prevalence of rice grass (*Spartina anglica*) can considerably alter the shoreline geomorphology and behaviour (Doody, 2008). Hence, 40 points that occur on rice grass infested shorelines (also mapped during the project) were excluded.
5. A total of 36 points were excluded as cartographic anomalies, as the digitised shoreline in some places did not represent the actual current position or shape of shoreline as mapped on the ground.

A total of 356 points were excluded for the five reasons listed above. A further 61 points associated with foredunes and beach ridges and 38 points associated with hard stable bedrock shores were excluded from the analysis. The remaining 576 points were separated into 507 points associated with fetch-dominated saltmarsh shorelines and 69 points associated with fetch-dominated non-saltmarsh shorelines. Of these, a further 28 points associated with stable shores were removed from fetch-dominated saltmarsh shorelines and fetch-dominated non-saltmarsh shorelines.

Statistical tests were run using one-way analysis of variance (ANOVA) for a confidence level of 95% to test whether the erosion status and scarp height of each of the soft shoreline types differed in their WFI. Erosion status was divided into five groups: actively eroding (AE); dominantly eroding (DE); intermittently eroding (IE); dominantly accreting (DA); and actively accreting (AA). Scarp height was divided into three groups for fetch-dominated saltmarsh shorelines: <0.2 m; 0.2-0.5 m; and unclassified (or no scarp). Note that the saltmarshes in the study area were found to occupy a height range of 0.5 m (see Appendix 4 Stratigraphy analysis – Technical Report). For the fetch-dominated non-saltmarsh shorelines, five of the six mapped groups were used: 0.2-0.5 m; 0.5-1.0 m; 1.0-2.0m; 2.0-6.0m; and unclassified (or no scarp).

Wind speed data recorded at Cape Grim (from 1991-2009) and Smithton (from 1997-2009) Bureau of Meteorology weather stations were collected and analysed for any changes in the wind climate. Mean wind speed data from Cape Grim were then assigned to two groups: CG1 (data for 1991-2000, 3283 observations) and CG2 (data for 2001-2009, 3251 observations). Mean wind speed data from Smithton were assigned to two groups: SN1 (data for 1997-2002, 2188 observations) and SN2 (data for 2003-2009, 2556 observations). Statistical tests were run using two-sample t-test to test whether the two groups for each weather station were significantly different.

Results

The erosion status of the fetch-dominated saltmarsh shorelines are strongly related to WFI ($F = 15.49$; d.f. = 4; $P < 0.001$). The actively eroding (AE) group was significantly different from both the accreting groups (DA and AA), while the dominantly eroding group (DE) and the intermittently eroding group (IE) were significantly different from the actively accreting group (AA) (Figure 5.35). Generally, the degree of erosion was positively correlated with WFI and hence the exposure of the shoreline to wind-wave energy. The erosion status for the fetch-dominated NON-saltmarsh shorelines were related to WFI ($F = 3.84$; d.f. = 4; $P = 0.007$). The actively eroding (AE) group was significantly different from the actively accreting group (AA), while there was a general trend towards increased erosion with high WFI (Figure 5.37).

Scarp heights for the fetch-dominated saltmarsh shorelines were strongly related to WFI ($f = 29.85$; d.f. = 2; $p < 0.001$). Scarp heights of <0.2 m and 0.2-0.5 m were significantly different from the unclassified group (encompassing shorelines with no erosion scarp). However, the two erosion scarp groups <0.2 m and 0.2-0.5 m had similar means and did not vary significantly from each other (Figure 5.37). Scarp heights for the fetch-dominated NON-saltmarsh shorelines were strongly related to WFI ($F = 15.49$; d.f. = 4; $P < 0.001$). The high scarps (groups 1.0-2.0 m and 2.0-6.0 m) were significantly different from the low scarps (groups 0.2-0.5 m and 0.5-1.0 m) and the unclassified group. However, the two high scarp groups were not significantly different from each other. Similarly, the low scarps and the unclassified group were not significantly different (Figure 5.38).

Comparison of the WFI of fetch-dominated saltmarsh and NON-saltmarsh shoreline types revealed that WFI, in general, was lower for the former (Table 5.3). Mean WFI for NON-saltmarsh shorelines was almost double as much for saltmarsh shorelines. Further, the mean WFI for saltmarsh shorelines also appears to approximate the wave power threshold above which shoreline erosion occurs.

Table 5.3. WFI mean and standard deviation (SD) for fetch-dominated shoreline types.

Fetch-dominated shoreline type	WFI-Mean	WFI-SD	Points
Saltmarsh	91,291	58,817	507
NON-saltmarsh	166,883	72,348	69

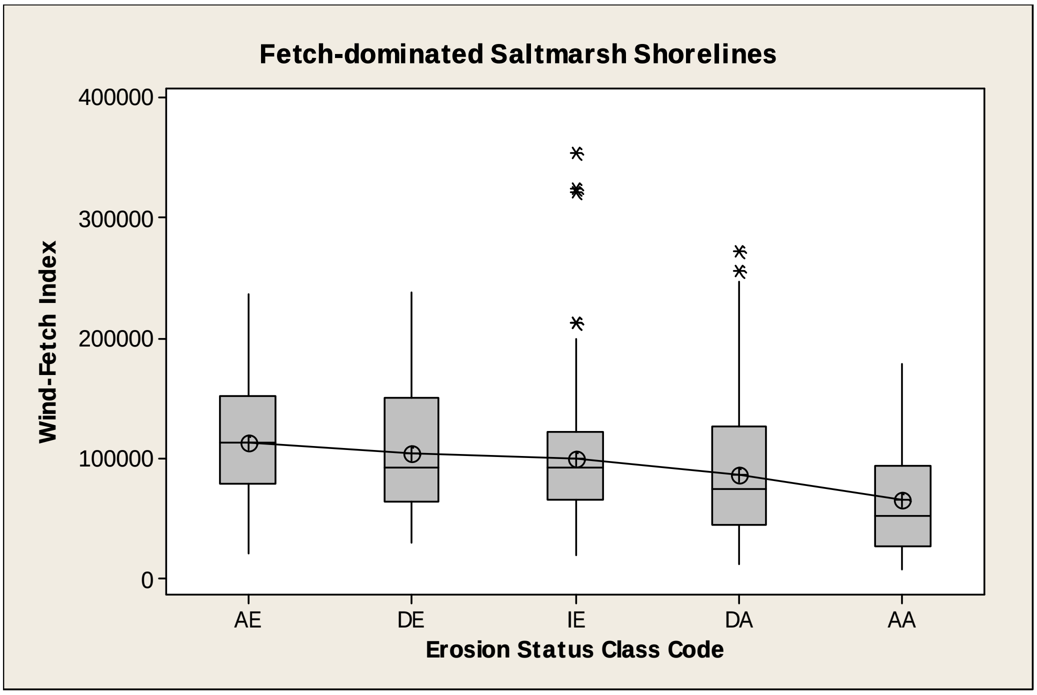

Figure 5.35. Box plot showing the relationship between WFI and erosion status class for fetch-dominated saltmarsh shorelines. AE – Actively eroding shores, continuous; DE – Dominantly actively eroding shores; IE – Intermittently eroding shores; DA – Dominantly accreting shores with some intermittent or prior erosion; AA – Accreting shores, no evidence of prior erosion. Boxes represent the data range between the first and third quartile (25-75% of the data). The middle horizontal line represents the median value. The circle with the cross represents the mean, with a line connecting the means. Whiskers extend to the maximum and minimum data points within 1.5 box heights. Outliers are represented by stars.

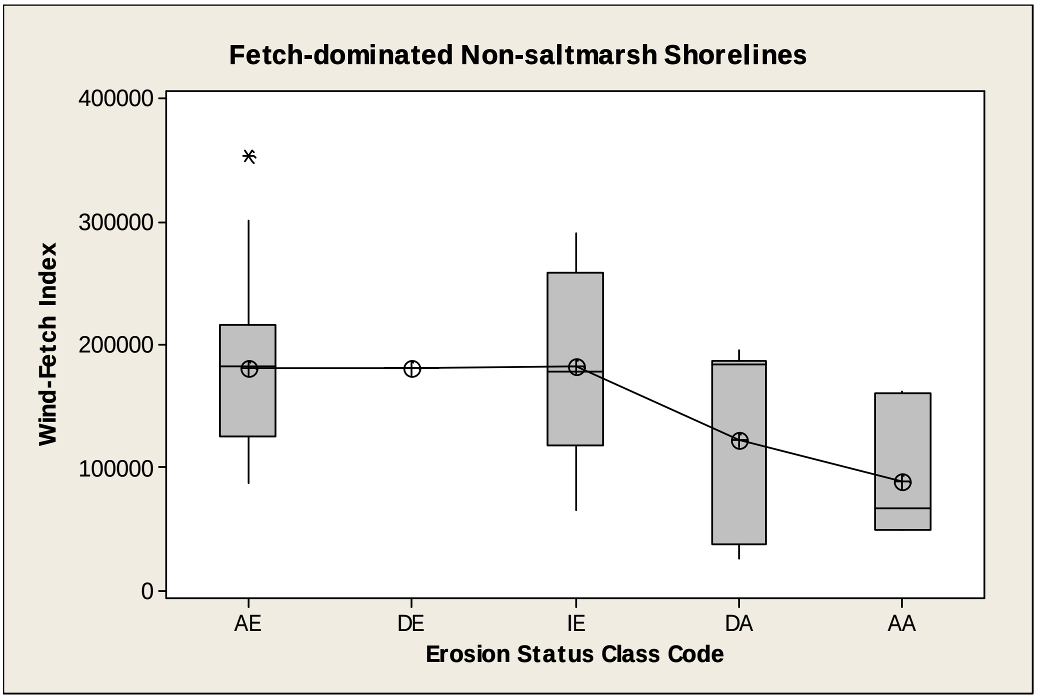

Figure 5.36. Box plot showing the relationship between WFI and erosion status class for fetch-dominated NON-saltmarsh shorelines. AE – Actively eroding shores, continuous; DE – Dominantly actively eroding shores; IE – Intermittently eroding shores; DA – Dominantly accreting shores with some intermittent or prior erosion; AA – Accreting shores, no evidence of prior erosion. Refer to Figure 5.35 for the key to the symbols used.

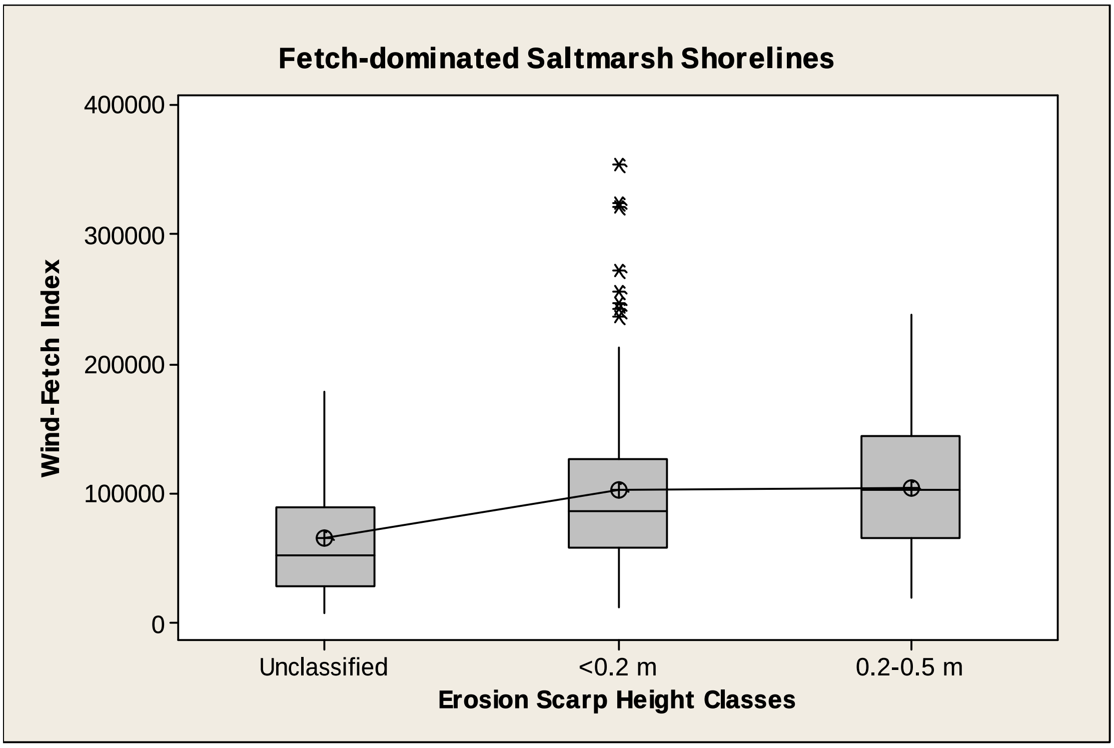

Figure 5.37. Box plot showing the relationship between WFI and erosion scarp height class for fetch-dominated saltmarsh shorelines. Refer to Figure 5.35 for the key to the symbols used.

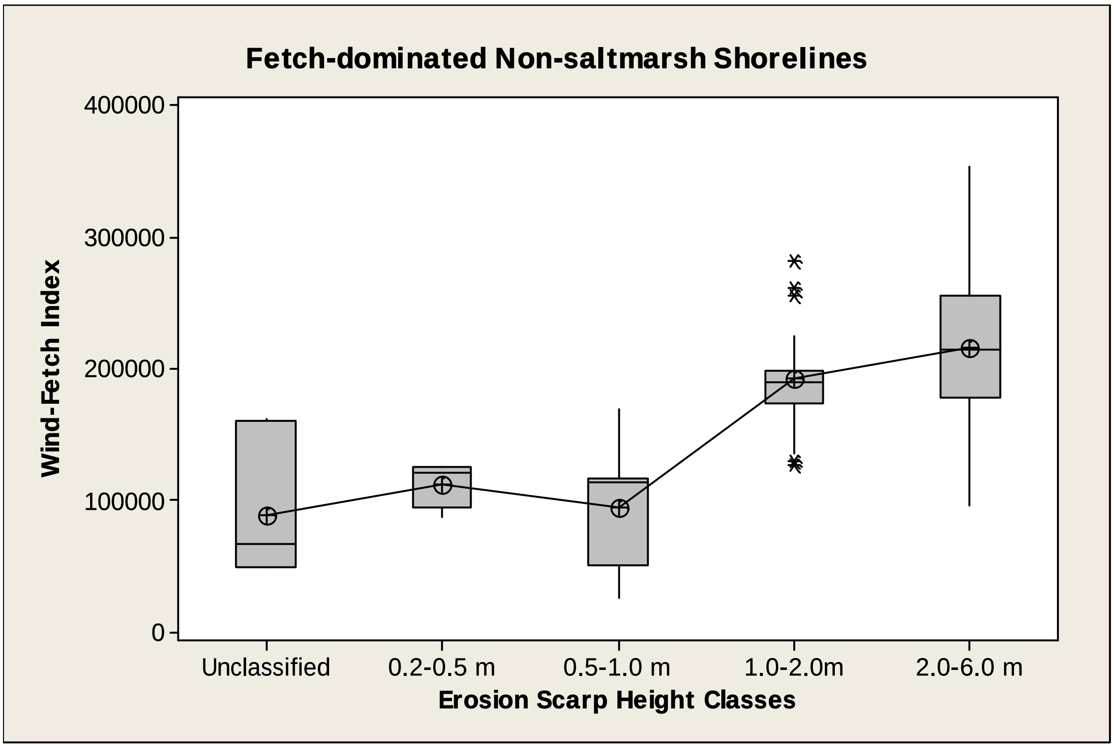

Figure 5.38. Box plot showing the relationship between WFI and erosion scarp height class for fetch-dominated NON-saltmarsh shorelines. Refer to Figure 5.35 for the key to the symbols used.

Changes in wind climate

Mean wind speeds recorded for the period between 2001 and 2009 at Cape Grim (CG2, M = 9.74, SD = 3.87) were higher than the mean wind speeds recorded between 1991 and 2000 (CG1, M = 9.35, SD = 3.72) (Figure 5.39). The two groups differed significantly with a T-value of -4.13 (DF = 6532) and a P-value less than 0.0001. The mean wind speeds recorded at Smithton did not reveal any strong signs of increase from 1997-2002 (SN1, M = 5.20, SD = 2.01) to 2003-2009 (SN2, M = 5.25, SD = 2.00). However, some difference was noted between the groups with a T-value of -0.92 (DF = 4742) and a P-value less than 0.5. Note that records from Smithton were available from 1997 on.

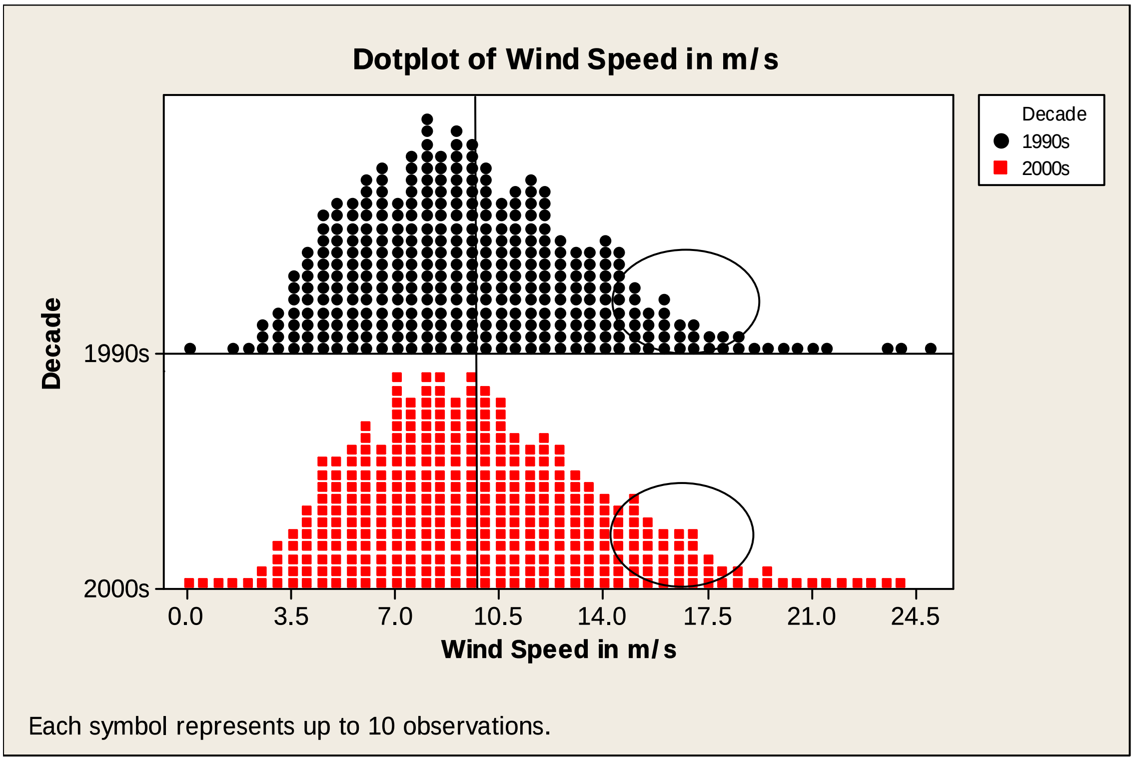

Figure 5.39. Cape Grim wind speed. Dot plot showing the mean daily wind speed recorded (in m/s) over two decades.

Discussion

The wave exposure analysis has shown that wave energy is a dominant factor in shaping the geomorphology of the fetch-dominated soft shorelines within the study area with erosion status and scarp height strongly related to wind fetch as a proxy for wave energy. This finding is consistent with similar studies from southeast Tasmania (Prahalad, 2009) and overseas (Schwimmer, 2001). Both those studies reported significant correlation between erosion rates and wave energy for saltmarsh shorelines. The findings from this analysis supports the statement made by Harris *et al*. (2002, p.868) that "[g]eomorphic changes resulting from an increase in wave power are likely to be most obvious for tide-dominated environments" in Australia.

Prahalad (2009) reported that wind energy in south-east Tasmania increased over the past 50 years, with a marked increase in intensity since 2000. The wind data from Cape Grim shows a similar sign of increased wind intensity since 2000 while the data from Smithton was available only from 1997 and did not reveal a significant change in wind intensity. In general however, the results indicate that there has been a change in the wind climate of the study area with an increase in the incidence of stronger winds. This follows a general trend observed elsewhere towards an increase in wind speeds as a consequence of global warming posing increased threats to coastal areas (Grevemeyer *et al*., 2000). A study of the effect of increased wind speeds on saltmarsh shorelines by van der Wal and Pye (2004) showed that “rapid phases” of erosion were associated with high intensity wind-waves.

The relevance of the wind-wave exposure to the understanding of sea level rise impacts is via the concept of accommodation space as outlined in Section 5.1 Sea level rise concepts and mechanisms. The idea is that if sea level is rising, we would be expecting the sediment levels on the sea floor and intertidal flats to rise as well as they will have “room” (i.e. accommodation space) for more sediment. This clearly depends on a continuing supply of sediment or at least a rearrangement of the available sediment. One source of sediment is the shores themselves and we propose that the most likely mechanism to mobilise that sediment in the fetch-dominated study area is that of wind fetch waves. The rate of the sediment movement is likely to be related to the amount of erosive power available at each section of the coast and that, as this section has shown, is related to the wind wave energy present.

5.2.4. Aerial photography time series analysis

Primary Authorship: Vishnu Prahalad

Introduction

The use of historic aerial photography, or aerial photography "time series", to analyse shoreline changes has been in practise for more than three decades now (e.g. Dolan *et al*., 1978; Phillips, 1986). The method has been employed successfully in Tasmania in recent years to analyse shoreline changes in beaches (Hayes, 2009; Sharples, 2010) and saltmarshes (Morrison, 2006; Prahalad, 2009). Analysing historical aerial photographs not only provides long-term shoreline accretion/erosion rates, but also gives us a historical perspective on other geomorphic changes associated with sea level rise (sea level rise "signatures"), such as changes in tidal channels, barrier island migration and longshore migration. These data becomes useful for understanding shoreline evolution under accelerated sea level rise, especially when analysed in the context of major environmental agents such as wind-wave exposure. The value of the high resolution shoreline erosion status mapping conducted as part of this project is increased by the historical shoreline data by combining analysis of the current status of the shoreline with the knowledge of its historical behaviour. Such analysis adds considerably to the understanding of sea level rise impacts and vulnerability.

Methods

Three representative case study areas within the Circular Head foreshore area were selected based on their position, level of human disturbance and relevance to the study. They are, from west to east, **Boullanger Bay** (including Kangaroo Island, Sealers Springs Point, Swan Bay, Harcus River estuary and Brick Islands area), **Big Bay** (including area east of Stony Point, Cades Bay, Acton Bay, Perkins Passage and the Jam) and **Duck Bay** (including the area between Griffiths Point and Lees Point and Deep Creek Bay). The aerial photography available for these areas was queried from TASMAP, Tasmanian Department of Primary Industries, Parks, Water and Environment, aerial photography database. Aerial photography covering the study area was available from the 1950's onwards with the latest series of photographs taken in 2006. The available photography was then closely inspected to identify and select best available photographs from different time periods to form a time series. Photographs taken at high tide, when the water levels were well over the shoreline position, were discarded. Finally, 19 photographs were selected representing five different time periods temporally spaced at a decadal scale. Aerial photographs for the 2006 period were already available as they were obtained and orthorectified for a CCNRM mapping project undertaken by the authors in 2009 (Mount *et al*., unpublished data). Six 2006 photographs were used along with the 19 older photographs for the time series analysis (Table 5.4).

The aerial photographs (as 8 bit grey scale and 24 bit colour) were scanned to a resolution of 1200 dpi and orthorectified in Landscape Mapper. The LiDAR digital elevation model for the study area and the LIST vector layers were used in the georectification process (image to image georectification done with control points selected from the LIST vector layers). The average root mean square (RMS) error from the process was 6.8 m, with 2006 images having a lower average RMS error of 3.1 m (Table 5.4). Hence, the 2006 images were used as the "base layer" to georectify other images further within the ArcGIS environment to reduce the “relative error” between the images. Through this process, the relative error was brought down to about 5 m, which is the relevant error margin for interpreting the results reported below for shoreline movements. For each time period, the shoreline position was digitised along the vegetation-tidal flat boundary. Shorelines backed by tidal barriers were not used as the barriers are likely to have altered the natural shoreline response to climate change and sea level rise. The 2006 shoreline position, being the latest available data and the most accurate, was used as the “reference shoreline” against which historic shoreline movements were measured and analysed at over 800 locations along the shore.

Table 5.4. Details of the photographs used in the time series analysis.

Photo Year	Film No	Frame No	Date Taken	Scale	RMS Error (m)
1951/53	244	46130	20.01.53	1:23760	12.0
	260	48501	23.02.53	1:23760	14.60
	226	41750	30.11.51	1:23760	6.0
1968	501	246	18.02.68	1:31680	16.40
	501	278	18.02.68	1:23760	6.88
	501	298	18.02.68	1:23760	22.0
		300			3.66
	505	20	19.02.68	1:23760	12.0
1979	808	10	24.11.79	1:42000	4.88
		13			5.32
	808	31	24.11.79	1:42000	6.44
1992	1190	210	10.03.92	1:42000	3.13
		212			2.71
	1191	93	24.03.92	1:42000	5.28
		97			1.57
2001	1340	261	01.01.01	1:42000	6.21
	1340	246	01.01.01	1:42000	5.87
		249			12.60
	1340	229	01.01.01	1:42000	4.47
2006*	1403	164	21.01.06	1:42000	1.920
		165			3.600
	1403	176	21.01.06	1:42000	2.050
		177			5.790
		180			2.600
		181			2.650

Shoreline responses were analysed separately for saltmarsh and non-saltmarsh shorelines as they have different substrate types and hence respond differently to change factors. Statistical tests were run using one-way analysis of variance (ANOVA) for a confidence level of 95% to test whether the shoreline movements measured for each time period relative to 2006 shoreline position differed significantly. The annual rate of retreat was calculated for shoreline movement data from each time period and averaged for each point on the shoreline. The average rate of shoreline movement/change was then tested using ANOVA for a confidence level of 95% with the mapped erosion status divided into five groups: actively eroding (AE); dominantly eroding (DE); intermittently eroding (IE); dominantly accreting (DA); and actively accreting (AA). The average rate of shoreline change was also compared with WFI using a two-sample t-test (at 95% confidence level), with the tested samples being: WFI observed for positive rates of shoreline change (accretion); and WFI observed for negative rates of shoreline change (erosion).

Results

Saltmarsh shorelines

A major part of the saltmarsh shoreline has been eroding, with over 75% of the observations registering erosion (Figure 5.40). Significantly greater erosion was observed prior to 1992 ($F = 22.59$; d.f. = 4; $P < 0.001$). The erosion relative to the periods 1968-1979 and 1979-1992, averaging over 8 m, was particularly significant (Figure 5.41). Erosion was less prominent from 1992 onwards with about 75% of observations falling within the +/- 5 m error margin (Figure 5.40). In particular, erosion from 2001 to 2006 was almost negligible with a mean of just over 1 m. However, rates of shoreline change between the study periods did not vary much and ranged from -12 cm/yr to -30 cm/yr, with the average rate of shoreline change being -22.7 cm/yr. A marginal increase in the rate of response of some shorelines was noted. The average rate of shoreline change dropped by 14% to -19.9 cm/yr when the data points associated with narrow tidal channels and river discharge channels (estuary mouths) were excluded as they can amplify the rate of erosion caused by climate change and sea level rise.

Erosion was particularly severe in some sections of the shoreline with records of over 70 m of retreat. The highest rates of retreat were recorded in Perkins Passage, where the Channel Marsh bordering the south east of Perkins Island retreated by about 20-70 m. This retreat has considerably widened Perkins Passage, with about 30 m increase at the narrowest point of the passage (Figure 5.46). Inspection of erosion between time periods used in the study indicates that the shoreline remained relatively stable between 1952 and 1968, but changed considerably from 1968 onwards. Similarly, the tidal channels in some marshes (especially in Big Bay) were observed to widen with a marked loss in sinuosity since 1968. Accretion was noted in some parts of the shoreline, with advancement of more than 10 m in places. However, the maximum rates of accretion were a third of the maximum rates of erosion with only 69 points showing a net rate of accretion as compared to 212 points showing net rates of erosion (Figure 5.42).

There was a strong relation between the average rate of shoreline change and the mapped erosion status ($F = 16.57.49$; d.f. = 4; $P < 0.001$). All eroding groups (AE, DE and IE) varied significantly from the actively accreting group (AA) (Figure 5.43). The dominantly accreting group (DA) did not differ much from the intermittently eroding group (IE), but differed from the dominantly and actively eroding groups (DE, AE). Comparison of the rate of shoreline movement with WFI revealed that accreting shorelines had lower WFI as compared to eroding shorelines (Figure 5.44). Significant difference was observed between the two groups: erosion (Mean = 104,422, SD = 54,057) and accretion (Mean = 77,096, SD = 53,529); T (105) = 3.38, P = 0.001. The mean WFI of both time series groups was 90,759, which is very similar to the mean WFI observed for fetch-dominated saltmarsh shorelines (91,291; see Section 5.2.3. Wind-wave exposure modelling) indicating that the time series locations are reasonably representative of these shorelines.

Non-saltmarsh shorelines

Similar to the saltmarsh shoreline, the dominant response of the non-saltmarsh shorelines over the time series was found to be erosion. Erosion was particularly significant relative to the 1968 shoreline position, with a mean of -6.8 m (Figure 5.45). However, erosion relative to the 1979, 1992 and 2001 shoreline positions were not found to be significant, with a mean of less than 2 m and well within the 5 m error margin. The rates of shoreline change varied from +0.1 cm/yr to -18 cm/yr with the average rate being -13 cm/yr. There was no strong relation between the observed rates of shoreline change and the mapped erosion status. Also, no strong relation existed between WFI and the accretion and eroding shorelines. It must be noted here that low sample sizes were used for non-saltmarsh shorelines as compared to saltmarsh shorelines due to the fact that most (70%) of the shoreline within the study area is comprised of the latter.

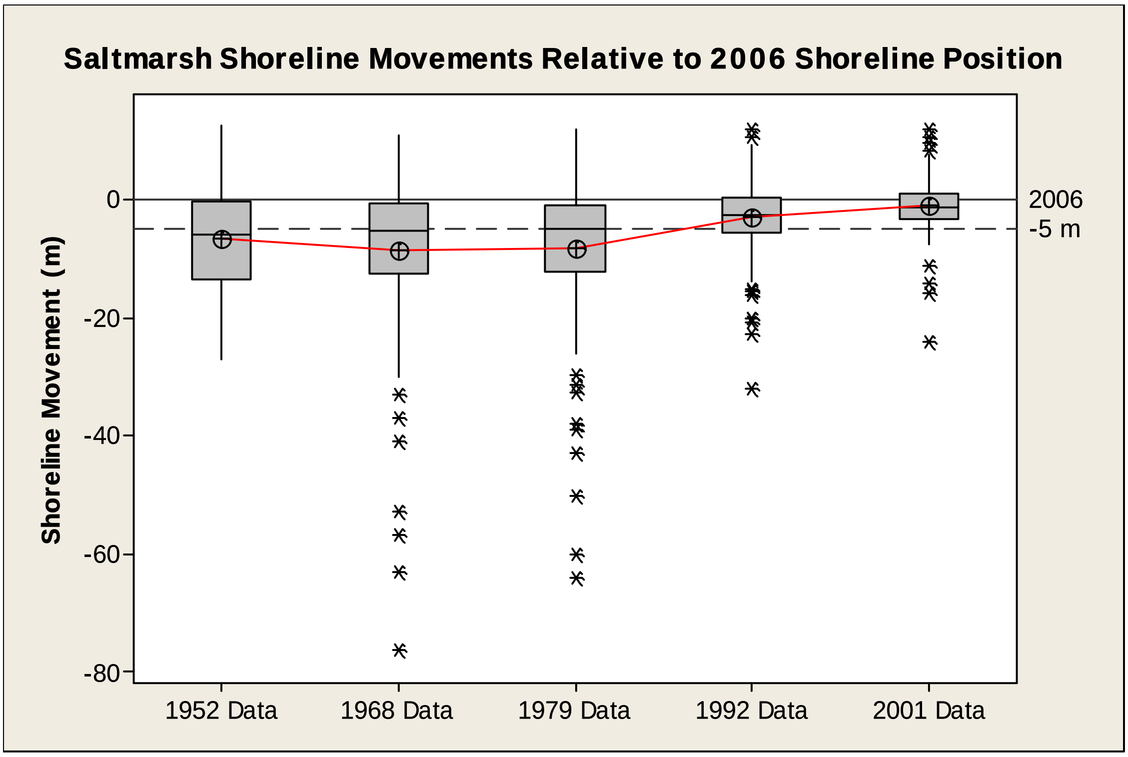

Figure 5.40. Box plot showing the relationship between shoreline movements (in m) between different time periods relative to the 2006 shoreline position (with a 5 m error margin). Refer to Figure 5.35 for the key to the symbols used.

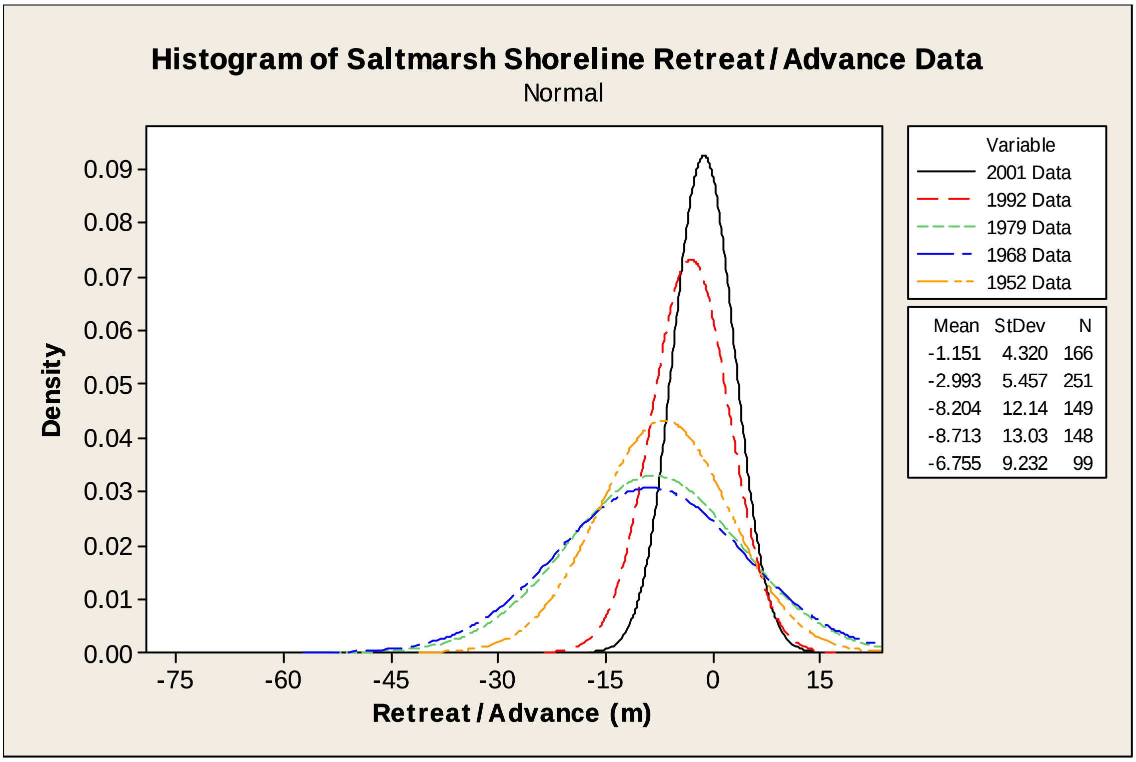

Figure 5.41. Histogram of the "time series" data plotted together to visualise the relative differences in saltmarsh shoreline movements from each time period relative to the 2006 shoreline position.

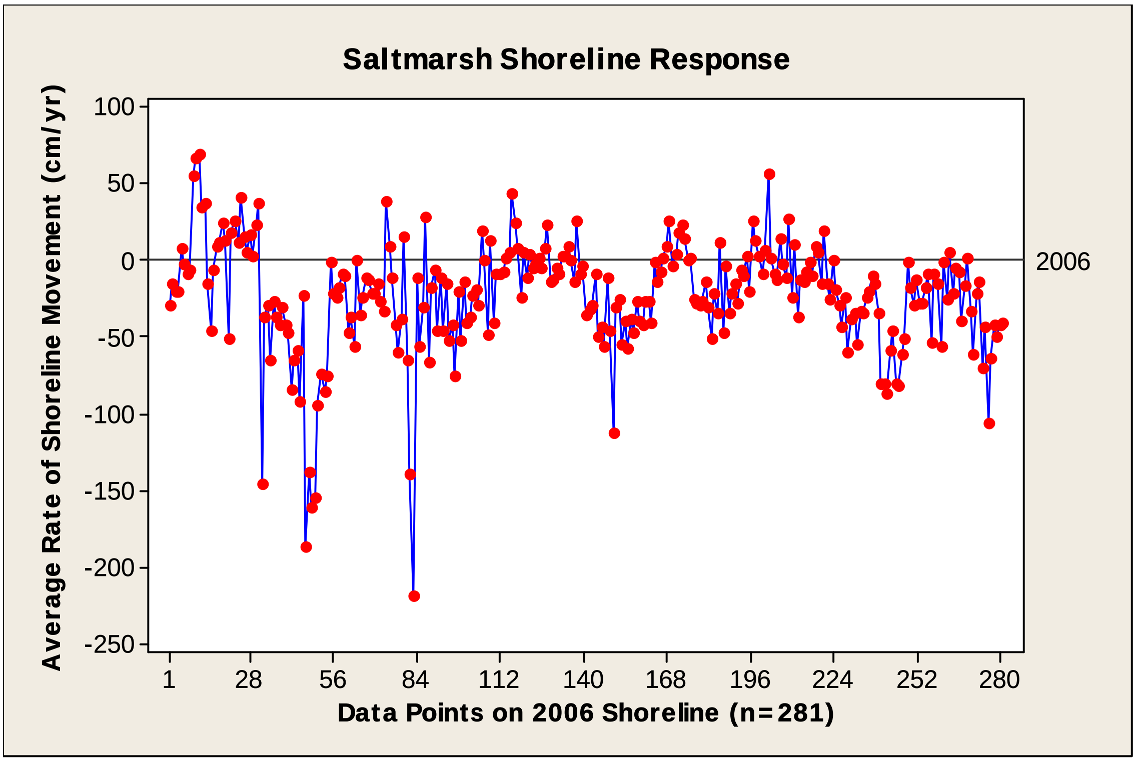

Figure 5.42. Saltmarsh shoreline response, as average rate of change (in cm/yr), measured at 281 sample points at 100 m intervals along the shoreline.

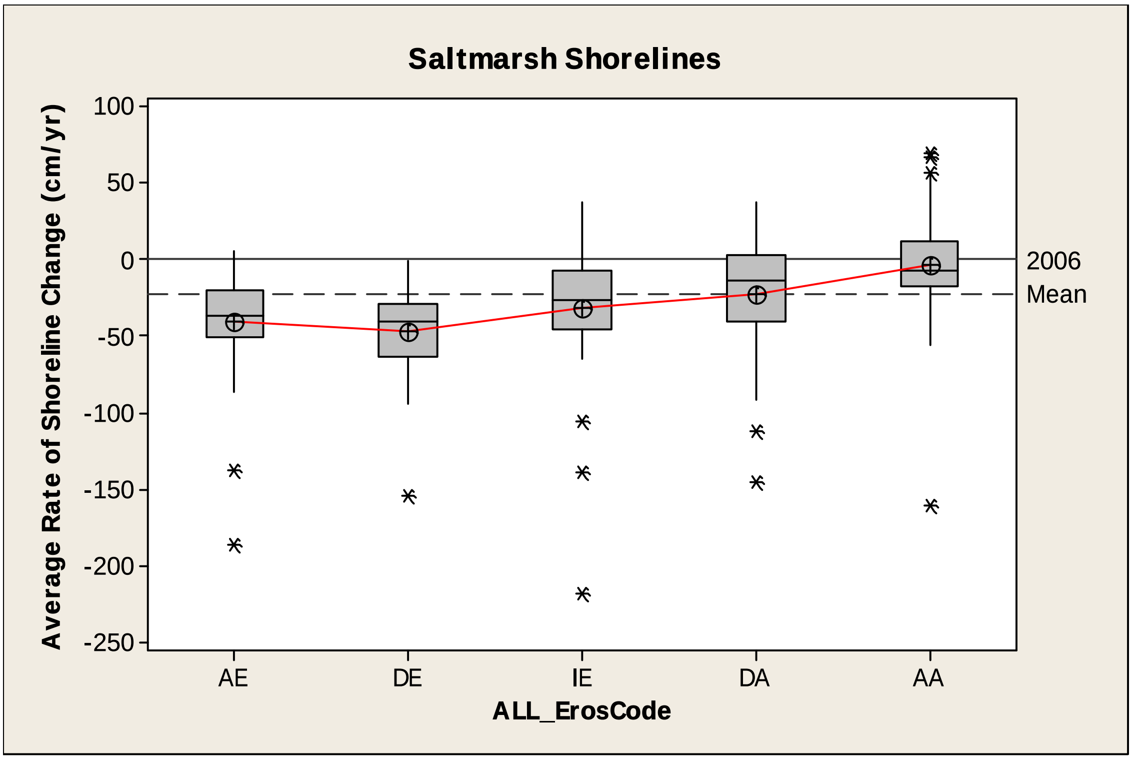

Figure 5.43. Box plot showing the relationship between the average rate of shoreline change (in cm/yr) and erosion status class for saltmarsh shorelines. All rates are relative to the 2006 shoreline position. Mean rate is -22.7 cm/yr. AE – Actively eroding shores, continuous; DE – Dominantly actively eroding shores; IE – Intermittently eroding shores; DA – Dominantly accreting shores with some intermittent or prior erosion; AA – Accreting shores, no evidence of prior erosion. Refer to Figure 5.35 for the key to the symbols used.

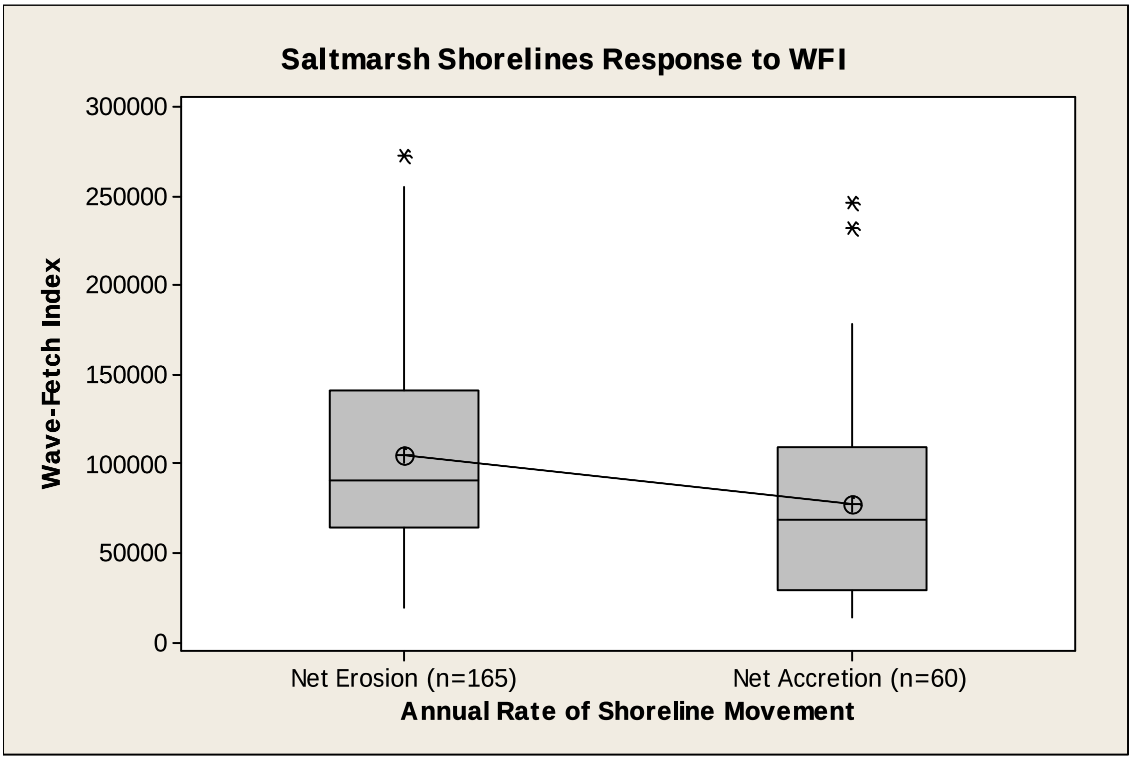

Figure 5.44. Box plot showing the relationship between WFI and the two sample groups, those with observed net erosion and those with observed net accretion. The difference is statistically significant.

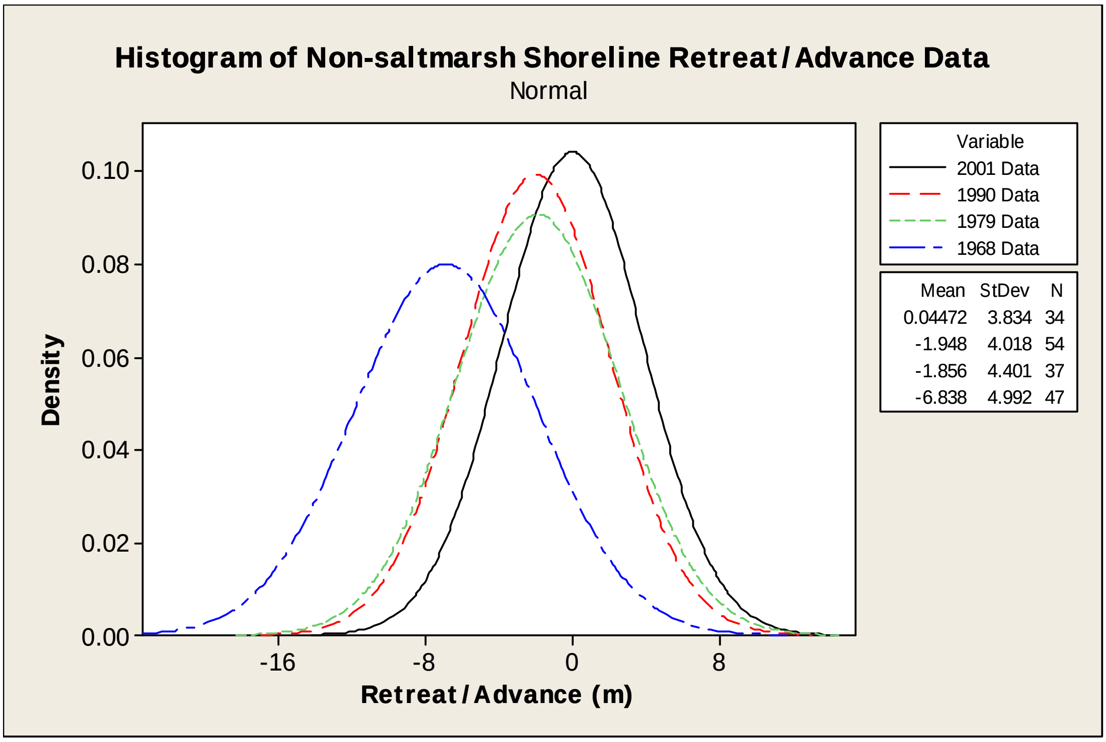

Figure 5.45. Histogram of the "time series" data plotted together to visualise the relative differences in non-saltmarsh shoreline movements from each time period relative to the 2006 shoreline position.

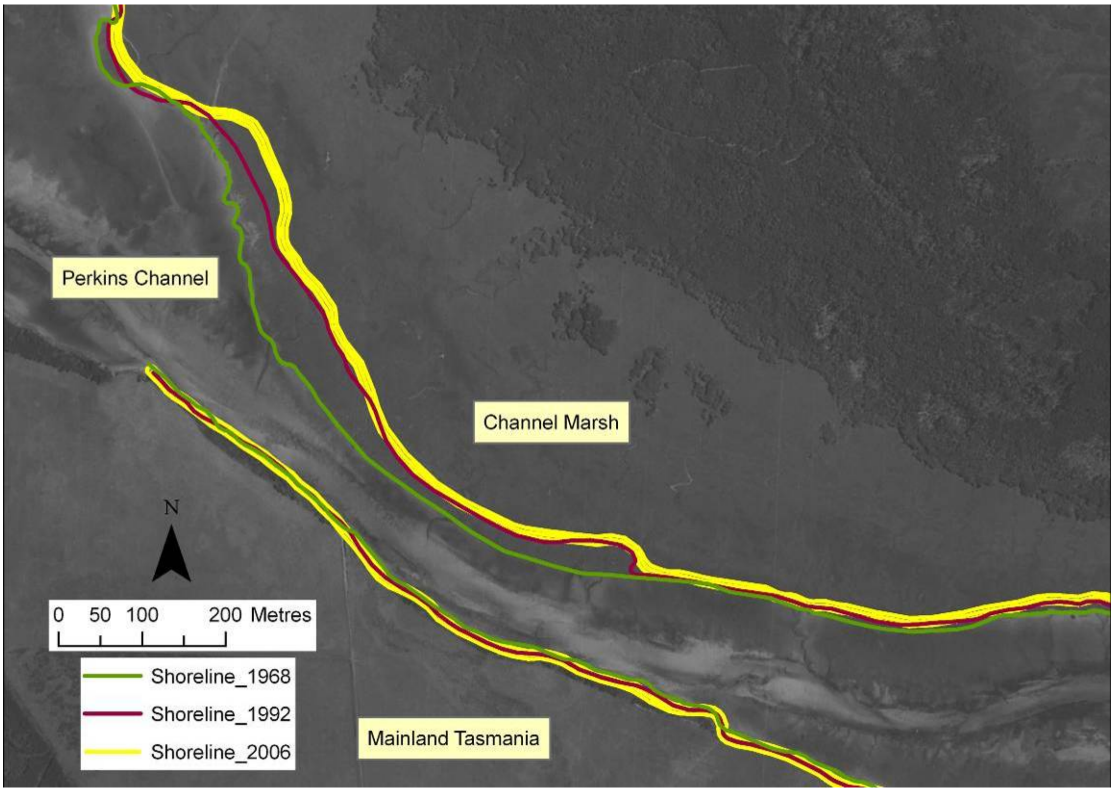

Figure 5.46. Shoreline erosion in the Perkins Channel area (1968 aerial photograph). Note that the Channel Marsh has retreated more than 70 m while the Jam, on the mainland, has retreated only about 10 m. The 2006 Shoreline has been shown here with a 5 m buffer to depict the error margin.

Discussion

The peripheral erosion of soft sediment shorelines in the study area has several analogues in similar environments worldwide (e.g. Cooper *et al*., 2001; Schwimmer, 2001; Hartig *et al*., 2004; van der Wal and Pye, 2004) and in Tasmania (Prahalad, 2009). The annual rates of shoreline retreat reported ranged from a few centimetres to more than three metres, with higher rates usually associated with a combination of erosive factors including sea level rise, coastal subsidence, high wave energy and anthropogenic stress. When one or many of these factors are absent, the rates of retreat can be relatively minor or even negligible, resulting in stable shorelines. Morrison (2006), in a study of fetch limited marsh shorelines in eastern Tasmania, reported stable shorelines with a cyclical process of erosion and accretion. While, Prahalad (2009) in a study of exposed marsh shorelines in south-eastern Tasmania reported highly eroding shorelines with an annual rate of 6-20 cm.

The erosion rates observed for Circular Head shorelines were about 12-30 cm/yr for saltmarsh shorelines and 0-18 cm/yr for non-saltmarsh shorelines. The rate of marsh shoreline erosion in the study area is relatively higher than the rate in south-eastern Tasmania, but lower than some rates reported elsewhere. The lower rates of erosion as compared to overseas studies can be attributed to the tectonic stability of Tasmania, lower rates of sea level rise and lack of major anthropogenic impacts such as oil drilling (which can cause local subsidence). The reasons for the minor difference in the rates of erosion between the study area and southeast Tasmania is unclear. However, both studies revealed that the length of eroding marsh shoreline is far greater than the length of accreting shoreline.

The time series analysis of aerial photography for the study area has indicated that erosion was most apparent from 1968 onwards, with little evidence of erosion preceding that date. The period from 1968 and 1979 has a significant amount of erosion. Van de Geer (1981) reported eroding saltmarsh shorelines with the deposition of washover fans (transgressing sand sheets/shell ridges) from a field survey in the area (circa 1975). This suggests that erosion might have initiated during the period between 1968 and 1975. Indeed, data from a study by Sharples (2010) suggests that shoreline erosion at Roches Beach, southeast Tasmania started around 1975-76.

Comparison with wind-wave exposure data (i.e. WFI) at each individual location has shown that the marsh shorelines that registered net erosion had much higher WFI than the shorelines that registered net accretion. This relationship adds further credence to the argument that wave energy is a dominant factor in shaping marsh shorelines (see Section 5.2.3. Wind-wave exposure modelling). Also, there was a positive correlation between the rates of shoreline change with the current shoreline erosion status as mapped by this project. These results indicate that the current status of the shoreline is generally a net result of its historical sedimentation characteristics (erosion/accretion) and relative exposure to wind-waves.

5.2.5. Changes in shoreline wetlands: vegetation and geomorphology

Primary Authorship: Vishnu Prahalad

Introduction

Changes in the vegetation and geomorphology of shoreline wetlands can be used as an indicator of climate change and sea level rise. Saltmarshes have been shown to be an effective indicator of sea level rise effects in south east Australia as early as 1988 (Vanderzee, 1988). A wide range of studies have reported changes in saltmarshes that are related to sea level rise impacts (e.g. Allen and Pye, 1992; Schwimmer, 2001; Hartig *et al*., 2002), and models have been developed for predicting saltmarsh response to sea level rise (e.g. Orson *et al*., 1985; Schwimmer and Pizzuto, 2000). Generally, vegetation and geomorphology have been the main focus in studying saltmarsh response to sea level rise. With respect to vegetation, increased sea level can change the hydroperiod and consequently alter the floristic composition of the marsh (Huiskes, 1990). The low marsh halophytes retreat landwards replacing the high marsh halophytes, which would in turn respond by retreating landwards replacing coastal glycophytic vegetation. In places where saltmarshes are backed by sea walls (or levees), or naturally occurring sharply rising hinterlands, they can be subjected to "coastal squeeze" (Cooper *et al*., 2001). The geomorphic response models for saltmarshes in the event of sea level rise generally suggest that saltmarshes would accrete vertically while eroding laterally. Where vertical accretion (aided by mineral and organic sedimentation) is not able to keep up with sea level rise, areas of saltmarshes can be subjected to drowning, i.e. converted to intertidal flats (Orson *et al*., 1985; Schwimmer and Pizzuto, 2000; FitzGerald *et al*., 2008). Along with sea level rise, climatic changes associated with global warming can also affect the saltmarshes by the creation of salt pans, acceleration of erosion caused by increasing wind energy and storm surge frequency, altering the dynamics that control interspecific interaction, among others (Prahalad, 2009).

In this section, some of the changes observed in the vegetation and geomorphology of the saltmarshes within the study area will be presented and discussed. These observations were made during ground surveys undertaken in the peak of summer, January 2010. It must be noted that some of the observations discussed here have not been scientifically (and statistically) tested, but presented here nevertheless to document the changes in light of similar patterns observed elsewhere known to be caused by climate change and sea level rise.

Boundary effects – edge accretion/erosion and landward advancement

On the landward side, saltmarshes generally move upland as a response to rising sea level and changes in tidal inundation patterns. The landscape topography of the Circular Head region is relatively subdued and has extensive low-lying areas into which the saltmarshes can move with sea level rise. However, several levees have been erected in recent decades to exclude sea water incursion and to claim land for agriculture (see Section 6.1 Direct anthropogenic impacts for a fuller exploration of the levees and their effects). The levees have prevented the landward movement of the saltmarshes and severely degraded the marshland seawards of these tidal barriers. In some areas however, the levees have been breached and saltmarshes have developed behind the failed tidal barriers. In places, halophytic vegetation has established behind the tidal barriers, perhaps enabled by shallow saline groundwater incursion and salt spray (Figure 5.47).

Where no artificial tidal barriers existed to landward, it was widely noted that halophytic vegetation was transgressing over glycophytic coastal vegetation which suffered die back probably caused by increased salinity from sea water incursion. The predominant glycophytic coastal vegetation type within the Circular Head region is *Melaleuca* swamp forest. It is known to occur on poorly drained areas and can withstand moderate amounts of salinity. However, an increase in salinity with increased periods of waterlogging with marine water has detrimental impacts on this vegetation community causing a reduction in seedling recruitment and dieback of mature trees (Salter *et al*., 2007). Several instances of *Melaleuca* dieback were recorded within the study area often with halophytic vegetation establishing within the degraded/dying swamp forest stands (e.g., Figure 5.48).

Vertical accretion and vegetation changes

Vertical accretion can be defined as the net increase in the surface elevation of the saltmarsh driven by both allochthonous (both mineral and organic matter from elsewhere) and autochthonous (production of organic matter from within the marsh) sediment inputs (FitzGerald *et al*., 2008). With a relative rise in sea level the marsh can be expected to accrete vertically, with generally higher rates of accretion in the low marsh compared to the high marsh (Cahoon *et al*., 1996). During storm events or river flooding events, rates of vertical accretion can be much higher and in its more noticeable form is manifested as transgressions of sand sheets and shell ridges on the marsh platform, especially near the seaward boundary. Apart from mineral sediment deposition, there is also the allochthonous deposition of organic debris usually comprising of decomposing sea grass and macro algae (generally known as the “wrack”). Both these mineral and organic deposits smother the saltmarsh vegetation, change the topography/hydrology and hence the vegetation composition.

Within the study area, numerous instances of mineral and organic deposits were noted on the saltmarsh platform. In some instances, the mineral deposits seemed to be formed recently as evidenced by the lack of pioneer saltmarsh species which usually colonise newly available areas. In other cases, the mineral deposits were noted to have been colonised to varying degrees by pioneer species (Figure 5.49; Figure 5.50). The primary pioneer species in the study area were noted to be the low marsh halophytes *Sarcocornia quinqueflora* and *Samolus repens*, with the invasive *Spartina anglica* widespread within Duck Bay. Where vertical accretion is not apparent in the form of transgressions by sand sheets and shell ridges, the presence of “disturbance halophytes” such as *Suaeda australis, Atriplex paludosa* and *Chenopoidum glaucum* (with the exotic *Atriplex hastata* occurring in some areas) acts as a potential indicators for “disturbance” associated with vertical accretion (Figure 5.51; Figure 5.52).

Organic deposits were noted smothering the saltmarsh vegetation to varying degrees, with the formation of bare areas and some marsh pools seemingly related to long term smothering and the eventual dieback of saltmarsh vegetation (Figure 5.53). Seagrass wrack was noted to be clinging to *Tecticornia arbuscula* bushes that appeared to be stressed (Figure 5.53). Wrack deposition is known to have a pronounced effect of reducing plant biomass (Tolley and Christian, 1999). Wrack-affected areas could suffer a substantial loss of organic soil carbon thereby reducing the ability of the marsh to maintain its elevation relative to sea level rise (Miller *et al*., 2001). Global warming is linked with the potential increase in storm frequency and wind intensity which can consequently increase storm-induced wrack deposition on the marsh.

Figure 5.47. Establishment of saltmarsh vegetation (and a general salinisation) in low lying agricultural land behind a tidal barrier possibly caused by shallow saline groundwater incursion and possibly aided by salt spray.

Figure 5.48. The succulent shrub *Tecticornia arbuscula* and other saltmarsh plants seen establishing in a *Melaleuca* forest with *Melaleuca ericifolia* dieback evident near the saltmarsh boundary.

Figure 5.49. Storm deposited vertical accretion ("overtopping") at the marsh shoreline boundary. The dead stems of *Tecticornia arbuscula* and the pioneering *Sarcocornia quinqueflora* are evident.

Figure 5.50. Another example of storm deposited vertical accretion ("overtopping") at the marsh shoreline boundary. Saltmarsh vegetation is seen colonising the newly created patch.

Figure 5.51. Seagrass wrack seen deposited on the marsh surface in the foreground. Extensive areas in the background are dominated by the disturbance halophyte *Atriplex paludosa*.

Figure 5.52. An example of marsh disturbance noted across the study area with: shoreline retreat with an erosion scarp; evidence of recent mineral sedimentation (shell ridges or sand sheets); wave scouring of saltmarsh platform and the resulting loss of understorey; and eventual dieback of emergent marsh plants replaced by disturbance halophytes (*Suaeda australis* seen here occupying the disturbed patches).

Figure 5.53. Figure to the left showing extensive deposits of seagrass wrack on the high marsh, with some *Tecticornia arbuscula* shrubs being smothered by wrack. Figure to the right showing the type of pond/bare patch created by long term smothering by wrack.

Status of *Tecticornia arbuscula*

The high marsh halophytic shrub *T. arbuscula* occupies a higher tidal range as compared to low marsh halophytes and is comparatively less well adapted to waterlogging. Sea level rise will increase the hydroperiod in the high marsh and create unfavourable conditions for the dominance of the high marsh halophytes. This can facilitate the gradual replacement of the high marsh halophytes by the low marsh halophytes as they retreat landward (Field and Phillip, 2000; Donnelly and Bertness, 2001). A recent study on south east Tasmanian saltmarsh vegetation communities indicated that large areas of *T. arbuscula* dominated marsh have been converted to *S. quinqueflora* dominance (Prahalad, 2009). The study also reported wide scale losses of *T. arbuscula* due to eutrophication and other anthropogenic impacts.

Historic data of saltmarsh vegetation distribution is not available for the study area and hence any change in the dominance of *T. arbuscula* cannot be ascertained. However, field surveys of saltmarshes in the study area indicated that in several areas *T. arbuscula* shrubs looked unhealthy and suffered dieback seemingly caused by a combination of factors including: increased waterlogging; wrack deposition; eutrophication (evidence by the presence of dense mats of filamentous algae); and direct loss due to erosion. Where wrack and filamentous algae were absent, the main causes of *T. arbuscula* loss seemed to be associated with increased waterlogging and erosion/shoreline retreat (Figure 5.54). Large losses of *T. arbuscula* were attributed to eutrophication and climate-driven salt pans in south east Tasmanian saltmarshes (Prahalad, 2009). In the case of the study area, eutrophication was moderate and restricted to few marshes (especially within Duck Bay and Big Bay). This could partly be due to the presence of the levees that collect most of the nutrient enriched surface run-off from the agricultural land in the catchment, and due to the high rainfall in the area (about twice that of south east Tasmania) which can "flush" nutrients from the marsh into the coastal waterways. High rainfall can also explain the absence of salt pans within the study area, while the low rainfall areas in south east Tasmania have well developed salt pans (Prahalad, 2009).

Figure 5.54. Examples of loss of *Tecticornia arbuscula* due to erosion/shoreline retreat from three different locations in the Duck Bay and Big Bay areas.

5.2.6. Synthesis of sea level rise evidence

The following is a synthesis of the evidence presented in the preceding sections on sea level rise and its effects and "signatures":

- **Sea level rise is happening**
  - Sea level has been rising at Burnie at a rate of 1.4 mm/yr (5.4 cm since 1966). This rate is linked to the observed marsh shoreline recession rate of around 22 cm/yr with an apparent onset of erosion around 1968-1976. Such a distinct onset of a long-term change in shoreline behaviour is an expected sea level rise "signature". It must be noted that there are often decadal and yearly variations in the sea level to which the marsh shorelines adjust by accreting and eroding based on the direction of change. Hence cyclical patterns of erosion and accretion are common in marsh shorelines, and there is evidence of this in the study area. However, when there is a *net* increase in the sea level there is resultant *net* erosion/recession in the marsh shoreline, which is and has been the case in the study area over many decades.
- **Sea level rise "signatures" are apparent**
  - Erosion trend – most of the study area has been eroding with net rates of erosion indicating shoreline retreat associated with sea level rise. The correlation between wave-power and shoreline erosion provides further evidence that the erosion of the shorelines is consistent with the mechanisms associated with sea level rise including:
    - greatest erosional response to sea-level rise where wave exposure (WFI) is highest; and
    - increased erosive power with increased water depth; and
    - increased demand for sediments as a result of increased water depth over, for example, the intertidal flats,

    rather than other contributing factors such as local autocompaction or other anthropogenic disturbances that favour marsh erosion.
  - Erosion of mature trees and shrubs – erosion of long lived mature *Melaleuca* trees and *Tecticornia* shrubs indicate that they have been on stable ground for a long time while growing to maturity and have only recently experienced erosion, suggesting recent onset of major coastal changes as expected from sea-level rise/
  - Erosion of very old deposits – along many shores, old (26,000 to 36,000 yr BP) peaty deposits and Pleistocene dunes are exposed and experiencing active erosion. This is the first time that these locations have been exposed to wave attack since they were formed.
  - Landward vegetation transgressions – the transgression (landward movement) of saltmarsh vegetation into the adjacent *Melaleuca* swamp forests and the dieback of *Melaleuca* trees is consistent with the elevation of the tidal frame with sea level rise. Further, *Juncus* roots were found in the intertidal sediment cores indicating that the saltmarsh was more extensive previously and has retreated landwards since. The widespread occurrence of shell ridges, sand sheets and wrack on the saltmarsh suggest a more energetic shoreline environment, i.e. more wave energy at the shores because of increased water depths as a consequence of sea-level rise.

5.3. *SLR scenario modelling*

5.3.1. Inundation (coastal flood) modelling

Primary Authorship: Michael Lacey and Vishnu Prahalad

Introduction

Inundation (coastal flood) modelling has been employed as a tool to assess the vulnerability of coastal areas to flooding impacts associated with sea level rise (Hubbert and McInnes, 1999; Purvis *et al*., 2008). It can be used as an effective first pass assessment of low lying areas or "pathways" for the intertidal profile (and coastal wetlands) to move into as sea level rises (Prahalad, 2009; Prahalad *et al*., 2010). The inundation modelling used here generated a series of digital map data sets that represent modelled potential inundation of a number of scenarios for the study area including combinations of sea level rise and storm surge at high tide (storm tide). Sea level rise scenarios used are the same as those applied in the Climate Change Risks to Australia's Coasts: A First Pass National Assessment (DCC, 2009) and include present day (0 m), upper limit of the IPCC projected A1FI sea level rise scenario for year 2030 (0.15 m) and a "high end" 2100 sea level rise scenario of (1.1 m). The modelling methodology has been described in detail below.

Methods

The Climate Futures LiDAR Digital Elevation Model (DEM) used for the inundation modelling was supplied via the Information & Land Services Division (ILS) of the Department of Primary Industries, Parks, Water and Environment (DPIPWE) or the Land Information System Tasmania (LIST), May 2008. The DEM is in Australian Height Datum (AHD Tasmania) and has a vertical and horizontal accuracy of +/- 25 cm. The AHD is intended to represent mean sea level based on the 1972 tide gauge data from Hobart and Burnie.[17] However, the actual mean sea level is about 6 cm higher than zero AHD. The sea level rise estimate of 0.15 m for 2030 was obtained from Hunter (2009). This estimate represents the upper end of the IPCC AR4 A1FI sea level rise projections for 2030. The 2100 "high end" estimate of 1.1 m SLR was sourced from Vellinga *et al*. (2008). The standard tidal range modelled data was obtained from the National Tidal Centre (NTC) in the form of a five minute resolution grid of points extending from longitude 111º to 116º East and from latitude 9º to 45º South. This model represents tidal amplitudes in metres between Mean Sea Level and Indian Spring Low Water multiplied by two to give an estimate of the complete tidal range. It includes the four main tidal constituents, M2, S2, O1 and K1, and was calculated as:

Tidal amplitude = (M2 + S2 + O1 + K1) amplitudes * 2

The NTC tide range grid was extrapolated into Boullanger Bay, Robbins Passage and Duck Bay. Additional points were first interpolated midway between the NTC grid points and then extrapolated toward the coast to produce a 2.5 minute grid of points using the following criteria:

- Outside the coastal area, points were interpolated from the existing points to produce a smooth surface.

[17] Geocentric Datum of Australia Technical Manual, Version 2.3. Available online at <http://www.icsm.gov.au/icsm/gda/gdatm/gdav2.3.pdf>, accessed 9th Nov 2009.

- Known tidal heights for Stack Island, Montagu River and Duck Bay were included.
- Mean High Water was estimated for the remaining region from the height of the lower edge of saltmarshes (based on on-ground observations).
- The height of one of the NTC tidal range points off the western end of Robbins Island was adjusted up to match newly calculated heights for eastern Boullanger Bay.

A project specific mean high water grid surface was then produced by spline interpolation from the 2.5 minute point grid.

Modelled storm tide data points representing a 1:100 year storm event and covering the Tasmanian coast were sourced from Kathleen McInnes of the Climate Change Research Group, CSIRO Marine and Atmospheric Research (McInnes *et al.*, 2009). The storm tide data was aligned with the adjusted tide range grid. An initial storm tide grid was produced by spline interpolation from the storm tide point file. An un-interpolated version of the NTC tide range grid (also produced by spline interpolation from point file) was subtracted from the storm tide grid to produce a difference layer. Heights were then sampled from the difference layer at 50 points along the coastline in the Boullanger Bay, Robbins Passage and Duck Bay areas where the coastline intersected a 5 minute reference grid. Average storm tide height over the region was thereby determined to be 0.55 m above the normal tidal range, with a standard deviation of 0.06 m. A new project specific storm tide surface grid was then produced by adding 0.55 metres to the new project specific mean high water grid (see above).

Inundation modelling used the “bathtub” inundation method (Eastman, 1993). This method is identical to the one used for the Climate Change Risks to Australia's Coasts: A First Pass National Assessment (DCCEE, 2009). In this approach, sea level components (including sea level rise estimates and tidal range) together with their associated uncertainty estimates are combined with a DEM to calculate a spatial grid over the area of interest showing the locations likely to be inundated given the model settings and constraints. Output grid values represent the probability (expressed as a percentage) of the sea level being at or above the height at the grid cell position. The potential positions of future shoreline can then be extracted from the grid model for any given probability level. It is important to note that the result does not show the “probability of inundation” per se but is actually showing a “spread” of estimated shoreline positions with a probability limited to that derived from the combination of uncertainties propagated from the inputs. It is designed to give the most likely position of a new shoreline but that likelihood is limited to what is known about the uncertainties in the data inputs. The starting inputs include:

- A DEM in which height uncertainty is estimated;
- The height datum of the DEM is AHD71, which was assumed to be mean sea level;
- Tide estimates including uncertainty estimates; and
- Sea level rise scenario heights (without any uncertainty estimates, i.e. treated as "given").

RMS uncertainty for the DEM was 0.25 m as specified in the DEM metadata. Uncertainty in the sea level rise value was considered as zero as the value was taken as a given absolute amount in this model. A national average estimate of height uncertainty in the tidal range model for 80 tide gauge locations was calculated as 0.155 m. Uncertainty in storm tide heights was taken as 0.0825 m. Combined RMS error was calculated as the square root of the sum of squares of the individual input uncertainty values. Combined RMS vertical uncertainty was 0.29 m for tide range models and 0.26 m for storm tide models. The inundation method was implemented in the ESRI ArcGIS 9.3 environment using a Python 2.5 script on a tile by tile basis. For each LiDAR tile and scenario the model produces an output probability grid containing integer values from 0 to 100. The inundation algorithm was implemented in Raster Calculator. This generates the probability of inundation, given the input DEM, sea level rise and RMS uncertainty inputs. A second output from the model is an "inundation" polygon shapefile that is then produced from this grid using the Raster to Polygon Tool, representing the modelled area that is expected to be inundated (>=50). Model outputs have been merged across the study region to generate two formats, namely:

1) Un-inundated land area within the study area for each scenario;
2) Inundation footprints which show only the inundated area inland of the currently mapped coastline for each scenario.

Results

Figure 5.55 and Figure 5.56 show the current and modelled extent of the modelled high water mark and storm tide mark respectively. In terms of the actual area inundated, while the inundation "footprint" of the present day storm tide was 1,176 ha (~12 km^2), it increased to 1,577 ha (~16 km^2) for a 15 cm sea level rise scenario (2030) and 3,486 ha (~35 km^2) for a 110 cm sea level rise scenario (2100). The inundation footprints without the storm surge components are - for a 15 cm sea level rise scenario was 382 ha (measured inland from the "coastline"), while a 110 cm sea level rise increased the area of inundation up to 2,536 ha (25 km^2).

Table 5.5 Area of inundation (coastal flooding) footprints within the study area in hectares (km^2 in brackets)

Scenario	High water mark only	Storm tide
2010 (0 cm SLR)	237 (~2)	1,176 (~12)
2030 (15 cm SLR)	382 (~4)	1,577 (~16)
2100 (110 cm SLR)	2,536 (~25)	3,486 (~35)

When the results, or inundation "footprints", from inundation modelling were overlain on the property types layer (obtained from LIST), it was revealed that about 75% of the inundation footprints were on private land while the rest were on authority land (i.e. under the jurisdiction of various government agencies, most of which was classified as Crown land). The private land affected largely included agricultural land predominantly used for cattle grazing. In the Duck Bay area, in the vicinity of Smithton, some built property was included in the inundation footprint.

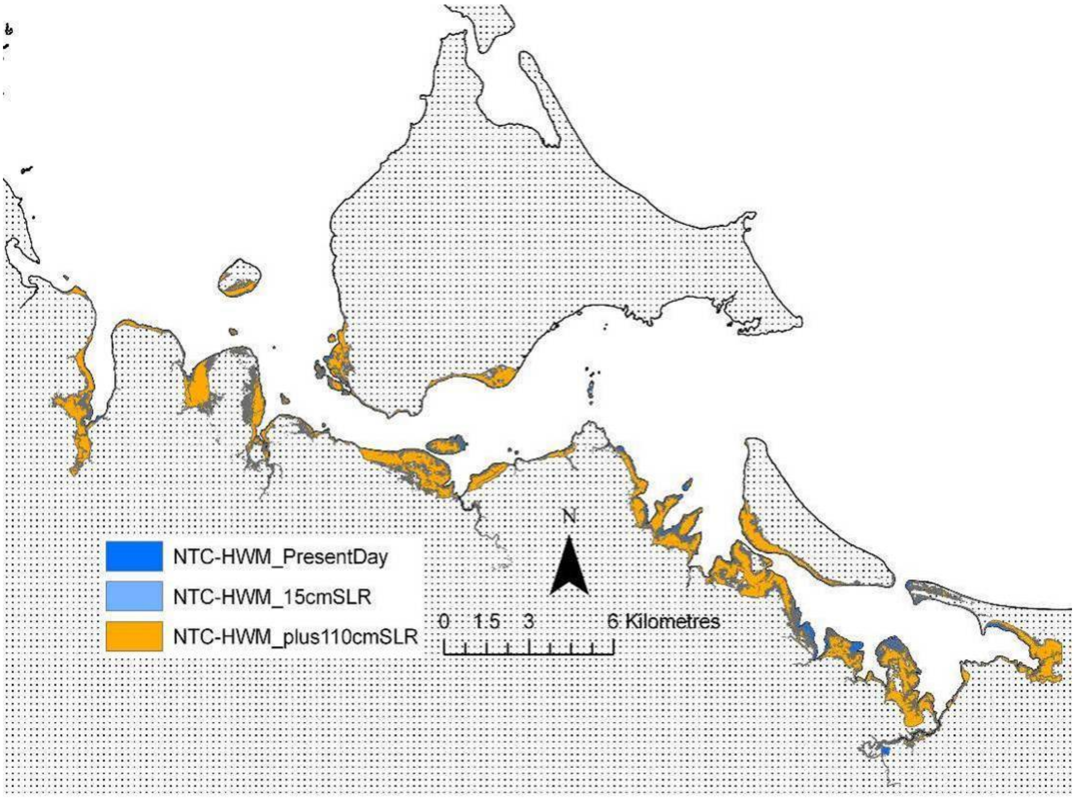

Figure 5.55. Results for inundation modelling showing the potential position of the modelled high water mark (HWM) for the present day and two modelled scenarios. There is very little difference between the Present Day and 15 cm SLR scenarios. The present day HWM was obtained from the National Tidal Centre (NTC) and adjusted to produce a project specific tide model.

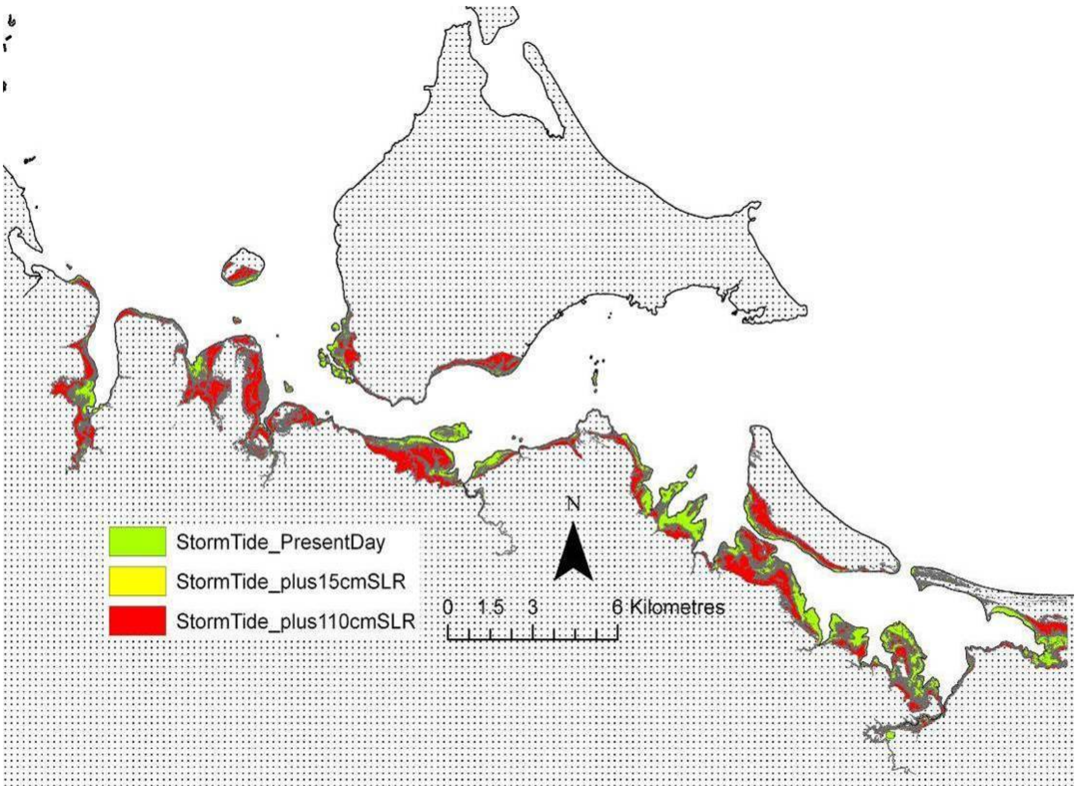

Figure 5.56. Results for inundation modelling showing the potential landward extent of storm tide for the present day and two modelled scenarios. There is very little difference between the Present Day and 15 cm SLR scenarios.

5.3.2. "Room to move" for the coastal foreshore profile

Primary Authorship: Vishnu Prahalad

Introduction

Shoreline, intertidal and subtidal wetlands are part of a continuum of coastal aquatic habitats that make up the coastal foreshore profile within the Circular Head region (Figure 5.57). With sea level rise, the coastal foreshore profile is expected to respond by moving upward and landward (Pethick, 1993) depending on sediment availability. Saltmarshes form the innermost part of this profile and are one of the first ecosystems to respond to the effects of sea level rise. The natural saltmarsh ecosystem response will be to retreat landwards where suitable low lying areas are available. In many parts of the world, especially in the UK and Western Europe, this landward movement of saltmarshes has been actively facilitated and managed.[18] Mechanisms for "managed retreat/realignment" or "planned retreat" or simply providing "**room to move**" are being developed and implemented as an important management response to sea level rise (Boorman, 1999; Adam, 2002; Townsend and Pethick, 2002). The need to give saltmarshes room to move inland has also been highlighted as an important management response to sea level rise in south east Australia (Harty, 2004) and Tasmania (Prahalad, 2009). In this regard, a recent pilot project identified potential areas adjacent to the Derwent Estuary that can provide room to move for the coastal foreshore profile (Prahalad *et al*., 2010). Similar modelling was done for the Circular Head region to identify retreat areas for the coastal foreshore profile to move into as sea levels rise.

Methods

The two main steps involved were: mapping of the current extent of saltmarshes; overlaying the inundation modelling and mapping of potential coastal foreshore habitat areas. The current extent of the saltmarshes was mapped employing the definition of saltmarshes presented in Section 4.2 Shoreline Wetlands (saltmarshes, beaches, tidal channels and *Melaleuca* swamp forests). The previous saltmarsh mapping done for this area by the authors was used as the base layer (Lawler *at al*., 2009). This layer did not include all the known saltmarshes especially within Duck Bay and Big Bay areas. The previous mapping was extended into these areas and updated such that the overall mapping for the study area was consistent to the scale of 1:1,000. The 2006 aerial photographs (obtained and georectified for the previous CCNRM project) were used as primary data layers, while Google Earth[19] satellite imagery, oblique photographs taken from the air in January 2009 and photographs and field notes taken during ground surveys in January 2010 were used as validation data.

Saltmarshes in south east Australia including Tasmania are generally known to occur in the upper intertidal profile between the area just below the mean high tide mark inland to the extent of storm tide inundation (Saintilan *et al*., 2009; Prahalad *et al*., 2010). This range is extended in some cases due to salt spray and/or shallow saline groundwater. To verify these general rules for the study area, the current extent

[18] See: The Online Managed Realignment Guide, available at <http://www.abpmer.net/omreg/>, accessed on 12 May 2010.
[19] See: Google Earth, available at <http://earth.google.com/>, accessed 12 May 2010.

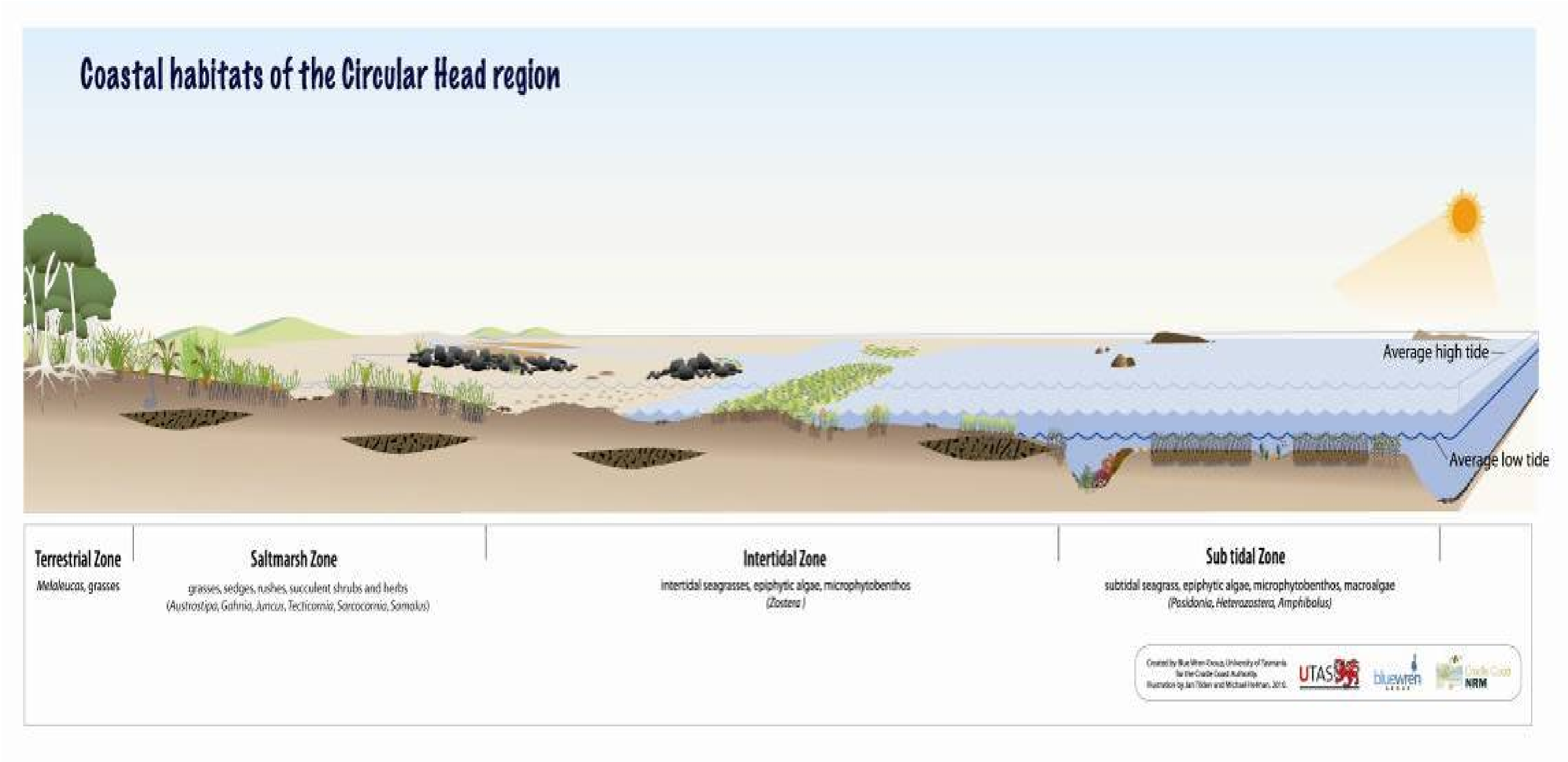

Figure 5.57. The continuum of coastal habitats (divided into four zones) spread across the coastal foreshore profile of the Circular Head region. With sea-level rise, each of these zones will move upwards and landwards.

of saltmarshes were overlayed over the current day storm tide inundation model generated for the project. While the storm tide inundation model clearly matched the extent of saltmarshes in general, in some cases *Melaleuca* swamp forests were also occupying areas of the modelled storm tide extent. This could be due to the ability of *Melaleuca ericifolia* to withstand moderate levels of salinity and reproduce clonally through extended root networks. Further evidence for the elevation range of saltmarshes in the intertidal profile comes from inundation modelling and stratigraphy analysis. Inundation modelling results (see Section 5.3.1 Inundation (coastal flood) modelling) showed that the mean elevation difference between the mean high tide mark and the storm tide mark is about 0.55 m, while height transects across the saltmarshes showed that they have an elevation range of close to 0.5 m (see Appendix 4 Stratigraphy analysis – Technical Report).

It must also be noted here that accurate tide data is not available for most parts of the study area, and the inundation modelling was done with interpolated tidal data (see Section 5.3.1 Inundation (coastal flood) modelling). Given the uncertainty about the accuracy of the tidal data and added to that a lack of any consideration for rates of sedimentation (as they are complex to model), the results presented here must be considered only an indication (or preliminary assessment) of which "path" the tide may take as sea level rises to create conditions favourable for the colonisation of halophytes and not the exact demarcation of future saltmarsh extent.

Results

The Circular Head region has extensive low lying areas near the coast and has considerable potential to allow the intertidal profile to move upwards and landwards (Figure 5.58).

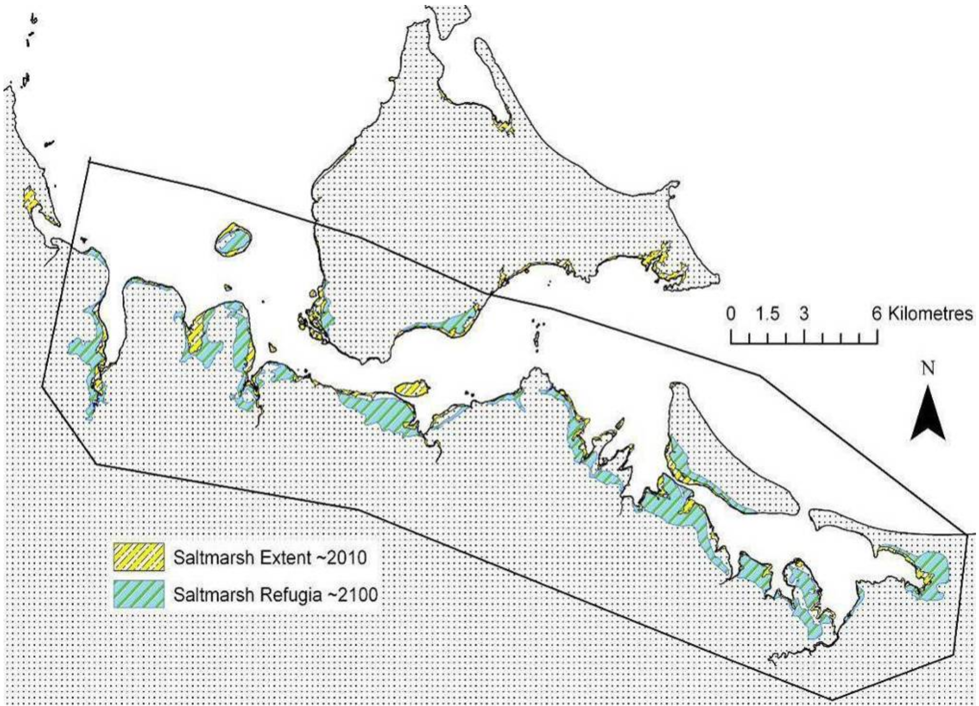

Figure 5.58. Map showing the current saltmarsh extent (circa 2010) and the projected probable saltmarsh refugia pathways (circa 2100) for a 1.1 m sea level rise scenario. The oblong black polygon includes the areas for which inundation modelling was done (other areas did not have the LiDAR DEM coverage).

The presence of levees however restricts the ability of saltmarshes to colonise landward. Prahalad (2009) identified four scenarios for the landward movement of saltmarshes in Tasmania under sea level rise:

- coastal squeeze or submergence – where saltmarshes will be lost due to drowning, i.e. converted to open intertidal areas;
- creeks and confined patches – where saltmarshes have natural or artificial barriers for landward movement, but can still move up creeks and exist within confined patches;
- islands – where saltmarshes retreat upwards forming islands as sea level rise drowns the surrounding areas; and
- uplands (landwards) – where extensive area of low lying land are available for saltmarshes to move into as sea level rises.

Of these four scenarios, most of the saltmarshes in the study area fitted within the uplands scenario. However, the presence of levees creates the coastal squeeze scenario. On-ground evidence of both scenarios actively taking effect was observed during field surveys. In the uplands (landwards) scenario, halophytes were seen invading glycophytes that were suffering dieback (see Section 5.2.5. Changes in shoreline wetlands: vegetation and geomorphology). In the coastal squeeze scenario, saltmarshes were noted to being subjected to coastal squeeze in front of levees (see Section 6.1 Direct anthropogenic impacts).

6. Other threats and stressors

Primary Authorship: Vishnu Prahalad (unless otherwise stated)

This section is important to include in any assessment of sea level rise impacts on natural assets such as coastal foreshore habitats and ecosystems because the ability of these systems to respond to the sea level rise hazard depends on their current condition. If they are "healthy" and resilient, they will be able to respond more strongly; however, weakened, threatened and pressured habitats will succumb to the added sea level rise hazard more readily. The degree of pressure on the habitats is directly relevant to an assessment of their capacity to continue to produce the ecosystem services (benefits) as the climate changes.

6.1. Direct anthropogenic impacts

Direct human impacts are well known to be one of the major threats to saltmarshes across the world (e.g. Bromberg Gedan *et al*., 2009). The types of direct human impacts and their contribution to saltmarsh stress and loss varies widely. With particular reference to the study area, human impacts on the saltmarshes can be summarised as below:

- development (landfill/tidal restriction/tidal manipulation);
- eutrophication and catchment modification;
- grazing and trampling;
- off-road vehicles;
- weeds (or invasive species);
- dumping rubbish;
- removal of fringing vegetation; and
- lack of landward buffers to accommodate saltmarsh response to sea level rise.

Of these impacts, one of the biggest contributors to saltmarsh loss and stress is due to "development" by landfill, tidal restriction or tidal manipulation. Almost one fifth (21.4 km) of the shoreline length mapped as saltmarsh were backed by levees or embankments (Figure 6.1). These tidal barriers have excluded the influence of the tide on the marshes and in the process, considerably reduced the saltmarsh habitat extent and quality (Figure 6.2). In many areas where levees occur, saltmarshes were being squeezed between the increasing sea level and the backing tidal barrier, with only fringing marshes remaining in front of the levees (Figure 6.3). The effect of levees, or dikes, on both the landward and seaward sides of the construction is documented in Hood (2004). Note that populations of the rare saltmarsh plant *Limonium australe* were recorded in these fringing marshes backed by the levees (Figure 6.4) which places them at risk.

The levees collect the nutrients and sediment running off from the immediate catchment in the channels behind them, with some having controllable release points like "taps" to flush the water collected in the channels into the sea. Where water stagnates in the channels, considerable amount of filamentous algae were present indicating high nutrient enrichment (eutrophication). Here, the services of saltmarshes such as nutrient sequestration and denitrification are not being employed to filter the nutrients running off from the land and instead allowed to run “untreated” into the sea at point sources. This could potentially increase the nutrient levels in the coastal waters causing water quality issues. Nutrient-enrichment is well known to cause catastrophic losses of seagrass in the intertidal and subtidal habitats (Burkholder *et al*., 2007), and has been linked to seagrass decline in Tasmania (Rees, 1993).

Within the study area, the rate of development of the watershed (land clearing for agricultural development) has to a greater or lesser extent been proportional to the loss of saltmarshes due to levee building and erosion. In addition, the removal of large areas of coastal fringing *Melaleuca* vegetation has potentially led to increased nutrient loading into the existing saltmarshes and coastal waterways. A 200 m buffer zone of hydric soils, such as that associated with *Melaleuca* swamp forests, has been shown to considerably reduce nutrient loading into the saltmarsh (Wigand *et al*., 2004). Except for some areas in Boullanger Bay and the nearby offshore islands, saltmarshes in the study area in general do not have sufficient buffer zones. Removal of fringing vegetation can further reduce habitat quality by exposing the marsh to other human impacts such as weed invasion and pollution due to increased temperature, light and noise.

Other main direct human impacts on saltmarshes in the study area include the use of off-road vehicles, livestock grazing and dumping of rubbish. In many areas, off-road vehicles have caused defoliation and soil-compression in the saltmarsh (Figure 6.6). More severely, grazing and trampling by cattle were noted to have caused significant detriment in some marshes opened to grazing (Figure 6.7). Extensive grazing can remove plant biomass, disturb the soil and clog up tidal channels thereby considerably reducing the habitat quality and function while undermining the natural saltmarsh resilience to sea level rise (principally by affecting accretion rates). Dumping of rubbish was noted in various sections of saltmarshes, with flotsam from the oyster farms in the area being a notable component (fig.). Littering can smother saltmarsh plants and impede the natural saltmarsh function thereby impacting habitat quality and services.

Another factor under the land managers’ control is the provisioning of landward buffer zones or retreat areas for saltmarshes (and the intertidal profile in general) to “respond” to sea level rise by moving upwards and landwards. In many areas, this natural response has been curbed by the building of levees and other tidal barriers. The future of saltmarsh ecosystem services in the area will depend upon relieving this stress and providing the marshes “**room to move**” with sea level rise.

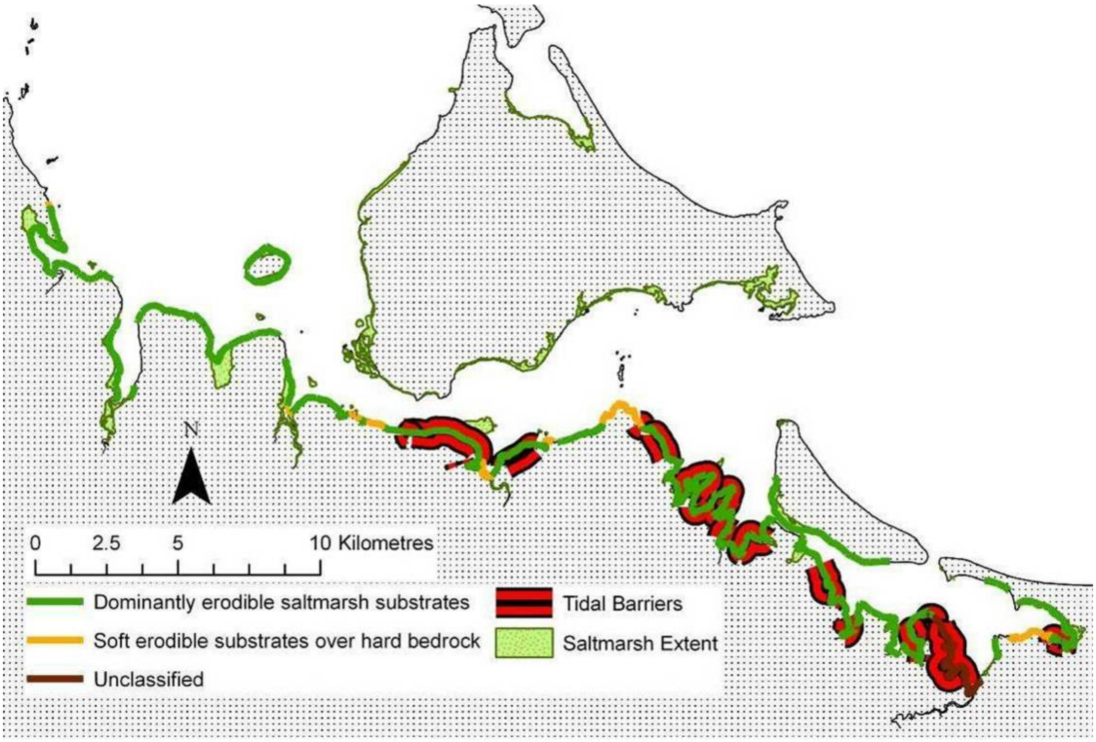

Figure 6.1. The extent of tidal barriers within the study area (for saltmarsh shorelines). The width of the barriers has been exaggerated for better visualisation.

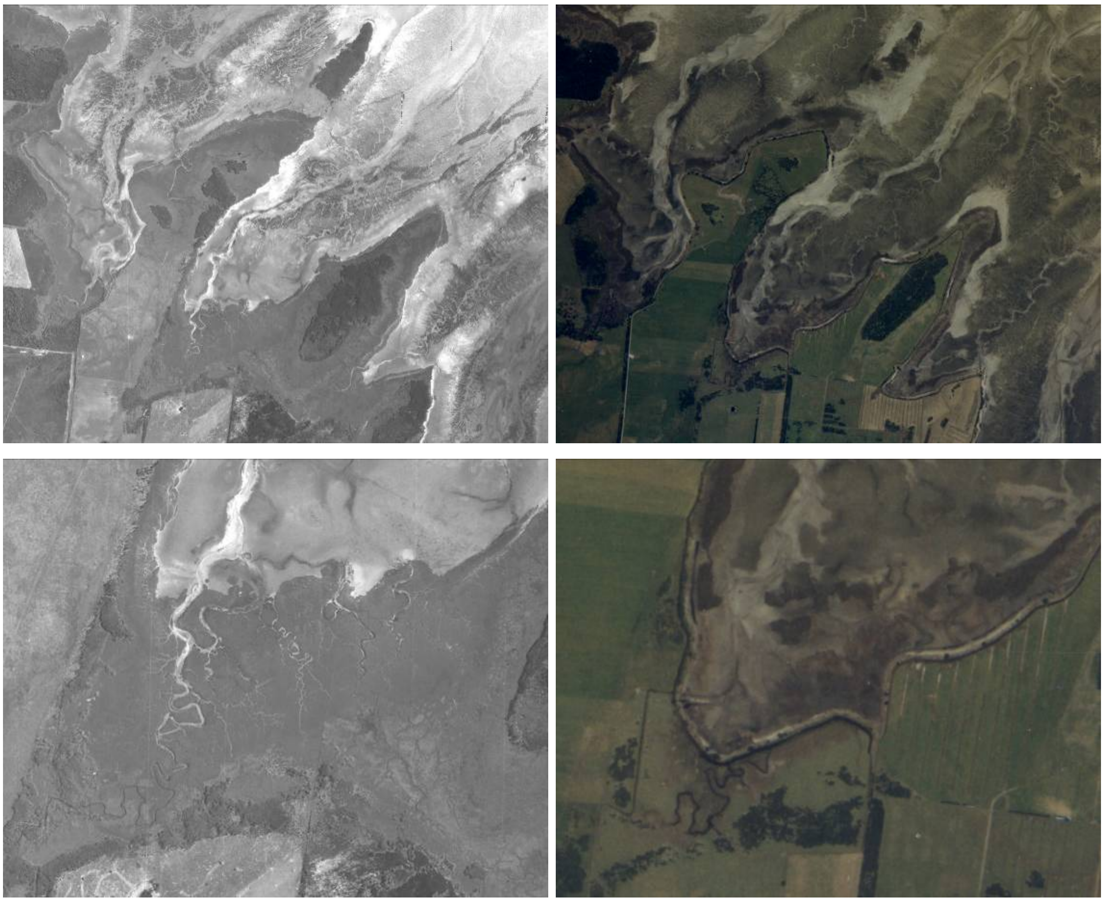

Figure 6.2. Two pairs of aerial photographs (from 1968 and 2006) showing the extent of levee building and the associated saltmarsh loss. The bottom pair (zoomed in) highlights the effect of levees clearly.

Figure 6.3. An aerial oblique view of the levees in Big Bay.

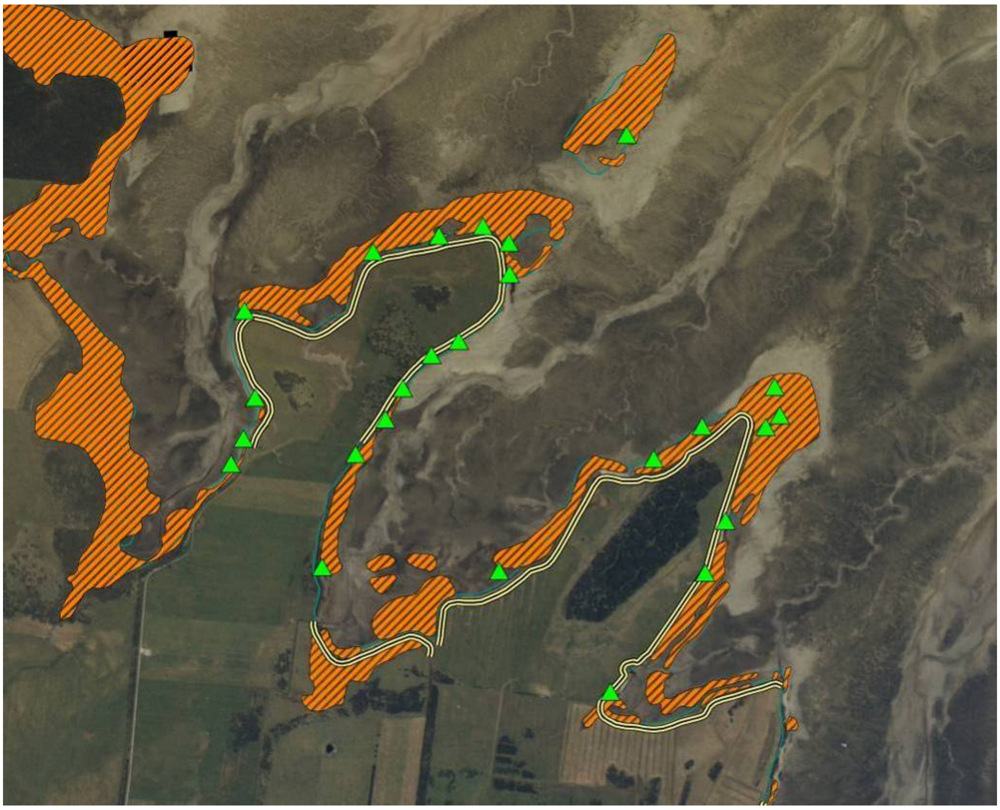

Figure 6.4. Image showing the current extent of saltmarshes (hatched polygons) along with the levees (thick lines) and also the distribution of the rare saltmarsh plant *Limonium australe* (triangles). These plants are at higher risk if the saltmarsh continues on a trajectory of loss.

Figure 6.5. This particular levee was built by dredging soil from both in front and behind the levee creating canals where water accumulates. When this water is not flushed regularly (by either the rain or tides), nutrient levels build up causing filamentous algal blooms. Also note the fringing marsh near the levee where the rare *Limonium australe* was recorded.

Figure 6.6. Defoliation and soil compression caused by the use of off-road vehicles.

Figure 6.7. Significant damage caused by cattle by directly feeding on saltmarsh plants and disturbing the soft saltmarsh substrate. Note the striking contrast in the saltmarsh health across the fence.

6.2. Rice grass (Spartina anglica) and other invasive species[20]

Within the Circular Head foreshore areas, the single most important weed species in saltmarshes and the adjacent intertidal flats is the introduced rice grass (*Spartina anglica*). This highly invasive hybrid grass occupies a wide tidal range and has high rates of sedimentation (generally 20–80 mm per year) aided by its rhizome root structure and dense growth habit (Doody, 2008). Rice grass can rapidly colonise and spread over bare intertidal flats and compete with the native saltmarsh halophytes (mainly *Juncus kraussii* and *Sarcocornia quinqueflora*) and the seagrasses (*Zostera muelleri*) which occur at the same tidal range (Figure 6.8). Uncontrolled spread of rice grass can considerably alter the geomorphology and hence the hydrology and ecology of the intertidal ecosystems in which they occur. This can have several negative implications for biodiversity conservation and affect the flow of ecosystem services from native habitats. Particularly, the expansion of rice grass can reduce the intertidal area available for aquaculture, affect local fish populations, take over shorebird feeding areas, and impact on recreational activities and tourism in the area.[21] Hence, the control of rice grass has emerged as an important management response in Tasmania (Kriwoken and Hedge, 2000) and within the Circular Head foreshore area (Campbell-Ellis, 2009).

[20] This section is only restricted to invasive flora and does not deal with invasive fauna as there are no known major threats to these wetlands from fauna related to sea level rise. See the *Community-based draft Management Plan for the Robbins Passage/Boullanger Bay wetlands 2006* for more information on invasive fauna.

[21] *See*: Resource Planning and Development Commission: Rice Grass management in Tasmania, at <http://soer.justice.tas.gov.au/2003/casestudy/13/index.php>, accessed on 21 April 2010.

The *Strategy for the Management of Rice Grass (Spartina anglica) in Tasmania, Australia 2002* listed Smithton/Stanley area as one of the seven distinct rice grass infested coastal areas in the State. The strategy recommended that "**eradication** be the ultimate area-based management objective for Smithton/Stanley" area.[22]

Within the mapped shorelines of the study area, rice grass infestations were recorded in several areas of the coastline from the Montagu area towards Smithton, with no records of its occurrence westwards from Montagu (also see Campbell-Ellis, 2009). Infestations were particularly severe within Duck Bay and Deep Creek Bay. A severe infestation of rice grass has been considered here to be a section of a shoreline whose geomorphologic behaviour has been considerably affected by the prevalence of the grass. Over 5 km (4.4% of the total shoreline length) of the shoreline mapped were classified to be severely infested by rice grass. Such shorelines may respond differently to sea level rise although there are no known studies currently available that has either documented or predicted such behaviour for the Tasmanian context. However, it is valid to hypothesise that the spread of rice grass can increase with sea level rise as they have a wide tidal range and can outcompete native marsh species with its much narrower tidal range. This could be further facilitated by their high sedimentation rates. Some evidence for this hypothesis can already be seen within Duck Bay, where rice grass has formed extensive areas of monospecific stands seawards from the eroding native saltmarsh edge (Figure 6.9). Furthermore, a study by Holmer *et al*. (2002) has suggested that sea level rise will have no direct detrimental impacts on rice grass (i.e. via waterlogging and anoxia) because of the oxygenating effect of its well developed root system.

Besides rice grass, sea spurge (*Euphorbia paralis*) is considered to be the other major invasive weed species in the area and has a current monitoring program (Campbell-Ellis, 2009). Sea spurge occurs mainly as back-beach communities and on sand dunes where they form extensive monospecific stands displacing native species. Within the study area, the extent of beach shorelines and hence the occurrence of sea spurge was restricted. Apart from a major infestation at the back of a cobble beach shoreline near Woolnorth Point, their occurrence in other mapped shorelines was limited (some were found on Perkins Island; also see Campbell-Ellis, 2009). Two other weeds, marram grass (*Ammophilia arenaria*) and sea wheat grass (*Thinopyrum junceiforme*), known to occur on sand dune systems have also been listed to of importance to the wetland area (TLC *et al*., 2006). Within saltmarshes, exotic species such as *Atriplex hastata*, *Parapholis spp.* were recorded, with the former occurring on disturbed patches and the latter on elevated patches dominated by grasses.

[22] Strategy for the Management of Rice Grass (*Spartina anglica*) in Tasmania (2nd Edition), Australia, 2002. Department of Primary Industries, Water and Environment, Tasmania, Australia.

Figure 6.8. Rice grass seen well established within the native saltmarsh and outcompeting the native saltmarsh herb *Sarcocornia quinqueflora*.

Figure 6.9. Rice grass developing in front of the eroding edge of the native saltmarsh.

6.3. Acid sulphate soils

Almost the entire extent of the Circular Head foreshore area has been identified to be an acid sulphate soil “hot spot” with extensive Holocene deposits that have acid sulphate soil potential.[23] Land use activities related to vegetation clearance, dredging, excavation, wetland drainage and groundwater extraction can expose these buried potential acid sulphate soils. When exposed, these soils oxidise and produce metal-rich acid that runs off into the receiving coastal waters causing flushes of heavy metal pollution and acidification events (Gurung, 2001). This can lead to the deterioration of the water quality in the coastal areas leading to fish kills, vegetation dieback and loss of aquaculture production, with public health implications.[24] Large extents of Holocene saltmarshes have been drained and dredged (to build levees) exposing saltmarsh soils to oxidisation and potential acid sulphate soil formation. The effect of Holocene soil exposure by coastal erosion and anthropogenic effects on acid sulphate soil formation and it subsequent effect on water quality in the study area is not fully understood and requires research.

6.4. Nitrogen and phosphorus[25]

Primary Authorship: Richard Mount and John Gibson

6.4.1. Introduction

The Duck and Montagu Rivers deliver among the highest loads of Total Nitrogen (TN) and Total Phosphorus (TP) of all Tasmania's Rivers into their respective estuaries (see Figure 6.10)(John Gibson, pers comm., 2010). The fate of those nutrients is complex and has not yet been determined. Given the large absolute amounts and high water column concentrations and given that seagrasses and algae are known to be nitrogen and phosphorus limited (Romero et al., in Larkum at al., 2006) these nutrients are highly likely to be having a substantial ecological impact. The eutrophication (nutrient enrichment) pathway is well documented for estuaries, saltmarshes and seagrasses (e.g. Burkholder et al., 2007) and includes seagrass growth associated with a initial mild fertilising effect, but then a cascade of effects leads to changes in the ecology and, frequently a shift from macrophyte (e.g. seagrass and saltmarsh) dominated habitats to algae dominated (including algal blooms). The loss of seagrasses can be dramatic, large and difficult or impossible to reverse (Gillanders, in Larkum et al., 2006). In part this is due to changes that take place in the sediments including an increase in anoxic conditions, release of previously bound phosphorus and an increase in damaging sulphides (Marba et al, in Larkum et al., 2006). This project undertook some sampling of sediment nutrient levels under the guidance of John Gibson, TAFI to compliment the nutrient cycle understandings emerging from the Landscape Logic project.

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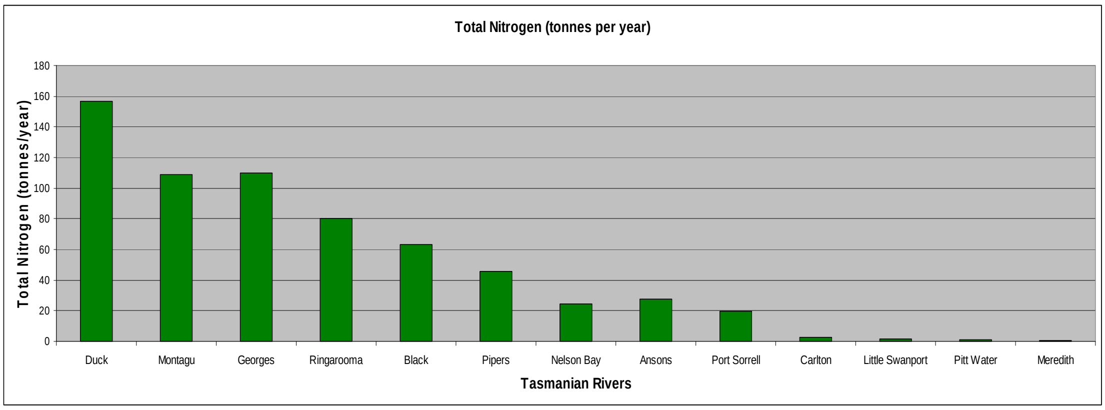
[23] *See*: Resource Planning and Development Commission, The Disturbance of Acid Sulphate Soils, <http://soer.justice.tas.gov.au/2003/lan/2/issue/91/index.php>, accessed 22 April 2010.
[24] *See*: OzCoasts, Acid sulphate soils, <http://www.ozcoasts.org.au/indicators/acid_sulfate_soils.jsp>, accessed 22 April 2010.
[25] Comment by John Gibson, Tasmanian Aquaculture and Fisheries Institute (TAFI) and Landscape Logic, April 2010. Lynda Radke, Geoscience Australia also commented.



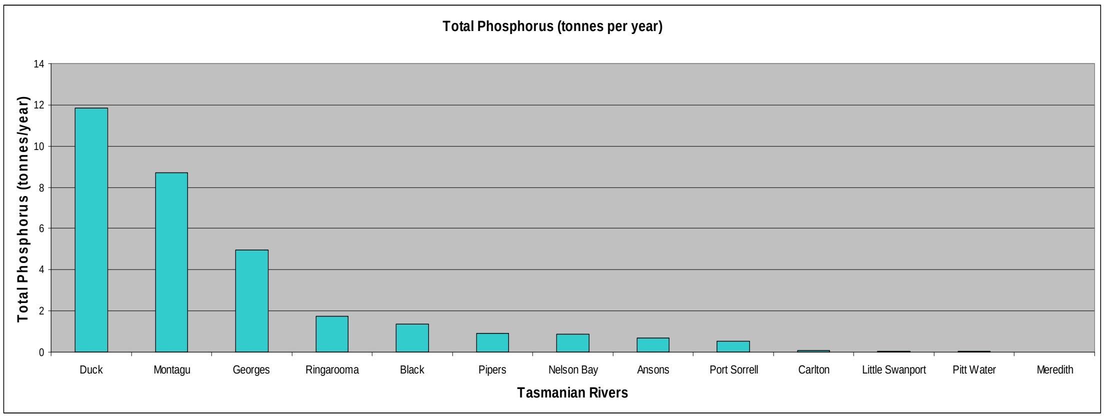


Figure 6.10 Nutrient loads for the Duck and Montagu Rivers are the highest in Tasmania. Source: John Gibson, TAFI, unpub. data.

Sediments in Tasmanian estuaries contain significant quantities of particulate nitrogen (N) and phosphorus (P). Within any particular estuary there is a near constant ratio between sediment N and P, though the absolute amounts of these elements varies as a function of particle size. In all estuaries total N and P inventories are much higher in the upper estuary where the sediment is muddy than near the mouth where the sediment is sandy. Comparative studies from a range of estuaries indicate that estuaries with significant agriculture in their drainage basins can have elevated P with respect to N. Further analysis of the Tasmanian data indicates that the N and P are probably behaving independently. The ratio between N and loss-on-ignition (a relatively crude measure of organic carbon) is near constant. In more or less natural estuaries (e.g. Ansons Bay), the amount of sediment P is low compared to N, reflecting the stoichiometry of phytoplankton (16N:1P – Redfield ratio) rather than seagrass (20N:1P – Romero et al., in Larkum et al., 2006). In rivers with high levels of agriculture in the catchment the inflowing water and sediment matter have high P concentrations resulting in an N:P ratio lower than the Redfield ratio.

6.4.2. Methods and results

Sediment N and P data were obtained for four transects in the study region (Figure 6.11). One transect was to the west of Robbins Island at Sealers Spring Point, the second at Brick Islands near Robbins Passage Crossing, the third in Big Bay near Stony Point to the east of the Montagu River estuary and the fourth in the western end of Duck Bay, part of the Duck River estuary. Ten 40 ml samples of sediment from the surface 20 mm were obtained along each transect ranging from just below the saltmarsh edge out across the intertidal sand flats about 1000 m. All samples were placed on ice in the dark and processed for total N & P by NATA accredited Analytical Services Tasmania Rpt No. 43077 (Appendix 3). All N and P data were of similar magnitude to that recorded in other studies (Heap et al., 2001), but until the data can be normalised with respect to grain size, it is not possible to say that the sediments analysed in this study were particularly N or P rich.

The N:P mole ratio, which is independent of grain size, showed marked variability Table 6.1across the study sites. There was little variability at Sealers Spring Point in Boullanger Bay and Bricks Island in Robbins Passage, and the ratio was in the range of more or less “natural” estuaries. The ratio was lower (i.e. P rich) at East Montagu at the meeting point between Robbins Passage and Big Bay, and lower again in Duck Bay. However, the ratio in the last transect (Trans 4) was still higher (i.e. more N to P) than the extremely low values in the main channel of the estuary (ration is 5.5 to 1 compared to 2.52 to 1).

Table 6.1. **N:P mole ratios in 4 transects in NW Tasmania.**

* - Data from other estuaries is provided for comparison (Gibson, unpublished data).

Location	N:P Mole Ratio
Trans 1 (Sealers Spring)	16.0
Trans 2 (Brick Islands)	15.8
Trans 3 (East Montagu)	11.2
Trans 4 (Duck Bay)	5.5
Montagu*	6.2
Duck River*	2.52
Black*	20.8
Ansons Bay*	15.2

6.4.3. Discussion

From the ratio of N:P, the Duck River estuary sediment is clearly higher in P than in the apparently relatively unimpacted Boullanger Bay sediment. The East Montagu transect (near Stony Point) was in between. The Duck River data from this study were less P-rich than those collected for the Landscape Logic project from the main channel (Gibson, unpublished data). These data indicate that the sediment on the nearshore open flats to the west of Robbins Island is relatively little affected by agricultural P, though this conclusion should be tested with further sampling in the Welcome and Harcus River estuaries to look for localised effects. The higher P at East Montagu may be due to input from the Montagu River which at times is known to have very high total nitrogen and phosphate concentrations (WIST, 2010). The Duck Bay data has the highest P (in ratio terms) though suggests lower relative P input than in the main channel, which could be due to differential transport of N and P within the estuary. Differential transport could occur where N is transported in dissolved forms which then flocculate, while P is transported on particles. Alternatively, N and P input in this region of Duck Bay could reflect the characteristics of some of the more minor tributaries to the estuary in this part of the bay (e.g. Scopus Creek).

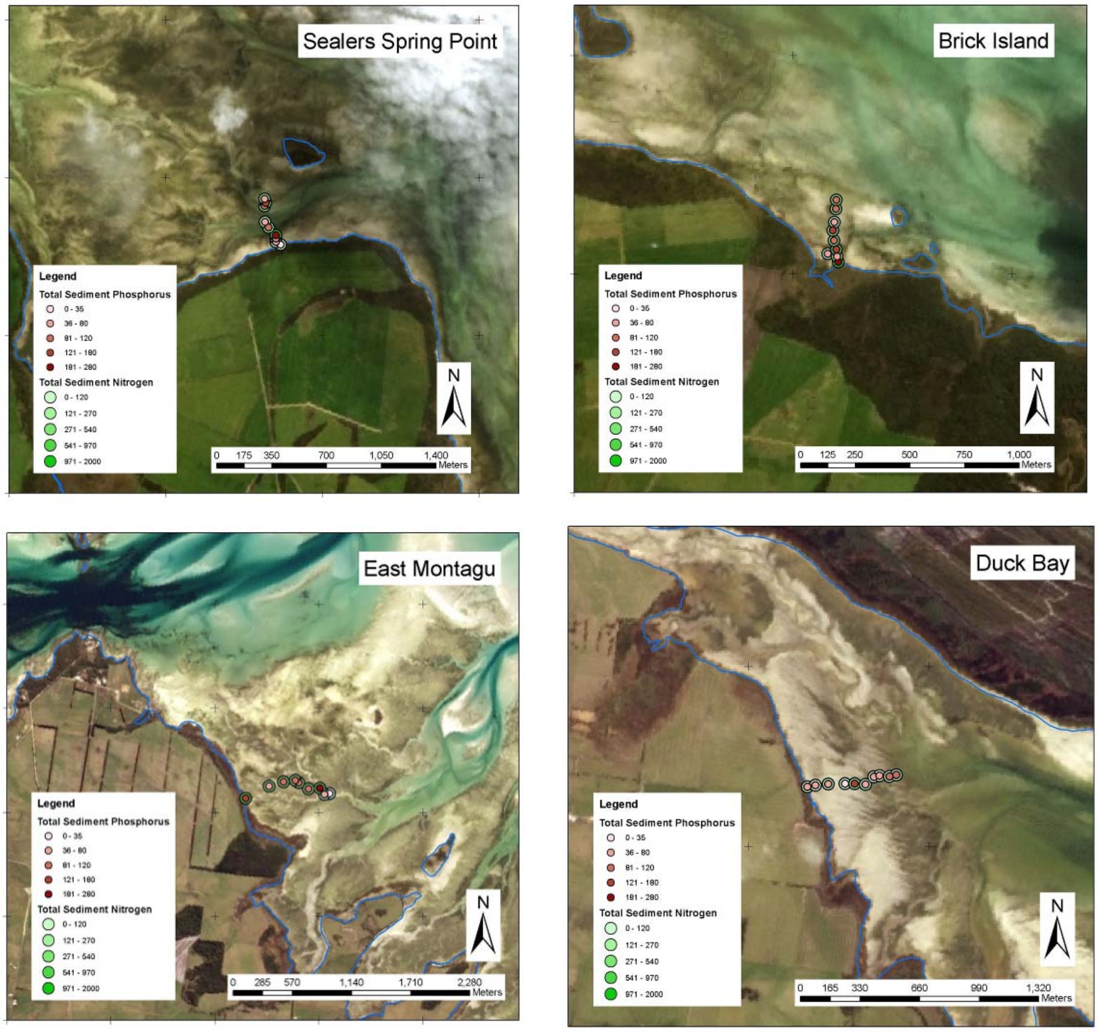


Figure 6.11 Intertidal flat sediment total nitrogen (N) and phosphorus (P) mg/kg DMB (Dry Matter Basis) (unnormalised) for four sites. Caution: these are the raw measurements and they were used to generate the ratios reported in Table 6.1. Further work is required to normalise them for particle size and produce nutrient concentrations.

In general terms, higher P in sediment is considered to be related to sedimentation rates. In Western Australian wave dominated estuaries, Radke *et al*. (2004) found that moderate sedimentation rates (i.e. about 6 kg m^2 yr^{-1}) correlated with poorer water quality (i.e. more algal blooms and higher TN, TP and chlorophyll *a*) while both lower and higher rates were correlated with macrophyte (e.g. seagrass) dominance, though for different reasons. Care needs to be exercised in inferring the status of the project study area from those findings as there are a number of factors that need to be assessed including the availability of iron and sedimentation rates and the nature and rate of weathering (Radke *et al*., 2004); however, that work has developed a useful conceptual model that may serve a basis for further investigation (Figure 6.12). It is expected that the Landscape Logic project will shortly deliver a deeper understanding of these processes.

The ecological implications of the high sediment P are uncertain. It is possible that these intertidal sediments may act as a long term P source, with the element being released slowly to the seagrasses (Romero et al, in Larkum *et al*., 2006), though generally, equilibrium is reached between P and iron in sediment (Radke *et al*., 2004).

Another view is that the “fertilising” effect of P on, for example, seagrasses is mainly driven through concentrations in the water column rather than through processes in the sediment, though note that the large dilution effect of the tidal exchange in this system is considered to minimise the effects of nutrient enrichment (Hirst *et al*., 2009). Alternatively, the nutrients flowing into the system via the rivers may lead to higher productivity in the sediments themselves through benthic primary productivity. High P may lead to the selection for nitrogen-fixing cyanobacteria, such as occurred in the Peel Inlet in WA. The greater productivity may continue up the food web, ultimately to the birds of the mudflats.

It is important to note that under eutrophic conditions the sediment is more likely to release phosphorus and become a source rather than a sink of phosphorus and accelerate the eutrophication process (Marba *et al*., in Larkum *et al*., 2006).

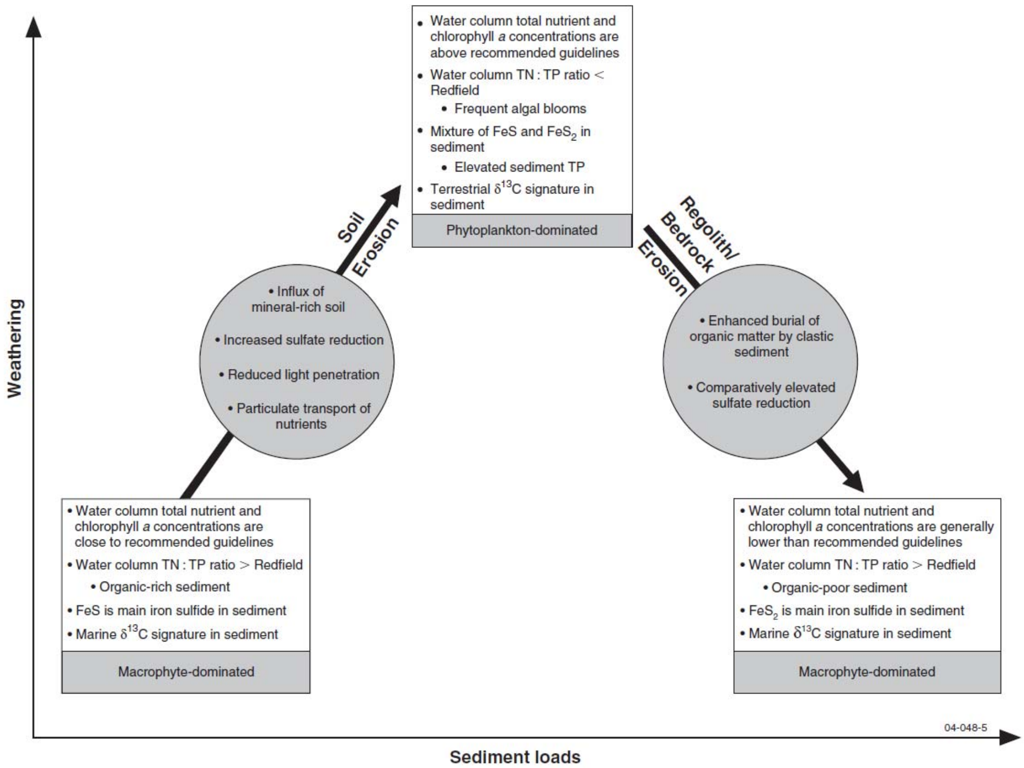


Figure 6.12 A conceptual model of changes in coastal water and sediment quality with sedimentation rates drawn from Western Australia (Radke *at al*., 2004)

6.5. *Climate futures*

Data from Climate Futures for Tasmania[26] indicates that both the average minimum and maximum temperature in northwest Tasmania will increase by about two degrees by the end of the century (Figure 6.13). This will increase the evaporation rates in the area, and CSIRO models predict that there will be up to a 12% increase in evaporation rates for every degree of temperature rise (CSIRO, 2001). While the Climate Futures data reveal no major changes in annual rainfall for the area, according to CSIRO models for Tasmania, rainfall will increase in winter and decrease in other seasons (CSIRO, 2001). A decrease in summer rainfall and increase in evaporation rates could have many physiological consequences for plants which are major "habitat engineers" in the Circular head foreshore habitats. For example, increased evaporation can both create "salt pans" within the saltmarsh (areas devoid of plant cover) (Bertness and Pennings, 2000) and amplify the effect of eutrophication by supporting excess algal growth (Welch *et al*., 2001). Furthermore, species distribution can be altered by changing the competitive ability of plants. Also, lack of frost can enable mangroves to start establishing and thereby change the habitat structure and dynamics of the area.

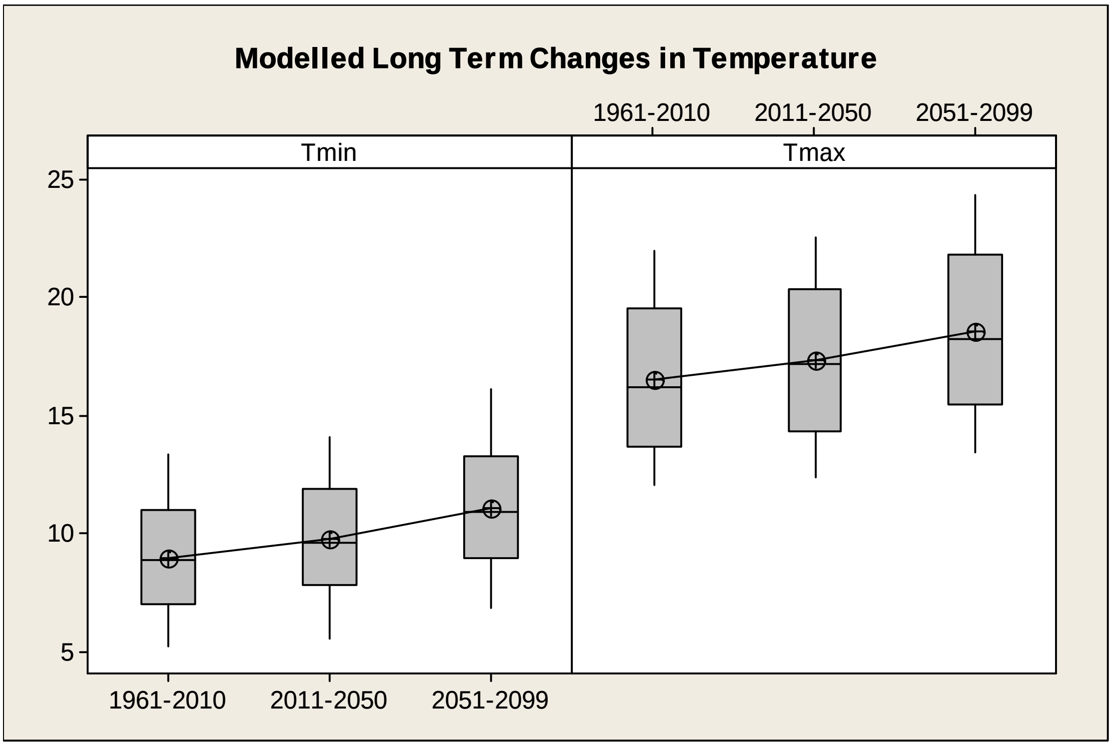


Figure 6.13. Modelled changes in temperature up to the year 2099, for a high emission scenario.

[26] See: Antarctic Climate and Ecosystems Cooperative Research Centre, *Climate Futures for Tasmania*, <http://www.acecrc.org.au/drawpage.cgi?pid=climate_futures>, accessed 27 May 2010.

7. Vulnerability assessment

Primary Authorship: Richard Mount

7.1. Introduction

There are many approaches to estimating and predicting sea levels and their rate of change. It is generally accepted that sea levels have changed by hundreds of metres through geological time. There is also strong evidence that there was a “recent” rise in sea level about 6,000 years ago that inundated the land and stabilised at the current shoreline. It is fairly obvious that specialist shoreline plants and animals have moved with those sea level changes. This means that, in general terms, the habitats are fairly robust to sea level changes. However, the current circumstances are different to those previous times of change as there are broad landscape scale alterations to the land, including along the coast, and a set of people with a mix of values and objectives that may be impacted by sea level changes. The vulnerability assessment is conducted specifically at the nexus between the objectives and values those people hold and the benefits that flow from the habitats that support those objectives and values.

The Australian Standard for risk management sets out a process for assessing and treating risks (AS/NZS ISO 31000:2009, was AS/NZS 4360:2004) as follows:

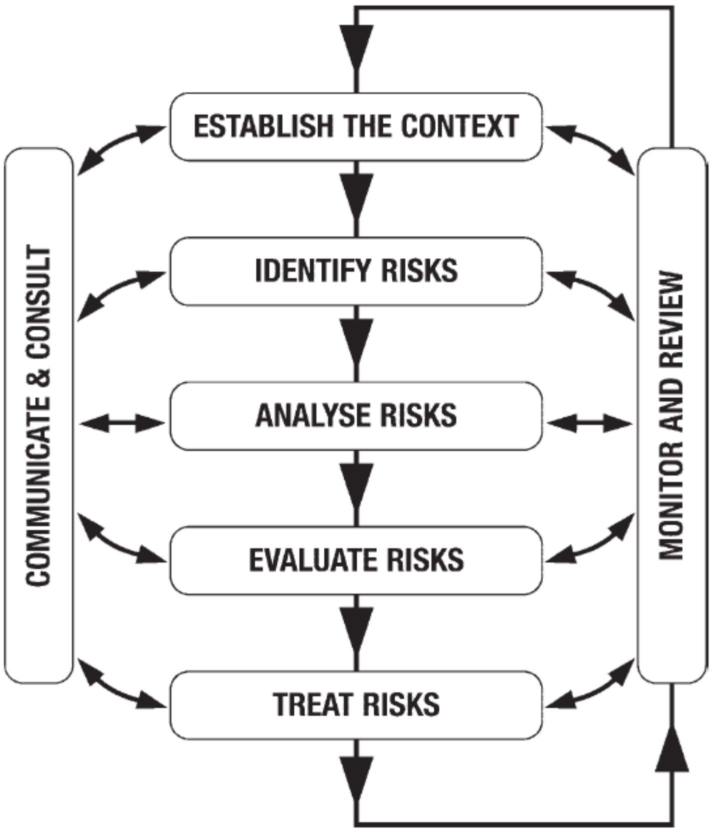


Figure 7.1. The standard risk assessment process. Source: Emergency Management Australia 2004 Emergency Management in Australia: Concepts and Principles.

The Tasmanian Department of Primary Industries and Water (DPIW, now DPIPWE) Coastal Risk Assessment Template (DPIW, 2009) has adopted the Australian Standard and the approach taken here is highly consistent with that approach, though adapted for the specific requirements of this project.

This project has the aim of answering the questions of:

- **How do the things people do and care about benefit from the coastal habitats found in the area?** and,
- **Are those benefits vulnerable to sea level rise?**

This aim was broken up and addressed by the project team as a series of questions (the brackets indicate the relevant part of the standard risk assessment process):

1. What are the things people do and care about (context and communicate and consult)?
2. What do we know about the environmental history of the area (context)?
3. What sorts of things grow and live around the shores (habitats) and how do they work today (context)?
4. Do the habitats help people to achieve their hopes and goals (assets and benefits)?
5. What signs or evidence is there of a change in the level of the sea (identify hazard)?
6. Are those benefits likely to be affected by sea level rise (analyse and evaluate risk)?
7. What can be done to maintain those benefits (treatment)?
8. The project has a complementary aim of communicating the results to those that can make the most of the information the project generates (communicate and consult).

While the project is called a “vulnerability” assessment that term is interpreted in the general sense and a broad generic risk assessment approach is taken. Formal scoring is not conducted as there are multiple organisations and management objectives and values in play which makes it impossible to identify absolute or even relative risk ranking as the context cannot be focussed narrowly enough. In response to this challenge, this project seeks, wherever possible, to quantify the assets, the benefits (ecosystem services) and hazards to provide the basis for specific risk assessments, for example, for a specific dairy farm or aquaculture location or for a specific purpose, such as the impact of sea level rise on carbon sequestration.

The use of the Environmental Condition Assessment Framework (ECAF) (Mount, 2008; see Box 1.1) has enabled a process of “filtering” the assembled information base of current understanding by assessing it against the stated management objectives and values. This means that given what we currently know about a habitat works, how it provides benefits and how those things will be impacted by sea level rise, which are the most important things to focus on. This “filtering” process has used a set of criteria as follows:

1. Must be a major impact (i.e. loss of benefit e.g. significant loss of land);
2. Must be something that can be addressed by the report recipients;
3. Must be supported by evidence.

This approach also aligns with and supports the frameworks underpinning the Communication Plan including the strategic Frame Analysis and the Seven Doors model (see Tilden *et al*., 2010). For the purposes of this project the following definition of terms and roles is used:

“Based on an asset’s value and its susceptibility (sensitivity or vulnerability) to a hazard assess the risk to an asset in terms of likelihood and consequence”, where:

1. “assets” are the coastal habitats and the benefits (ecosystem goods and services) they provide;
2. “values” are as defined by currently documented management objectives and values underpinning current human activities;
3. “susceptibility” is derived from the current understandings documented in the conceptual models and key environmental process analyses and includes the concept of habitat “resilience” that may be affected by pressures and threats (hazards) other than sea level rise;
4. “hazard” is primarily sea level rise and related mechanisms (Other hazards are taken into account including other climate change processes and local human pressures in the “susceptibility” component;
5. “likelihood” is informed by the current evidence and sea level rise scenario modelling based on best current understanding; and
6. “consequence” is about the degree of loss of benefits (ecosystem services) to the hazard and is informed by the linkages between the benefits and the sea level rise hazard.

7.2. *Vulnerability assessment*

The following table sets out the major assets and benefits at risk from sea level rise (SLR). It lists some general consequences and treatments. More detail is provided in the following sections.

Asset	Context	Susceptibility to SLR	Consequence	Risk	Treatment (general)
Shoreline and seabed stability	Almost the entire shoreline profile is soft, erodible and subject to wind waves and tides. Coastal habitats provide a tough resilient and responsive barrier.	Seagrasses and saltmarsh are providing long term protection and are responding to SLR. Resilience is currently high though pressures are apparent.	Very large scale sediment movement; shoreline erosion; valuable food production areas lost to coastal flooding and salinisation.	high	Provide natural assets with “room to move”; maintain habitat resilience including by controlling nutrient and sediment pollution. Reduce other pressures on habitats.
Coastal water quality	Saltmarshes, seagrasses and intertidal sediments are filtering and buffering nutrient and sediment loads. The region has a high tidal flushing rate and high rainfall.	Habitats may “drown” or face significant disturbance from SLR thus reducing their production of benefits. A high tidal flushing rate is assisting resilience.	Potential for algal blooms; loss of aquaculture production; reduced marine productivity; impact on recreational activities.	high	Provide natural assets with “room to move”; maintain habitat resilience including by controlling nutrient and sediment pollution. Reduce other pressures on habitats.
Food security	Many people receive health, social and economic benefits from the high levels of coastal habitat primary productivity and associated food webs.	Primary productivity is threatened by SLR through habitat loss, sediment disturbance and reduced water clarity.	Marked reduction in fisheries and aquaculture production, including recreational and indigenous fisheries.	moderate	Provide natural assets with “room to move”; maintain habitat resilience including by controlling nutrient and sediment pollution. Reduce other pressures on habitats.
Carbon sequestration	Seagrasses and saltmarshes and associated primary producers sequester considerable amounts of carbon and are long term carbon reservoirs.	Loss of carbon sequestering capacity and carbon reservoirs due to large scale habitat loss and destruction of reservoirs.	Long term consequences for atmospheric carbon concentrations.	moderate	Provide natural assets with “room to move”; maintain habitat resilience including by controlling nutrient and sediment pollution. Reduce other pressures on habitats.
Preservation of future options	Habitats provide complex ecosystems, including biodiversity and geodiversity.	Habitat loss may be accelerated with SLR; resilience to SLR may be reduced with poor management practices.	Loss of opportunities for this and future generations.	high	Provide natural assets with “room to move”; maintain habitat resilience including by controlling nutrient and sediment pollution. Reduce other pressures on habitats.

8. Communicating the key messages (story lines)

Primary Authorship: Jan Tilden, Richard Mount and Vishnu Prahalad

The Communication Plan for the project was developed as a complementary sub project lead by Dr Jan Tilden (Tilden *et al*., 2010). The plan is intended to advise Cradle Coast NRM of the primary audience, the key messages drawn from the project and propose some options about how those messages may be best communicated. While this report and the Communication Plan have different purposes, there is a clear overlap with regard to the establishment of the key messages. To that end this report will cross reference the key messages here.

Given the findings of this report, the messages are carefully structured in the following form:

1. People benefit, in their social and economic activities, from goods and services provided by coastal habitats. Coastal habitats are natural assets.
2. These habitats are dynamic and are shaped by many environmental influences, two of which are people and sea level rise. In some cases sea level rise is already having an adverse impact on services provided by these habitats. In other cases, threats from other factors such as excess nutrients and changes to sediment movement are threatening the resilience of habitats to sea level rise.
3. People can "work smarter" by working with nature, taking action to assist the habitats to continue to produce the benefits. In making management decisions (including decisions about how to deal with climate change impacts), land managers can ask "Is there a way to do this by working with nature to minimise costs and maximise benefits?"

Actions people can take to protect ecosystem services are summarised in Section 9 under Management Options. Evidence to substantiate the key messages can be found in the preceding sections of this report, and has not been repeated here.

Key messages summary

Message A. Coastal habitats and their vegetation (*Melaleuca* swamps, saltmarsh and seagrass) work interdependently to protect coasts from erosion, damping the effects of waves, holding sand in place with their roots and building up soil along the shoreline. As well as being nature's first line of defence against shoreline erosion, they provide many other valuable benefits. It is very worthwhile, both economically and in terms of protecting the lifestyles valued by the people of the Circular Head region, for the community to work together to look after these vast natural assets.

Message B. Healthy saltmarsh and seagrass beds help keep the water clean and clear, maintaining suitable conditions for a variety of human uses including aquaculture and recreational uses.

Message C. The shorelines, intertidal and subtidal habitats of the Circular Head region are primary producers on a massive scale, supporting food-webs in the immediate coastal areas and far beyond. In this way, they contribute to Australia's food security and also to the health of people living in Tasmania's North West.

Message D. On a daily basis, the saltmarshes and seagrasses of the Circular Head region take carbon from the atmosphere and store it as residual plant matter through burial in the sea floor (a process known as carbon sequestration) thus helping to slow the progress of climate change. In addition, the vast saltmarshes and subtidal seagrass beds of Boullanger Bay are protecting carbon that has been removed from the atmosphere over thousands of years in their deep subsurface mats and soil profiles. They are large carbon "sinks" or reservoirs (storage areas).

Message E. Every ecosystem is highly complex and there are many things that people do not yet understand about them. Further, it is possible to predict that new activities and values will develop in the future that we do not know about now. For these reasons, large complex functioning ecosystems hold potential and opportunities for people that are likely to be realised in the future by our descendants, yet can be destroyed in the present. Protecting ecosystem functioning, biodiversity and geodiversity can be regarded as a form of ecological banking as it maintains valuable assets into the future that are difficult, expensive or impossible to reinstate once destroyed.

8.1. Key messages and storylines

Message A. Shoreline and seabed stability

Coastal habitats and their vegetation (*Melaleuca* swamps, saltmarsh and seagrass) work interdependently to protect coasts from erosion, damping the effects of waves, holding sand in place with their roots and building up soil along the shoreline. As well as being nature's first line of defence against shoreline erosion, they provide many other valuable benefits. It is very worthwhile, both economically and in terms of protecting the lifestyles valued by the people of the Circular Head region, for the community to work together to look after these vast natural assets.

1. Coastal landholders benefit from services provided by coastal habitats, namely the *Melaleuca* (tea tree or paperbark) swamps, saltmarshes and seagrasses that grow along the shore, on the intertidal flats and in the subtidal areas. In the very dynamic setting of a sandy coast, these tough habitats stabilise the shore and help protect it from erosion. When conditions allow, saltmarshes claim land from the sea, building soil upwards and outwards from the shoreline while seagrasses hold sand in place, reducing the energy of waves that pass over them. This natural behaviour of coastal vegetation is advantageous for coastal landholders because it reduces erosion.

As well as buffering the land from erosion, these habitats provide many other benefits not only to coastal landholders but also to people living far from the Tasmanian north-west.

Melaleuca swamps and saltmarshes process run-off from the land, removing sediment, nutrients and toxic substances before they have a chance to pollute the sea water. Seagrasses are impressive primary producers, supporting recreational and commercial fisheries, including the south-east Australian trawl fishery. As well, these habitats store carbon, helping to reduce climate change. These are just a few of the benefits, all of which can be costed in economic terms.

In fact, these coastal habitats are so valuable, that in places where they have been lost (mostly due to the activities of people), large sums of money are spent trying to re-establish them through "ecological engineering" (e.g. Kooragang Wetland Rehabilitation Project in New South Wales; Streever, 1998).[27] However, successful habitat rehabilitation is generally a tedious long term process involving considerable expenditures and hence, prevention is a better strategy than cure. Circular Head is

[27] A study on the 'trends in Australian wetland rehabilitation' (by Streever, 1997) indicated that 10 out of 78 rehabilitation projects across Australia were focussed on saltmarshes.

endowed with diverse and extensive coastal habitats, many of which are still in their natural state and are worth protecting.

2. Our research indicates that the extent of saltmarshes, in particular, has decreased in recent decades. This will have flow on effects to the other habitats (seagrasses in particular). Sea level rise is impacting on saltmarsh, which is struggling hard to resist shoreline erosion. The natural response of saltmarshes in areas of erosion is to retreat landwards (where suitable low lying areas exist) and re-establish themselves further back from the shoreline, where they will continue to cling staunchly to the land and resist further erosion. Without the saltmarshes, erosion will be quicker and much more dramatic. This has been demonstrated in other parts of Australia and worldwide (e.g. Doody, 2008).

Because the land in this area is so agriculturally productive and valuable, there is a natural tendency to protect and even extend it with tidal barriers. However, sea level rise is now inevitable and ongoing. In the face of creeping saltwater, which will intrude underground and well as on the surface, barriers and levees will provide diminishing returns as they become more expensive to maintain and less effective. As well, establishing levees to keep saltwater at bay destroys saltmarsh habitat inside and outside of the levee until, with further sea level rise, there is no saltmarsh left. When this happens, all the benefits derived from saltmarshes are lost. Other pressures that reduce saltmarsh resilience include trampling and grazing by stock, vehicle track damage and weeds such as rice grass (*Spartina anglica*).

3. Economic analysis shows the value of these saltmarsh benefits is much greater than the value of the land being protected and it is the *entire* community that benefits. For this reason, cooperation is needed from all sectors to secure the future of these valuable natural assets. Economic incentives to landholders who maintain healthy saltmarshes rather than attempting to protect their pastures with barriers would help make the situation equitable and encourage landholders to cooperate in working with nature rather than against it[28].

To protect land close to eroding shorelines, as well as protecting the other services saltmarshes provide, the optimum approach, and the one that works with nature, is to give saltmarsh “room to move” by removing artificial tidal barriers or not establishing them in the first place. This will allow saltmarshes to respond to sea level rise and buffer the shoreline against increasingly aggressive erosion.

If coastal landholders take this action, they will be extending their current stewardship role of caring for land that produces meat and dairy products. They will be taking on the additional responsibility of stewardship of the shoreline. The shoreline vegetation, as well as protecting from erosion, is an important link in the food chain of sea life, so coastal landholders will also be taking care of the food assets of the sea thus providing benefits to the wider community.

[28] See more about environmental stewardship from the Australian Government at <http://www.nrm.gov.au/stewardship/index.html> and <http://www.marketbasedinstruments.gov.au/DesigningMBIs/Othertypesofincentives/Stewardshipandecosystemservices/tabid/87/Default.aspx>

Message B. Water quality

Healthy saltmarsh and seagrass beds help keep the water clean and clear, maintaining suitable conditions for a variety of human uses including aquaculture and recreational activities.

1. Many industries and other human pursuits, including aquaculture, fisheries, recreation and tourism rely, either directly or indirectly, on water that is both clean and clear. Saltmarsh and seagrass help to regulate the amount of nutrients in the water (nitrogen and phosphorus in various forms) as well as trapping sand and mud (sediments) and toxic chemicals. As a result, the water is less muddy, contains fewer harmful bacteria and has lower nutrient and toxicant levels. Harmful algal blooms are less likely to occur, light can penetrate to the sea floor and plants and animals that need clean water, such as those that are consumed by oysters, will continue to thrive.

2. While saltmarsh and especially seagrass have been doing an important job of processing large quantities of sediments and nutrients entering the marine waters of the Circular Head region, sea level rise will place additional pressures on these habitats and the benefits they provide. To give saltmarsh and seagrass the best chance of surviving sea level rise (i.e. to maximise their resilience) reducing the amount of excess nutrients and sediment entering the marine environment is important. There is clear evidence of elevated nutrient levels entering the coastal foreshore areas via the rivers and estuaries.

3. Coastal landholders and landholders in the catchments of estuaries flowing into the Circular Head region's coastal foreshore areas can take various actions to ensure the amount of nutrient and sediment flowing into the waterways is sustainable and doesn't undermine the resilience of the key coastal habitats. Some of these actions, such as best practise application of fertiliser, will save money. Others, such as following best practice with dairy effluent disposal and protecting riparian vegetation, will attract assistance from government sources.

Message C. Food security

The shoreline, intertidal and subtidal habitats of the Circular Head region are primary producers on a massive scale, supporting food-webs in the immediate coastal areas and far beyond. In this way, they contribute to Australia's food security and also to the health of people living in Tasmania's North West.

1. The healthy saltmarshes and seagrass beds, along with the thriving microscopic plant life (microphytobenthos) that coats the intertidal flats of the Circular Head region, contribute to Australia's food security, supporting fisheries far beyond the immediate region (for example the south-east Australian trawl fishery). In addition, by supporting wild harvest, the impressive primary productivity of the sea in this region contributes to the health and well-being of the people of North West Tasmania. While this productive plant life sustains human food sources, it also supports the wildlife that abounds in the area (including the migratory birds for which the Circular Head region is renowned internationally), providing additional, indirect benefits to people.

2. The ecosystem services provided by habitats of the Circular Head region are related to their primary productivity. This means that threats from sea level rise that impact one habitat type (for example saltmarshes) will affect the ability of the other habitats (intertidal sandflats and subtidal seagrasses) to maintain high rates of primary productivity. The current study has demonstrated the impacts of sea level rise on saltmarsh ecosystems in the region. Saltmarshes are moving inland in a natural response to sea level rise and, as they are driven towards artificial barriers placed along the shore, they are being squeezed out. With the loss of the saltmarshes, there will be more nutrients entering the water, increasing the likelihood of algal blooms, which will in turn threaten the seagrass beds. Also, as shoreline erosion increases due to sea level rise, exacerbated by the loss of saltmarsh, both the amount of suspended sediment and the mobility of sediment in the system will increase. This will threaten the microphytobenthos and seagrass beds with being smothered or uprooted and also block the sunlight required for photosynthesis. Again, this will interfere with the primary productivity of all habitats in the area.

3. There are many large and small actions land managers (such as coastal landholders, land and coast care groups, coastal planners and policy makers) and users of the Circular Head region (such as fishers, boaters and oyster farmers) can take to increase the resilience of the coastal habitats to sea level rise, to protect the habitats from damage by human activities or minimise demonstrated sea level rise impacts. All these actions will help to protect the primary productivity of the coastal habitats and the myriad benefits this productivity brings to people.

Message D. Carbon sequestration

On a daily basis, the saltmarshes and seagrasses of the Circular Head region take carbon from the atmosphere and store it as residual plant matter through burial in the sea floor (a process known as carbon sequestration) thus helping to slow the progress of climate change. In addition, the vast saltmarshes and subtidal seagrass beds of Boullanger Bay are protecting carbon that has been removed from the atmosphere over thousands of years in their deep subsurface “mattes” and soil profiles. They are large carbon “sinks” or reservoirs (storage areas).

1. Human-induced climate change is one of the biggest threats yet faced by humankind. Without doubt, as a result of a rapidly warming planet with unstable weather conditions, rising sea levels and acidifying oceans, the adult lives of our children will be very different from the lives led by adults today. It is important that we quickly learn ways of storing carbon out of the ocean and atmosphere and that we protect existing carbon stores from being released. Just as forests store carbon, the vast saltmarshes and seagrass beds of the Circular Head region store carbon in their dead plant matter. In particular, the subtidal seagrasses of Boullanger Bay have been building up a carbon store in their root mattes and also exporting carbon to sediments on the surrounding continental shelf since the beds established after the last ice age, that is, for anything up to 5000–6000 years. The habitats of the region provide an important benefit in keeping a significant store of carbon out of the atmospheric circulation, where it would further contribute to climate change and accelerated sea level rise. Likewise, the saltmarsh vegetation in the area is removing carbon from the

atmosphere and storing it in the plant material and in the peaty (organic) matter that builds up under saltmarshes.

2. Seagrasses will be challenged as the sea level rises, though it is important to note that they have successfully met this challenge many times before. As the water becomes deeper, if all other factors remain the same, sufficient light will no longer penetrate to the deepest seaward edge of the seagrass beds to sustain healthy seagrass. This is likely to lead to the loss of seagrasses on the seaward edge. However, it is also likely that the shallow edge of the seagrass will grow shorewards. This will be happening as the shoreline itself moves slowly inland. Saltmarsh is already responding to sea level rise by moving inland where its shoreward migration is not blocked by levees and barriers squeezing the saltmarsh habitat out.

3. Governments are working to find ways to lessen the long-term effects of sea level rise and many are looking at solutions that put a price on carbon. Meanwhile, private enterprise, seeing that this is the likely direction for the future, is already starting to trade in carbon. For example, companies are beginning to pay Tasmanians to retain forests on private land for their value as carbon “offsets” (which are designed to compensate for carbon pollution occurring elsewhere). In many cases, the allocation of forested private land for carbon offsets is becoming more lucrative than clearing them for agriculture. Saltmarsh and seagrass also have good carbon offset potential. A case could be made for paying landholders to protect these natural assets for their carbon offset value.

Message E. Preservation of future options

Every ecosystem is highly complex and there are many things that people do not yet understand about them. Further, it is possible to predict that new activities and values will develop in the future that we do not know about now. For these reasons, large complex functioning ecosystems hold potential and opportunities for people that are likely to be realised in the future by our descendants, yet can be destroyed in the present. Protecting ecosystem functioning, biodiversity and geodiversity can be regarded as a form of ecological banking as it maintains valuable assets into the future that are difficult, expensive or impossible to reinstate once destroyed.

1. We benefit today from the ecosystems that are here today, and our forebears benefitted from these same ecosystems. It is reasonable to assume that our descendants will benefit from then as well, though perhaps in ways that we do not yet understand.

2. Ecosystems are often complex with several components and linkages, one measure of which is expressed in terms of biological diversity, another geological diversity (covering the abiotic components such as land forms). The conservation and sustainable use of the biodiversity and geodiversity in natural ecosystems is increasingly a major focus internationally and within Australia, and has been translated into various policies and legislative measures. Note though that while the Australian Government and the State of Tasmania have specified many clear environmental and conservation values and objectives in policies and legislation, their translation into on-ground outcomes does not match the stated objectives. Ecosystems, their biodiversity and geodiversity are already under pressure from sea level rise and other human activities. The lack of consistency between the stated

objectives and management action constitutes an additional threat to the ecosystems as some people may falsely think the threats are in hand and thus weaken their motivation to support or take further action.

3. Simple actions can enhance the resilience of these systems e.g. habitat protection, shorebird conservation. Consistency between objectives, values and action supports efficient management of natural resources.

9. Management options summary

Primary Authorship: Richard Mount, Vishnu Prahalad and Jan Tilden

In this section, a number of clear management options that answer the question "What can be done?" have been set out for consideration of stakeholders:

Message A. Shoreline and seabed stability

Identifiable actions:

- for planners, policy makers and legislators at all levels of government – develop programs and incentives to support landholders to give shoreline vegetation room to move in response to sea level rise. Where an undue burden falls on the individual landholder that burden should be shared by all who benefit from the protection of ecosystem services including the wider community;

- adopt "ecological engineering" as a response to sea level rise, rather than the more expensive and ecologically harmful response of trying to harden coasts against sea level rise with barriers and levees;

- for coastal landholders – when considering how to protect land from sea level rise, rather than establishing levees, give the shoreline vegetation "room to move" inland. While this means sacrificing a little land to the sea, the loss of a small area for grazing or other uses is balanced by services provided by saltmarshes that will have room to move back as the sea level slowly rises. These saltmarshes will continue to cling to the land, minimising shoreline erosion. It will also act as a buffer zone to filter run-off from the land, protecting other beneficial habitats such as the intertidal seagrass beds;

- retain or rehabilitate *Melaleuca* (tea tree/paperbark) vegetation behind shoreline wetlands (saltmarsh) and give this room to move as well, as this will protect the upper saltmarsh vegetation from land based effects and retain the integrity of the coastal habitat zones. This may include finding substitute firewood sources from other more abundant and resilient forest types;

- for Landcare/Coastcare groups and environmental educators – assist landholders with access to information and funding opportunities to carry out work protecting and rehabilitating shoreline vegetation (*Melaleuca*, saltmarsh);

- for research bodies and coastal land management authorities – quantify and publish widely the economic benefits of the coastal habitats of the Circular Head region in order to develop a rational basis to protect these habitats;

- for policy makers and legislators – introduce measures to have saltmarsh communities considered for listing as threatened under State and Commonwealth legislation;

- for those implementing climate change adaptation plans – the suggested innovations will likely be challenging for landholders to adopt because of their limited trial-ability and the long lag before seeing results. Techniques that may assist include trialling the suggested measures on Crown land, identifying potential early adopters and assisting them to give their shoreline wetlands vegetation (saltmarsh) room to move and working with existing networks and/or developing networks to encourage conversations about the new sustainable practices;

- communicate about the suggested innovations which draws out their compatibility with the existing values and practices of coastal landholders, namely stewardship of natural resources that produce food;
- for local councils - ensure Council Planning Scheme clause 6.5.1 (see Section 2 Management values and objectives) relating to the protection of shoreline stability, saltmarsh, tidal flats and lagoons is adequately applied.

Message B. Water quality

Identifiable actions:

- for coastal landholders – retain 50–100m of riparian vegetation between paddocks and stream banks or foreshore habitats (including saltmarshes). Fence riparian areas and provide off-stream livestock watering points;
- calculate fertilisation rates and apply fertiliser in a way that ensures all is used by pasture or other desired plants and little or none is washed into the sea;
- manage dairy effluent conscientiously so it does not contaminate waterways and find its way into the sea;

(Tasmanian and Australian government programs offer assistance to land managers undertaking these kinds of actions to protect the environment. Information about programs can be obtained from industry bodies.)

- for research bodies and coastal land management authorities – further explore the links between clean water and resilience of habitats to sea level rise;
- for landcare groups and environmental educators – communicate the message that, in the face of sea level rise, it is even more important for land holders to achieve best practice in managing dairy effluent and rates of fertiliser use, in order to give habitats the best chance of surviving the changes ahead;
- for local council – ensure all potential sources of excess nutrients are well managed including sewage;
- communicate the links between clean water and resilience of habitats to sea level rise.

Message C. Food security

Identifiable actions:

All actions identified under the two previous key messages will also help to protect the primary productivity of the Circular Head region's coastal foreshore habitats. Some additional actions include:

- for recreational users – refrain from driving recreational vehicles over shoreline wetlands (saltmarshes);
- refrain from driving boats over seagrass in shallow water and pulling it up;
- refrain from anchoring over seagrass beds or taking other actions that pull up seagrass;
- reduce or stop stock trampling and feeding on saltmarsh;
- guard against shoreline weeds such as rice grass (S*partina anglica*) and sea spurge (*Euphorbia paralias*).

Message D. Carbon sequestration

Identifiable actions:

All actions identified under the three previous key messages will also help to protect the carbon sequestration and storage going on in the Circular Head region's habitats. Some additional actions include:

- for all users and managers of the Circular Head area – avoid "engineering" the intertidal and subtidal environment on any scale in ways that interfere with tidal flow. This will help to protect the seagrass beds and saltmarshes;
- for conservationists, coastal managers and others – work to have saltmarshes and seagrass beds recognised as an efficient carbon store and appropriately acknowledged in carbon accounting systems.

Message E. Preservation of future options

Identifiable actions:

All actions identified under the four previous key messages will also help to preserve the future options in the Circular Head region's habitats. Some additional actions include:

- for all users and managers of the Circular Head area – increase the resilience of the coastal habitats to sea level rise (and climate change) thereby promoting ecological diversity and preserve (or promote) future options.

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Appendix 1 Landsat time series satellite imagery

Table 1 Imagery list of Welcome Inlet time series

Acquisition date	Sensor	Elevation	Azimuth	Other information
29/12/1990	Landsat 5 TM	Sun elevation at: 50	Sun azimuth at: 79	Image time at: --
16/02/2000	Landsat 7 ETM+	Sun elevation at: --	Sun azimuth at: --	Image time at: --
9/05/2001	Landsat 7 ETM+	Sun elevation at: 23	Sun azimuth at: 37	Image time at: 23:54:14
26/04/2002	Landsat 7 ETM+	Sun elevation at: 26	Sun azimuth at: 39	Image time at: 23:53:03
15/05/2003	Landsat 7 ETM+	Sun elevation at: 21	Sun azimuth at: 36	Image time at: 23:52:57
10/06/2004	Landsat 5 TM	Sun elevation at: 17	Sun azimuth at: 36	Image time at: 23:45:34
4/11/2005	Landsat 5 TM	Sun elevation at: 52	Sun azimuth at: 58	Image time at: 23:52:22
22/10/2006	Landsat 5 TM	Sun elevation at: 49	Sun azimuth at: 52	Image time at: 23:58:27
7/09/2007	Landsat 5 TM	Sun elevation at: 33	Sun azimuth at: 43	Image time at: 23:57:24
11/10/2008	Landsat 5 TM	Sun elevatino at: 45	Sun azimuth at: 52	Image time at: 23:48:27

Table 2 Imagery list of Sealer springs time series

Acquisition date	Sensor	Elevation	Azimuth	Other information
29/12/1990	Landsat 5 TM	Sun elevation at: 50	Sun azimuth at: 79	Scene scan time: --
28/11/1999	Landsat 7 ETM+	Sun elevation at: 56	Sun azimuth at: 65	Scene scan time: 23:57:02
16/02/2000	Landsat 7 ETM+	Sun elevation at: --	Sun azimuth at: --	Scene scan time: --
09/05/2001	Landsat 7 ETM+	Sun elevation at: 23	Sun azimuth at: 37	Scene scan time: 23:54:14
26/04/2002	Landsat 7 ETM+	Sun elevation at: 26	Sun azimuth at: 39	Scene scan time: 23:53:03
08/02/2003	Landsat 7 ETM+	Sun elevation at: 46	Sun azimuth at: 65	Scene scan time: 23:52:54
23/04/2004	Landsat 5 TM	Sun elevation at: 25	Sun azimuth at: 42	Scene scan time: 23:44:10
04/11/2005	Landsat 5 TM	Sun elevation at: 52	Sun azimuth at: 58	Scene scan time: 23:52:22
22/10/2006	Landsat 5 TM	Sun elevation at: 49	Sun azimuth at: 52	Scene scan time: 23:58:27
08/04/2007	Landsat 7 ETM+	Sun elevation at: 31	Sun azimuth at: 44	Scene scan time: 23:54:46
07/11/2009	Landsat 7 ETM+	Sun elevation at: 53	Sun azimuth at: 58	Scene scan time: 23:54:46

Appendix 2 Data dictionary for erosion mapping

Shore and coastal zone landforms:

Mapped using Smartline landform attributes and classes (Sharples et al., 2009). This work effectively updates the Smartline for the project area. That data is being supplied to the national custodian of the Smartline data set, Geoscience Australia.

Shoreline erosion /accretion status

Data model

Conceived as additional attributes for the Tas. Smartline and then separated off as a project specific file. This means that the data model is consistent with the Smartline and can be used in conjunction with that data set

Data set title: Shoreline erosion accretion status: Circular Head region
Projection: GDA94 geographicals
Data Source: All based on field mapping by C. Sharples January 2010

Field	Type	Width	Attributes	Comments
Erosfeat_n *Erosfeat_v*	string (text) string (text)	3 100	Numerical string code Verbal label See Erosfeat table below	Feature or substrate into which erosion scarp is cut (where shoreline is eroding), or would be cut into (if shoreline were to erode).
Status_n *Status_v*	string (text) string (text)	3 100	Numerical string code Verbal label See Status table below	Shoreline stability status; i.e., eroding, stable, accreting, etc.
Height_n *Height_v*	string (text) string (text)	3 100	Numerical string code Verbal label See Height table below	Erosion scarp height classes (metres, grouped into several broad classes).
Other_info	string (text)	254	Verbal notes	Additional information relating to shoreline type, erosion, artificial features, etc.

Attribute tables

The following attribute tables provide relatively detailed attribute classes describing the erosion status and related characteristics of the mapped shorelines. Although this attribute system may at first appear a tad complicated, note that the attribute tables are hierarchical; thus this attribute system provides the ability for the data to be finely differentiated, or lumped together into much simpler classes as appropriate. A lumping of attributes that was used for the purposes of this project is indicated by summary tables following the *Erosfeat* and *Status* attribute tables below. Note also that not all categories listed in the following attribute tables were actually mapped in the study area; rather some of the categories listed are logical possibilities which are included in the tables for completeness.

Erosion scarp substrate (feature)

Field name: ***Erosfeat***

Explanation: Feature or substrate into which erosion scarp is cut or would cut if shoreline were to erode (i.e., may include currently stable or accreting shores). Includes shoreline substrate types where the shore is essentially stable on human time frames (i.e., hard rock shore). The substrate types listed here are specific to the Boullanger Bay – Duck Bay region, and may not apply elsewhere.

Attributes:

Numerical Code *Erosfeat_n* (3 characters)	**Verbal Label** *Erosfeat_v* (100 characters)	**Description and Comments**
100	Bedrock undiff	
110	Hard bedrock	Where bedrock eroding or stable (as per *Status* attribute)
111	Soft clayey-sand marsh soils over hard bedrock	Both exposed, soil eroding or with potential to erode
112	Podzolic sand soils over hard bedrock	Hard bedrock overlain by podzolic windblown sand soil, both exposed, sand eroding
119	Undiff soil over hard bedrock	Hard bedrock overlain by unspecified soil types, both exposed, soil eroding
120	Soft bedrock	Where soft (incl. weathered) bedrock eroding or stable (as per *Status* attribute)
121	Soft clayey-sand marsh soils over soft bedrock	Both exposed in erosion scarp or with potential to erode, soft bedrock includes weathered bedrock types
122	Podzolic sand soils over soft bedrock	Soft (incl. weathered) bedrock overlain by podzolic windblown sands, both exposed in erosion scarp.
129	Undiff soil over soft bedrock	Soft (incl. weathered) bedrock overlain by unspecified soil types, both exposed in erosion scarp
200	Pebble / cobble substrate undiff	
210	Pebble/cobble beach ridge	
300	Soft clayey-sand marsh	Soft Holocene coastal saltmarsh or

	soils	melaleuca swamp soils, grey-brown, relatively soft.
400	Semi-indurated peaty sand deposits	Relatively tough Pleistocene freshwater swamp deposits; may be overlain by podzolic sands in the backshore but not exposed in erosion scarp
401	Semi-indurated peaty sand deposits overlain by soft clayey sand soils	Relatively tough Pleistocene freshwater swamp deposits overlain by soft Holocene saltmarsh or melaleuca swamp soils; both units eroding in scarps
402	Semi-indurated peaty sand deposits overlain by podzolic sands	Relatively tough Pleistocene freshwater swamp deposits overlain by softer but podzolic Pleistocene or Holocene sands (windblown or beach ridge sand deposits); both units eroding in scarps.
500	Peaty marsh substrate undiff	Saltmarsh or melaleuca swamp peaty soils or substrates of uncertain age or origin (used where substrate type not clearly identified, could be Holocene marsh soil or older Pleistocene substrates colonised by Holocene marsh).
600	Podzolic sands	Pleistocene or Holocene sands (windblown or beach ridge sand deposits) with moderately- to well-developed podzolic profiles exposed in erosion scarps, not Holocene foredunes, no underlying indurated peaty sands exposed in erosion scarps
700	Sand undiff	Sands without significant podzolic profile development. Mainly Holocene dune sands.
701	Sand foredune	Holocene sand foredune, generally without major podzolic profile development
702	Sand beach ridge	Holocene beach ridge, generally recent without notable podzolic profile development.
705	Shelly sand beach ridge	Holocene shelly beach ridge, generally recent without notable podzolic profile development.
900	Unclassified	

Grouped substrate classes

The above classification is relatively detailed; however the detailed classes can also be readily combined into related groups as follows:

Grouped Group	Numerical codes (***Erosfeat_n***)
Dominantly erodible saltmarsh soil substrates	121 300 400 401 500
Soft erodible substrates over hard bedrock	111 119
"Cut and fill" shorelines – foredunes and beach ridges	210 701 702 705
Other sands (including older podzolic beach ridge or aeolian sand sheet deposits)	112 122 402 600 700
Dominantly soft rock shores	120 129 200
Dominantly hard stable bedrock shores	100 110

Shoreline stability status

Field name: ***Status***

Explanation: Shoreline stability status or condition; i.e., eroding, stable, accreting, etc. This classification distinguishes shorelines according to both their spatial and temporal patterns of erosion insofar as these can be observed or confidently inferred. The *primary* aim is to record current erosion status without necessarily inferring whether erosion is progressive and non-reversing, or cyclic (e.g., a cut-and-fill cycle). However where clear evidence of cyclic erosion – accretion is visible (e.g., old erosion scarps behind current accretion) or can be confidently assumed (e.g., sandy foredunes on swell-exposed coasts), then these are classified as "temporally intermittent".

This classification of shoreline stability status was developed for the study area, based on observations of patterns evident in the study area, and is not necessarily transferable to other regions or other shoreline types.

NOTE re "accretion": In this classification, "accretion" refers to horizontal accretion (or progradation) only, not to vertical accretion. Whilst horizontally accreting shores are generally vertically accreting as well, there are also some horizontally receding saltmarsh shores at

Boullanger Bay that are vertically accreting too (overwash sediment is being deposited on the saltmarsh behind the erosion scarp).

Attributes:

Numerical Code *Status_n* (3 characters)	**Verbal Label** *Status_v* (100 characters)	**Description and Comments**
100	**Spatially continuous erosion undiff**	
120	**Spatially continuous active erosion**	Continuous stretches of shoreline erosion scarp displaying indicators of recent active erosion, including: - fresh scarp faces, under-cut scarps in soft substrates, recently collapsed scarp blocks and debris, no signs of accretion or shoreface rebuilding.
130	**Spatially continuous inactive erosion**	Continuous stretches of shoreline erosion scarp displaying rounded-over and/or partly re-vegetated erosion scarps, but no other signs of accretion or shoreface rebuilding.
200	**Intermittent erosion undiff**	Spatially and/or temporally intermittent erosion scarps undifferentiated
201	Intermittent erosion undiff, erosion dominant	
202	Intermittent erosion undiff, erosion / accretion 50/50	
203	Intermittent erosion undiff, accretion dominant	
210	**Spatially intermittent active erosion**	Spatially-intermittent active erosion scarps – alongshore sections of actively eroding shore with intervening stable or accreting shore sections (on scales metres to approx 10m long sections)
211	Spatially intermittent active erosion, erosion dominant	
212	Spatially intermittent active erosion, erosion / accretion 50/50	
213	Spatially intermittent active erosion, accretion dominant	
220	**Spatially intermittent inactive erosion**	Spatially – intermittent inactive erosion scarps – alongshore sections of inactive erosion scarp with intervening stable or accreting shore sections (on scales metres to approx 10m long section)
221	Spatially intermittent inactive erosion, erosion dominant	

222	Spatially intermittent inactive erosion, erosion / accretion 50/50	
223	Spatially intermittent inactive erosion, accretion dominant	
230	**Temporally intermittent erosion undiff**	Temporally – intermittent erosion, with older inactive erosion scarps fronted by accretion features (secondary saltmarsh, incipient sand dunes, etc), undifferentiated
231	Temporally intermittent erosion, recent active erosion dominant	Temporally – intermittent erosion, currently or recently dominantly eroding with evidence of previous accretion
232	Temporally intermittent erosion with inactive scarps	Temporally – intermittent erosion, with inactive scarps but no significant recent accretion
233	Temporally intermittent erosion, recent accretion dominant	Temporally – intermittent erosion, currently dominantly accreting with evidence of previous erosion.
235	Temporally intermittent erosion assumed, currently stable	Shore substrates (e.g., sand or cobble foredunes or beach ridges) currently showing no sign of erosion or accretion, but expected to episodically erode and rebuild in a "cut-and-fill" cycle
240	**Spatially and temporally intermittent erosion undiff**	Spatially intermittent actively eroding and accreting shoreline segments with old inactive scarps also located behind presently accreting shoreline sections
300	**Accreting or stable shore undiff**	Mainly soft (e.g., saltmarsh or sandy) shores showing no clear erosion or accretion indicators.
400	**Stable shore**	Negligible change expected in human time frames. Mainly hard-rock shores.
500	**Accreting shore**	Includes prograding sandy shores and most saltmarsh shores not displaying erosion indicators; if these shores are not eroding, they are assumed to be accreting sediment. Also includes most rice-grass shores, which also tend to be sediment – capturing shores.
900	**Unclassified**	

Grouped status classes

The above classification is relatively detailed; however the detailed classes can also be readily combined into related groups as follows:

Grouped classes	Numerical codes (*Status_n*)
Actively eroding shores, continuous	120
Dominantly actively eroding shores (with some sub-ordinate intermittent stability or accretion)	100 201 211 231
Intermittently eroding shores (some spatially or temporally intermittent accretion, but accretion not dominant)	130 200 202 210 212 220 221 222 230 232 235 240
Stable shores (i.e., mainly hard bedrock, or soft shores with no indication of accretion or erosion)	300 400
Dominantly accreting shores with some intermittent or prior erosion	203 213 223 233
Accreting shores, no evidence of prior erosion	500

Erosion scarp height classes

Field name: ***Height***

Explanation: Erosion scarp height classes (metres, grouped into several broad classes into which study area erosion scarps were subjectively judged to be clustered).

Attributes:

Numerical Code *Height_n* (3 characters)	**Verbal Label** *Height_v* (100 characters)	**Description and Comments**
100	<0.2m	Very low scarps; includes evidence of sediment removal such as exposed roots, but with little actual scarping. In many cases, this probably represents incipient or only-just-commenced erosion
200	0.2 – 0.5 m	Low scarps; this is the most common saltmarsh erosion scarp height in the study area, since the saltmarsh soil substrates are rarely thicker than approximately 0.5 metre, which effectively limits possible erosion scarp heights in these substrates
300	0.5 – 1.0 m	Moderate scarps
400	1.0 – 2.0m	Moderate to high scarps
500	2.0 – 6.0 m	High scarps; mainly found eroded into thick podzolic or foredune sand deposits.
900	Unclassified	Generally refers to shores where no erosion scarp is present. These may be stable shores or (in the case of saltmarsh or “cut-and-fill” shores) accreting shorelines.

Appendix 3 Sediment nutrient report

Analytical Services Tasmania Report results from Report Number 43077
Issue No. 1, Full Report 17/2/2010

Organic and Nutrient Testing
2202-Soil: Total N & P in Soil, Sediment & Other Solids. Work Conducted at: New Town

LabNo	SampleID	Date	N_mgkgDMB	P_mgkgDMB
163340	A1	25/01/2010	250	35
163341	A2	25/01/2010	220	57
163342	A3	25/01/2010	150	59
163343	A4	25/01/2010	2000	280
163344	A5	25/01/2010	160	58
163345	A6	25/01/2010	350	98
163346	A7	25/01/2010	270	56
163347	A8	25/01/2010	520	120
163348	A9	25/01/2010	920	180
163349	A10	25/01/2010	410	67
163350	B1	26/01/2010	250	76
163351	B2	26/01/2010	1600	250
163352	B3	26/01/2010	310	70
163353	B4	26/01/2010	730	180
163354	B5	26/01/2010	360	110
163355	B6	26/01/2010	350	140
163356	B7	26/01/2010	140	74
163357	B8	26/01/2010	300	110
163358	B9	26/01/2010	330	110
163359	C1	25/01/2010	57	29
163360	C2	25/01/2010	140	54
163361	C3	25/01/2010	920	220
163362	C4	25/01/2010	400	94
163363	C5	25/01/2010	540	97
163364	C6	25/01/2010	410	91
163365	C7	25/01/2010	450	94
163366	C8	25/01/2010	310	59
163367	C9	25/01/2010	970	140
163368	D1	27/01/2010	170	58
163369	D2	27/01/2010	120	53
163370	D3	27/01/2010	160	71
163371	D4	27/01/2010	48	30
163372	D5	27/01/2010	370	150
163373	D6	27/01/2010	200	80
163374	D7	27/01/2010	92	46
163375	D8	27/01/2010	110	59
163376	D9	27/01/2010	260	97
163377	D10	27/01/2010	200	110

Appendix 4 Stratigraphy analysis – Technical Report

Primary Authorship: Brigid Morrison

1. Stratigraphy sub-project background, aims and scope

The aim of this study is to determine the evolution of the Circular Head coastal foreshore including an assessment of the origins and role of extensive black deposits that were evident from an initial reconnaissance of the area in June 2009. The scope of the stratigraphic investigation was set to focus on three sites within the Circular Head foreshore area. These sites were selected based on their different energy levels within the broader area.
Initially the black deposits were thought to be remnants of eroded Holocene saltmarshes. However, more extensive field observations in January 2010 revealed that the deposits were exposed in tidal channels at low tide, and were overlain by Pleistocene dunes at the landward edge. This indicated that the deposits were older than Holocene, and unlikely to be associated with saltmarshes, considering that sea levels were much lower than present during the late Pleistocene, and that tectonic activity has been minor during at least the Holocene epoch. Because of its apparent extent it was also clear that the deposit has played a major role in the evolution of the current coastal landform, and that an improved understanding of the study area's response to changes in sea level and climate in the past will inform how it will respond in the future.

The broad approach of the study was to first determine the nature of the deposit, including its age, lithology and the palaeoenvironment of deposition. Site 1 Sealers Springs Point has extensive exposure of the deposit at the surface of the intertidal zone and efforts for stratigraphic analysis were concentrated on this site. As well, it was necessary to determine if the apparent exposures of the deposit throughout the area were the same by comparing their lithology and depth relative to mean sea level (MSL). The objective was to quantify how much of a role the deposits have played in influencing the current processes occurring in the Circular Head coastal foreshores.

This report covers the methods used in this study, detailed results of the analyses undertaken, interpretation of the results, and their relevance for developing a coastal evolution model of the Circular Head coastal foreshores.

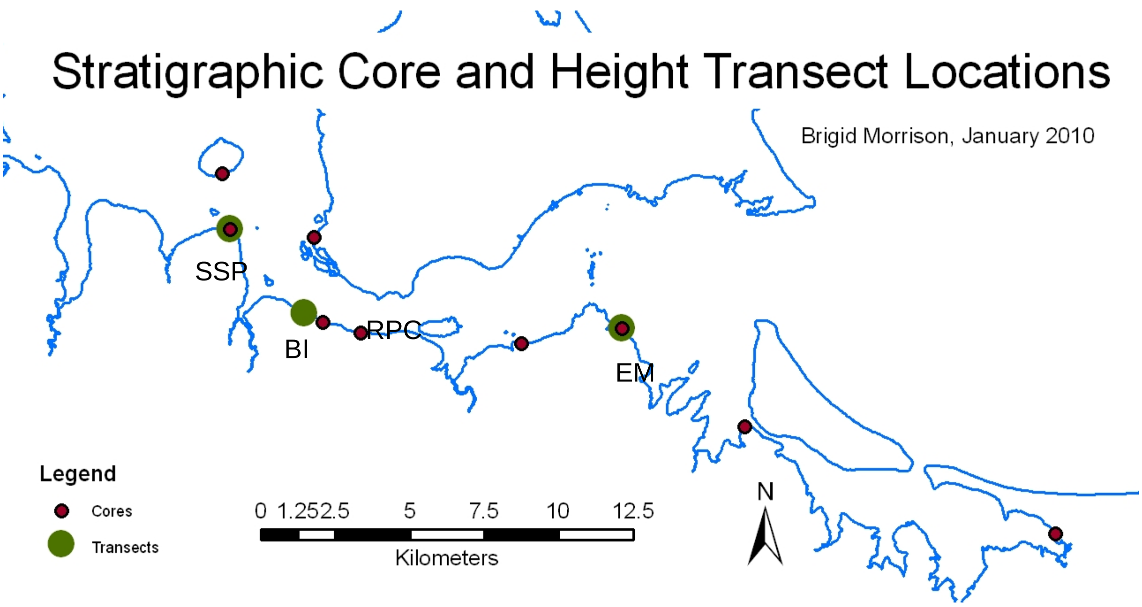

Figure A4.1 Stratigraphic cores and height transects.

2. Methods and results

Core collection and sampling

Selection of core locations was based on field observations indicating where the black deposit could be retrieved in the core. Cores were taken at the Sealers Springs Point (SSP), Robbins Passage Crossing (RPC) and Brick Islands (BI) sites. Initial coring attempts revealed a shallow saltmarsh substrate of around 50 cm overlying thick sands that were not penetrable with hand operated coring equipment. A double-tube coring device adapted from Tratt and Burne (1980) was built and operated by Mr David Shaw of Shaw Engineering. This device is designed to penetrate compacted sandy environments and was used to core until refusal at each location attaining a maximum core length of 2.2 m at Sealers Springs Point. Cores were sawn on location and split lengthways, logged and sub-sampled. Core locations were flagged and surveyed for elevation except at Robbins Passage Crossing where GPS recordings only were taken.

Surveying

Precise locations and heights were obtained to enable stratigraphic models to be generated both within and across sites. Marks were established consistent with the TasMARC protocols (Hunter *et al.*, 2004) that will enable monitoring and further work. Elevation relative to mean sea level was determined for Sealers Springs Point using a Leica 1200 GPS and Leica TC407 Total Station differential GPS base station deployed on the marsh terrestrial transition zone. Satellite data was downloaded for one hour and height resolution derived from the AUSPOS and tied to the Australian Height Datum 1983 (AHD83). Heights were collected across each site using a Leica TC407 Total Station using crystal prism staves. The Total Station was tied to the GPS derived location.

Transect 1 at Sealers Springs Point was deployed perpendicular to the shoreline with a tidal channel used to indicate the low tide mark as the true edge is more than 2 km across the sand flats. A series of nine pit cores were carefully excavated with a large blade kitchen knife from the eroding modern saltmarsh edge, across the beach to the edge of the channel. Each pit was surveyed for elevation along with changes in micro-relief, across the deposit to its cliffed eroding edge that terminated in the large channel that dissects the tidal flats. Surveying of the surface elevation continued over the flats to encompass the broader topography and sea grass beds.

At Transect 2 at the Brick Islands Site (BI) one survey control point was installed on Brick Islands with an unobstructed view to the shoreline to the west, and into Robbins Passage to the east. A 900 m transect was deployed and again because the low tide line was not visible, the configuration of the seaward edge of the marsh was used to ensure the transect was perpendicular to the shoreline. To further characterise the core location setting a second transect was deployed to the east of the main transect and surveyed for micro-relief using an NA270 Leica automatic level. The main transect began at the landward end at a tidal creek that was incorporated in the survey using the electronic total station. Although core Site 3 at Robbins Passage Crossing was not surveyed for elevation an outcrop of the deposit within the main tidal channel, approximately perpendicular to the core was surveyed as an offsite during the Transect 2 survey. The core site was linked to the channel elevation.

Transect 3 at East Montagu (EM), east along the shore from Stony Point, was also surveyed with a Total Station tied to the State Fiducial network including AHD83. Again the transect was positioned perpendicular to the shoreline and extended from the landwards side of the saltmarsh out across the intertidal flats to a tidal channel in a way that ensured heights were obtained of the black deposit.

Table 0.1 Heights of key features from the 4 surveyed transects.

Feature	Sealers Springs Point	Brick Islands	Little Island	East Montagu
Tidal channel	-0.801	-0.806		-0.423
Oxidised peat	0.08 to 0.13	0.089		-0.08 to -0.112
Eroded modern peat	0.8	0.79	0.78	0.8
Salt marsh edge	1.101 scarp	0.79 no scarp	0.80 no scarp	1.019 scarp
Juncus dominance	1.19	1.21 -1.29	NA	1.082
Tea tree edge	1.6	1.3+	NA	1.53

Core chronology

One sample of the deposit collected from the base of Core 3 at SSP and one collected from a shovel pit core from the cliffed channel exposure were sent to Beta Analytic Laboratories in Florida US. Both analyses reported adequate carbon for analysis. Two other samples from higher up the core were sent to the Australian Institute of Nuclear Science and Technology Laboratory in Sydney Australia. However, one sample was destroyed in the pre-treatment stage and the other was considered too contaminated with modern material to continue processing. Unfortunately, dateable material for the Holocene is proving difficult to attain, due to the penetration of the marsh by Melalueca root, resulting in contamination with modern material. Other options, including picking foraminifera for dating has proven problematic because the species present are agglutinated and have used fragments of the oxidized peat to build their tests. Therefore, the foraminifera samples would be contaminated with old carbon. However, Beta Analytic Laboratories has recently confirmed that they can analyse micro samples of ostracods that have been found in the Holocene deposits and have not incorporated old or new carbon.

Table 0.2. AMS carbon 14 results.

Site	Sample code	Material and pre-treatment	Height relative to present MSL	Conventional Radiocarbon Age
Sealers Springs Point	SP1SWE	Plant material: Acid/alkali/acid	-0.10 m	26,720 +/-180 BP
Sealers Springs Point	T1SPC3146-147	Peat: Acid washes	-1.1 m	36,930+/- 400 BP
Sealers Springs Point	T1SSSPC476-77	Peat: Pre-treatment failed		unknown
Sealers Springs Point		Ostracod micro samples		pending

Sediment analysis

Standard geological sediment characterisation analysis was conducted for all cores to determine the lithology of each facies. These characteristics were used to aid interpretation of the processes of deposition. Detailed grain size analysis was conducted on Core 4, Sealers Springs Point using a Saturn DigiSizer 5200 V1.09, at the Department of Chemistry, UTAS. The method for fine soil sediments described by Jason Beard was used (personal communication, 25/2/2010). Grain size for all other cores was conducted at 10 cm intervals down the core using standard sieving techniques through 500 μm, 210 μm, 150 μm, 125 μm and 63 μm sieves. Peaty samples were wet sieved and the fraction that passed through the

63 μm mesh retained, dried and weighed to determine the clay and silt sized particle component. Samples were prepared for foraminiferal analysis by wet sieving to minimize damage to testes. Sediment texture for pit core samples at SSP were conducted in the field using the texture by feel method (Singer, 1992).

Percent organic content was determined to further characterise facies and again infer processes of deposition and the nature of the past environment using standard methods described by Berglund (1986). Carbonate content analysis was not required as microscopic observation revealed little to no calcium carbonate fragments through the cores. Microscopic observations of the mineral content showed that each quartz grain is coated with the black sediment. Washing with sodium metahexaphosphate easily and completely removed all black material from the quartz grain and microscopic observation showed the black material to dissolve into a powdery form in suspension. This indicates a high degree of decomposition of the organic material.

Due to the compaction of the deposit, ordinary loss on ignition (LOI) methods for determining actual organic carbon content were not providing useful comparative results. In attempt to "shake off" the black sediment from the quartz grains to further characterize the lithology, dry sieving through 210-63 μm was conducted. A reasonable volume of black sediment was separated from the fine quartz grains and LOI showed the < 63 μm fraction to be composed of 74% organic material. On this basis the sediment of the black deposit qualifies as peat. In situ the peat behaves as an indurated mass, in that it has cement-like qualities of resistance to deformation. However, when dry the peat completely disaggregates into a powdery form. Clearly its preservation in the intertidal zone is a consequence of the fine silt and clay sized organic particles that absorb and retain moisture thereby binding it together. In this case the term "indurated" can only be loosely applied because it infers that chemical precipitation of minerals has cemented the particles together to form rock.

Particle roundness was assessed for the 63 μm and 125 μm fraction under a binocular microscope, for all facies types. However, visual categorizations into divisions of roundness classes were difficult to differentiate between subangular and subrounded. According to Powers (1953), the term subangual-subrounded is the appropriate class in this instance and is often the case when working with granular or smaller sized particles.

Microfossil analysis

Fossil analysis at this stage has been conducted at the reconnaissance level which is sufficient to describe the kinds of past environments of the different facies throughout all cores (Cochrane and Wilson, 2007). Firstly, foraminifera analysis was conducted as these are marine sarcodine protozoans that only inhabit the sediments of marine to brackish environments (Hayward *et al*., 1999). The focus of the investigation was to identify marine from freshwater sediments by presence or absence respectively. Where present, analysis of species was conducted as shallow marine inhabitants are useful indicators of salinity and elevation relative to the tidal frame.

Although the absence of forams indicates non marine conditions it is not conclusive. Therefore, the presence and type of diatoms present was investigated. Diatoms are unicellular algae that exist in marine, brackish and freshwater environments and species have distinct ecological requirements (Reid *et al*., 1995). Their siliceous cell wall preserves well in most environments and they are widely used as palaeoecological indicators of past environments. Sufficient pre-existing knowledge of Tasmanian marine and freshwater diatoms is available for application in this project. Specific work has been conducted in the Boullanger Bay and Duck Bay areas to identify species and their ecological range (pers. comm., Mr Steven McGowan, 1/2/2010).

Table 3. Grain size analysis results for each study site.

Location	Sample depth (cm)	Organic C (%dry weight)	Mean grain size µm	%Sand	%Silt	%clay	>250 µm (% weight)	>150 µm (% weight)	>125 µm (%weight)	>63 µm (% weight)	<63 µm (% weight)	Roundness
Sealers Springs Point												
T1SSPC4	5		78									Subangual-subrounded
T1SSPC4	20-21		157									Subangual-subrounded
T1SSPC4	30-31		185									Subangual-subrounded
T1SSPC4	46-47		149									Subangual-subrounded
T1SSPC4	57-58		116									Subangual-subrounded
T1SSPC4	64-65		205									Subangual-subrounded
T1SSPC4	70-71		153									Subangual-subrounded
T1SSPC4	90-91		150									Subangual-subrounded
T1SSPC4	110-111		151									Subangual-subrounded
T1SSPC4	119-120		195									Subangual-subrounded
T1SSPC4	140-141		181				0	-	95	2	3	Subangual-subrounded
T1SSPC4	160-161		174									Subangual-subrounded
T1SSPC4	200-201		210									Subangual
T1SSPC4	220-221		293									Subangual
Robbins Passage Crossing												
C1RIR	20-21						15	38	26	21		Subangual
C1RIR	70-71						12	39	27	23		Subangual
C1RIR	90-91						17	29	21	17		Subangual
Brick Islands (Modern)												
+9	1.62		218	70	33	3						Subangual
+19	1.44	0.17	210	66	32	2						Subangual
+25	1.275	0.12	210	67	32	2						Subangual
+32	1.025	0.49	220	78	22	<1						Subangual
+37	0.93	0.52	220	55	41	4						Subangual
+39	0.885	0.65	220	69	36	5						Subangual
+41	0.84	0.86	220	45	64	10			80			Subangual
+48	0.625	0.84	220	33	74	8						Subangual
+50	0.54	0.84	210	35	70	6						Subangual
+52		0.90		17	75	9						Subangual

Foraminifera

Samples were collected from each facies in Core [X] and wet sieved through a 63 μm sieve and where fossils were rare or the samples barren the 125 μm fraction was scanned as prescribed by Hayward *et al*. (1999). Individuals were not picked in accordance with the reconnaissance level investigation although all samples have been retained for further numerical analysis.

Foraminifera were present in all facies above the black deposits, and were dominated by agglutinated species that take up small fragments of the available minerals in their immediate vicinity to build their test. These species are known to preserve better than calcareous species and therefore it is difficult to identify known assemblages of organisms that can collectively indicate the tidal inundation period experienced at that depth in the core. However, *Elphidium excavatum* occurred frequently and is a common intertidal to subtidal inhabitant of brackish to slightly brackish environments within the middle reaches of estuaries or tidal inlets (Hayward *et al*., 1999). *Ammobaculites exigus* was also frequent, and is known to inhabit slightly brackish water in shallow sub tidal environments of the outer and middle reaches of estuaries.

Table 4 Results for foraminiferal and other microfossil analysis.

Location	Sample (core/ depth in cm)	Abundance	*Ammobaculites spp.*	*Quinquelina seminula*	*Elphidium exclavatum*	*Textularia earlandi*	Others	Ostracods	Plant fragments/seed
Sealers Springs Point	0-5	Abundant	23	3			P		P
	30-35	Abundant	20	0			P	4	P
	66-67	Abundant	15	3	6		P	10	P
	140-141	Barren					P		P
	200-210	Barren					P		P
	219-220	Barren					P		P
Brick Islands	39-41	Abundant	20		15			5	P
		Barren							P
Robbins Passage Crossing	20-21.5	Abundant	20		5		P	4	P
	70-71.5	Abundant	20	4	10		P	1	P
	90-91	Abundant				3	P	6	P
	139-141	Present				5	P	2	P

Diatoms

Diatom analysis was also conducted at the reconnaissance level with the assistance of Mr Steve McGowan at the NCMRS laboratories. Temporary water mounts were prepared to investigate the presence and preservation state of diatoms to further clarify the nature of the oxidized peat. Diatoms were present in low numbers using this technique but two types with relatively good preservation occurred consistently. The most frequent was *Nevicula spp.* and *Chalteroceros spp*. Both of these are known to inhabit slightly brackish to fresh water environments, and are presently abundant in the upper reaches of the Duck Estuary. One individual of *Fragilaiopsis sp.* was detected, and is known to be restricted to fresh water environments (pers. comm., Steven McGowan, 3/3/2010).

Rarely is more than one ecological indicator used. However, due to the apparent diversity of environments represented by each facies, at Sealers Springs Point, a cursory investigation into the isolation of pollens was conducted.

Pollens

Samples for pollen analyses were taken from the core at 10 cm intervals and were then prepared by Ms Phillipa Strickland in the Geography and Environmental Studies Laboratory, University of Tasmania in accordance with methods outlined in Ellison 2008.
The Pollen diagram (Figure A4.2) shows the relative representation of each taxon recorded in samples down core 4 Sealers Springs Point as a percentage of the total pollen sum which includes trees, shrubs, ferns and aquatics. Other palynomorphs such as fungal spores, microforaminifera, dinoflagellates and chlorophyllaceae were excluded. Pollen numbers are extremely low which is probably a consequence of the dry conditions during sea level fall and increasingly arid conditions during the Last Glacial Maximum after 267,000 yr BP. Desiccation will cause the pollens to oxidize and degrade. On this basis the peat deposit is termed hereafter "oxidized peat".

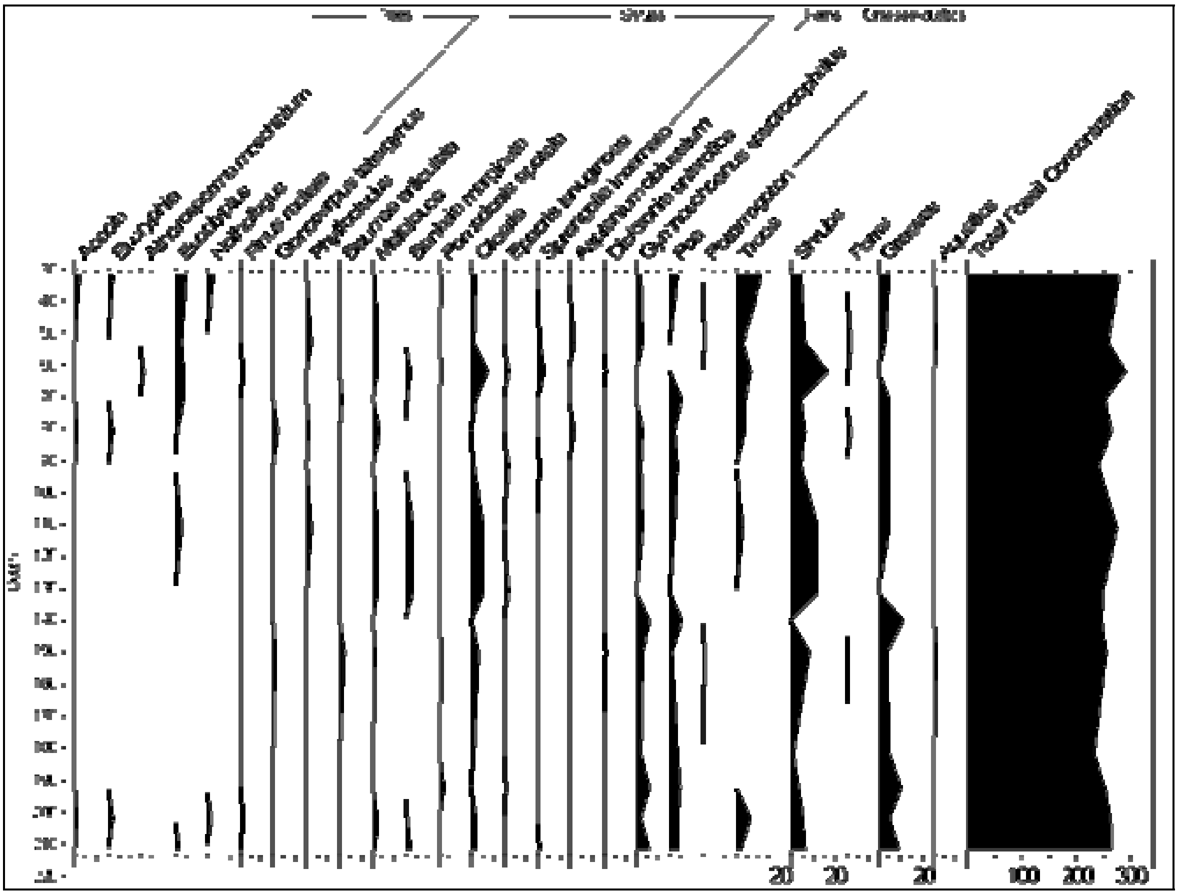

Figure A4.2. Pollen diagram showing that the relative abundance of each species is extremely low and can be used as guide only. It is most likely that the low numbers are a consequence of oxidation due to the deposit drying out due to climate change after its deposition.

Remote sensing

Collectively the investigations outlined above strongly indicated that the exposed oxidized peat deposits were of similar lithology and age, and geographically extensive. However, their broader extent and spatial connectivity was difficult to map in the field, thereby limiting a full understanding of the evolution of the area. To extend this understanding, and support the findings of the stratigraphic investigation, a satellite imagery digital image analysis was conducted to study the oxidised peats in the case study area around Sealers Springs Point and the Brick Islands. Please see Section 4.3.1 Description of Intertidal Flats for more details and results.

3. Site specific results

Introduction

The geomorphology of Boullanger Bay is consistent with the prevailing view that Holocene coastal landforms in south-eastern Australian are the result of interactions between the antecedent Pleistocene substrate that they overlie, the current boundary conditions (sediment type and supply), and forcing factors of relative sea level and climate (Sloss *et al*. 2007). However, in comparison with other stratigraphic records exhibiting similar minor tectonic movement, both from Tasmania (Cochrane and Wilson, 2007) and the Australian mainland (Nichols and Murray-Wallace, 1992), the stratigraphic record from this study is unique in the broad temporal span that has been captured at shallow depths relative to mean sea level. Most Australian geomorphic models of coastal evolution have been developed in the broad, low lying embayments of coastal plains, between rocky headlands and fluvially cut valleys that have been filled with transgressive sands during the Last Marine Transgression, culminating approximately 6,000 yr BP (Sloss *et al.,* 2007). These models indicate that since this time, continuous long shore drift of sediment has produced seaward barriers and associated lagoon and estuarine wetland systems seen today. These overlie or replace the late Pleistocene landforms that were eroded by the transgressing sea. Sloss *et al.* (2007) describe how the nature of sediment infill between locations is largely a consequence of the depth of the receiving basin.

The results of this study show that at Boullanger Bay and Robbins Passage the depth of the receiving basin available for filling (otherwise known as “accommodation space”), for the Holocene transgressive sands is shallow due to the extensive oxidized Pleistocene peat that is either exposed, such as at Sealers Springs Point, or just 50 cm below the modern upper intertidal sands as at Brick Islands. The deposit was not located at the Robbins Passage Crossing marshes although it is evident in the main tidal channel seaward of the marsh. Aerial photographic and remote sensing evidence suggests it extends from the lower tidal flats, and field observations show exposures at marsh seaward edges, and throughout the tidal creek network. It was also evident that the deposit underlies the current terrestrial deposits. Although its landward extent is difficult to quantify without extensive coring efforts, there are direct comparisons which can be drawn with other deposits in the region west of the peninsula at Stanley.

Earlier research at Pulbeena Swamp around Smithton, which is about 50 km south east of Boullanger Bay, documents sequences of freshwater marl and swamp peat deposits that developed under the influence of fluctuating groundwater conditions in palaeo-floodplain and sand dune swale environments over last 50,000 to 11,000 yrs BP (Colhoun *et al.*, 1982). Previous investigations described similar sequences at Mowbray and Broadmeadows Swamp where peat and sandy peats were shown to develop in the swales between sand ridges more than 37,000 years ago (Gill and Banks, 1956). Correlation between the sequences at these inland locations and those shoreline sequences of this study can be made by comparing the comparison of the chronology, sedimentology and microfossil evidence. Furthermore, since the earlier studies, better definitions of climatic fluctuations during the last glacial phase, provided by glacial reconstruction of the West Coast Range (Colhoun *et al*., 1999) and Mt Field (Mackintosh *et al*., 2006), enable interpretation of the past environments. Such correlations are relevant to the reconstruction of Boullanger Bay, in that the nature and extent of the oxidized peat acts to preserve the original morphology of the coastal plain and links the past and present processes.

Most analysis was conducted on the deepest core retrieved from Sealers Springs Point where the oxidized peat is exposed at the surface. Analysis of cores at the other sites was conducted with the view to comparing the main features identified from SSP and assessing the hypothesis, that accommodation space for the recent transgressive sand has been limited by the indurated nature of the deposit. This induration (hardening) has made the deposit resistant to erosion, compared to the unconsolidated nature of other late Pleistocene sedimentary landforms that characterizes much of the south eastern Australian coast. If this is the case, it can be assumed that the current broad extent of the intertidal sand flats is a consequence of the interaction between a meso-tidal regime and a limited accommodation space, smaller in volume than the sediment supplied by offshore sand transgression. In such cases, sediment will fill the most proximal areas first and then because there is still more sediment than space, landward progradation will occur (Coe *et al*., 2003).

Structure of detailed site specific results

The structure of each of the following result sections includes a brief site and core location description. Descriptions of the stratigraphy for SSP have been divided into 5 sedimentary units that represent different sets of coastal processes. For the Pleistocene facies that have been carbon dated in this study, a description of the prevailing climate for each unit is provided. This is based on a review of climate proxy data collated from Tasmanian studies of glacial reconstruction, (Mackintosh *et al*., 2006) and past environment reconstruction in the state's NW, using C_{14} dating and pollen analysis (Colhoun *et al*., 1982). The relevant sedimentological and microfossil results for each are then presented, followed by the inferred palaeoenvironment. Core diagrams are provided for each site to aid interpretation of the results.

The stratigraphic record contains evidence of both the late Pleistocene era when sea levels were falling, and the Holocene epoch when sea levels rose and subsequently stabilized around 6,000 yr BP. An approach that pieces the evidence together from specific observations is employed to illustrate how these units stack due to changes in accommodation space with the changes in relative sea level (after Coe *et al*., 2003).

Sealers Springs Point

Site location and description

Sealers Springs Point (SSP) is an exposed site relative to the other core locations in this study. Initial reconnaissance of the site in July 2009 revealed extensive erosion of the sea ward edge of the saltmarshes. Micro-cliffing is evident along the shoreline, cutting into remnants of what would normally constitute the mid to upper marsh dominated by the reed *Juncus kraussii* and the terrestrial edge dominated by *Melalueca spp.* swamp forest. This modern marsh remnant overlies the oxidized peat which outcrops at the marsh seaward edge. At this location the peat deposit is most extensive and forms a tabular surface across the upper intertidal zone (see Figure A4.3).

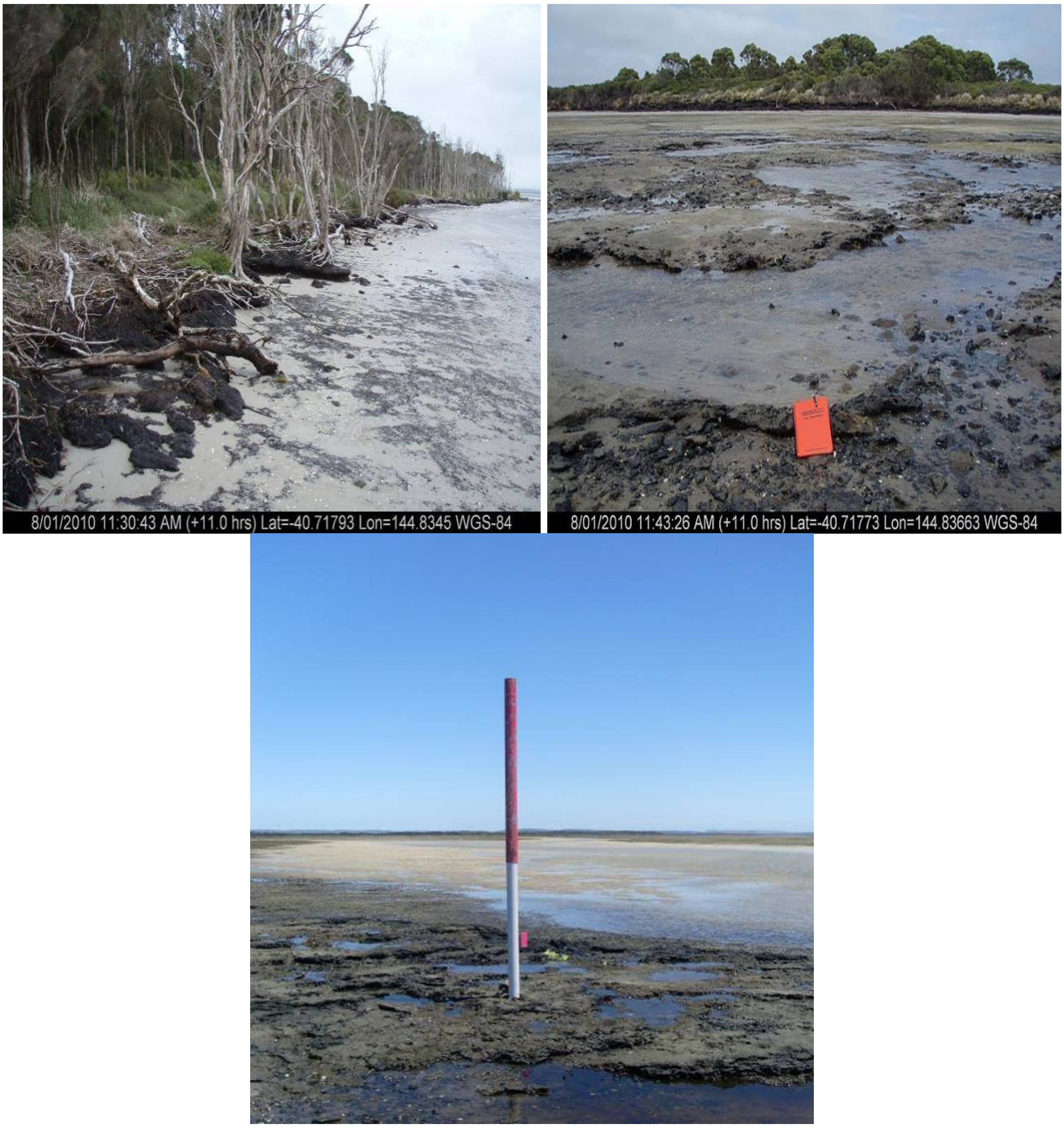

Figure A4.3. Images from clockwise: 1a - Eroding modern marsh edge, overlying the eroded black deposit; 1b - Extent of black deposit, note the tabular surface; 1c - Location of Core 3, Transect 1, Sealers Springs Point.

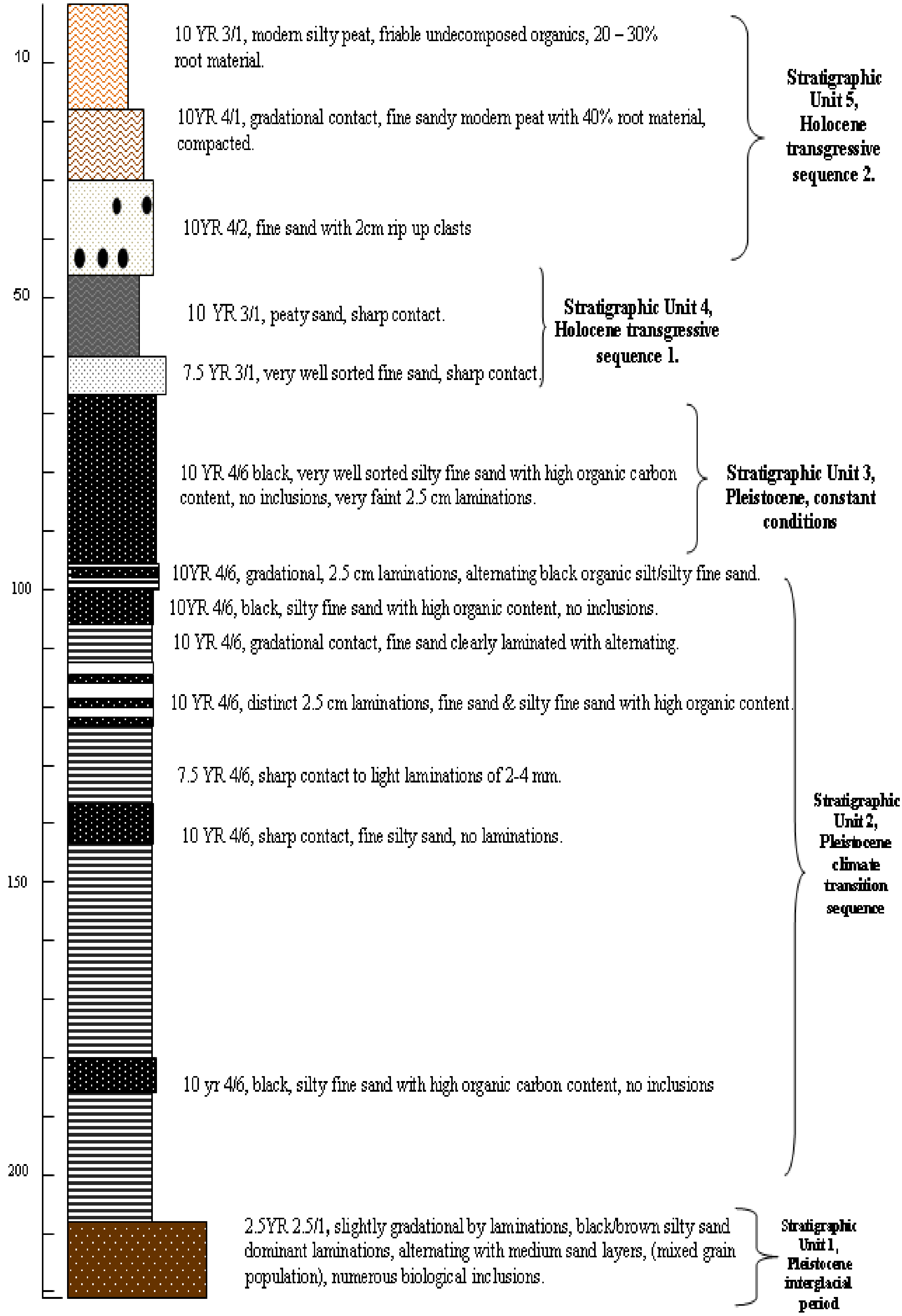

Figure A4.4 Diagram of Core 4 at Sealers Springs Point. The diagram shows the composition of the 5 stratigraphic units. The width of each facies is proportional to its mean grain size.

The Pleistocene sequence

Stratigraphic Unit 1, Marine Oxygen Isotope Stage 3 (middle), Tasmanian glacial retreat

Climate correlation

The bottom of the stratigraphic sequence at SSP has a radiocarbon age of 36,930 +/-400 yr BP. It correlates with the middle of late marine oxygen isotope stage 3. At this time sea levels were approximately 30 to 27 meters below current MSL (Cann *et al*., 1988, 1993, 2000, in Murray-Wallace, 2002). In Tasmania, middle MIS 3 climate was cool temperate and described as intermediate between interglacial and glacial conditions, (Colhoun *et al*., 1999) with relatively high precipitation compared to late MIS 3 (Mackintosh, 2006).

During the same time at Pulbeena Swamp a wet period is indicated at around 40,000 years by a marl deposit and *Melaleuca-Leptospermum* wet coastal woodland communities (Colhoun, 1982). Evidence from Pulbeena Swamp indicates that a progressive moisture decline occurred from this time and accelerated from 35000 yrs BP. This is marked by a reduction in wet forest communities and an increase in Gramineae and Compositaea which become competitive under dry conditions of low temperatures (Colhoun *et. al*., 1982).

Facies

Facies 1 extends from 221 to 208 cm depth in the core (see Figure A4.4). It was designated based on colour and the variation in grain size compared to the consistency of those above it. Although the sands are predominantly fine sand, they are larger than the fine sands upwards through the core. At 220 cm the only medium size sands occur with a mean of 292 µm (see Figure A4.5). This sand is moderately well sorted and positively skewed. At 217 cm mean grain size is 70 µm, poorly sorted and negatively skewed. These differences produce slight laminations and the variation reflects the variable processes of deposition that can be explained by proximity to fluvial processes (Boggs, 1987).

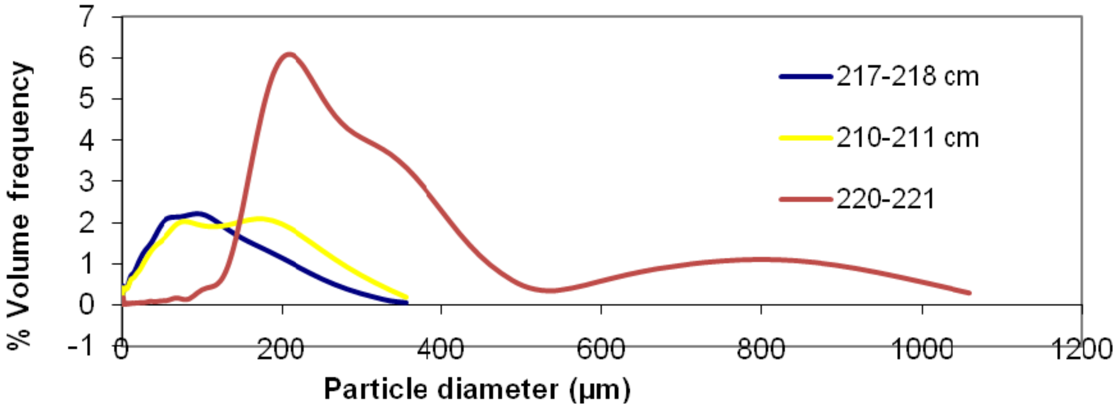

Figure A4.5 Particle distribution for stratigraphic unit 1, showing the heterogeneity of the grain population. Variation such as this reflects different energies of the processes of deposition and point toward fluvial deposition processes.

Palaeoenvironmental interpretation

Correlation of all points of evidence collected in this study, with that of broad climate proxies from those cited above, indicate that the environment from around 36,700 yr BP at Sealers Springs Point was influenced by predominantly freshwater inputs of variable energies. Most significant is the relative heterogeneity of the grain population which is characteristic of fluvial deposition. Fluvial deposits tend to be poorly sorted due to the wide range of particle sizes available for transport by rivers and various sizes can be deposited when energy levels wane (Boggs, 1987). The inclusion of minor lithic components is also consistent with a fluvial outwash environment whereby material has been transported from the land surface, rather than reworked from marine sources. The presence of biological inclusions such as unidentified seeds and plant fragments further supports this.

Pollen analysis in this study suggests proximity of the sample to freshwater sedgeland by the presence of *Gymnoschoenus sphaerocephalus* (buttongrass) and associated wet coastal scrub communities. No foraminifera or anything of marine origin was detected. Collectively, five points of evidence point toward a fluvial outwash environment;

1. No marine micro or macro fossils,
2. Poorly sorted grain population within and between samples of facies 1, particularly sample 218-219 that is positively skewed, consistent with fluvially deposited sediments (Boggs, 1987),
3. Numerous micro inclusions of biological origin and minor lithic fragments,
4. Pollens of wet coastal woodland and buttongrass moorlands, (this study) and
5. Global sea level around 30 to 27 meters below current MSL.

Stratigraphic Unit 2, Marine Oxygen Isotope Late Stage 3, Tasmanian glacial advance

Climate correlation

Facies 2 through to 10 span the time period from around 37,000 yr BP to around 26,700 yr BP, the latter just preceding MIS 2 and the onset of the Last Glacial Maximum at 20,000 yr BP. It is a phase of the beginning of glacial advance in Tasmania, when the Tasmanian climate was experiencing a rapid decline in temperature (Mackintosh, 2006). Persistent high wind speeds can be expected to predominate in the increasingly cold, dry climatic conditions.

Facies

Stratigraphic unit 2 contains facies 2-10 and extends from 217 cm to 96 cm (see Figure A4.4). These are collectively distinguished on the basis of colour and grain size. Whilst all are composed predominantly of very well sorted silty fine sands that are negatively skewed, individual facies are distinguished by colour and relative volumes of organic silt and fine sand and the depth of individual laminations (see Figure A4.6). For example, facies 3 (185 – 180 cm), has a high organic content with similar lithological characteristics as the oxidized peat deposit with slight laminations. Facies 4 (179 to 144 cm) occurs above this with a sharp contact to a clearly laminated facies where layers range in depth from 2-4 mm intervals. The pattern repeats through facies 5 and 6. Facies 7 is strongly laminated and layers deepen to around 1.5 – 2 cm depth from 137 – 114 cm.

Analysis of the two alternating layers shows that the modal grain size in each facies ranges from around 171 µm to 188 µm, the means range from 150 µm to 188 µm (see Figure A4.6). The difference is that the darker laminations contain a larger volume of organic material that is comprised of very fine sand/silt and have a smaller mean.

Facies 8, 9 and 10 repeat the pattern again although the depth of the laminated facies decreases as the lithology is increasingly dominated by the oxidized peat. The sequence is indicative of interbeds because it shows a progression from the dominance of the laminated facies at the base, to those which are organically enriched at the top, see Figure A4.6). Such sequences are termed intercalated and occur under very gradual changes in depositional processes, (Boggs, 1987).

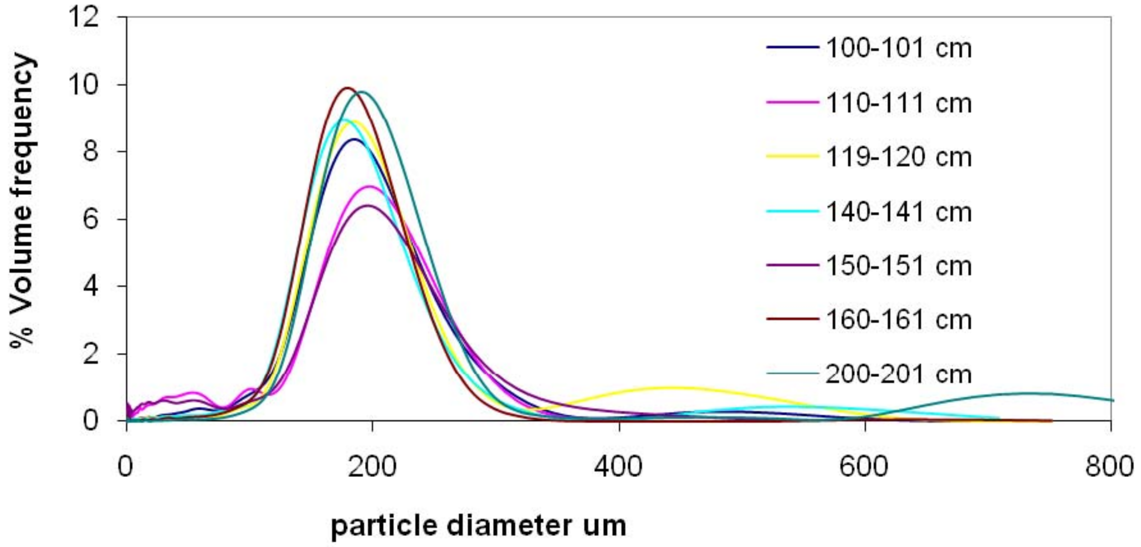

Figure A4.6 Particle size distributions of samples from facies 2 – 9 showing the well sorted grain population and the variation in the tails where some are coarse and some fine. This is a consequence of the alternating composition of the laminations.

Mineral composition is >99% quartz grains, with only a few fragments of mica and other minor lithic components. The entire sedimentary unit is barren of foraminifera or other marine microfossil. Diatoms were rare and highly damaged and were not detected in sufficient numbers to determine any genera. However, some pollen types were isolated and the most discernable trend is in the gradual reduction *G. sphaerocephalus* (button grass) and an increase in *Olearia* spp. (see Figure A4.2). In coastal habitats *Olearia phlogopappa* is a member of coastal woodlands (Kirkpatrick, 1991).

Palaeoenvironmental interpretation

Stratigraphic unit 2 contains a sequence of facies that cover a broad temporal span of around 10 000 years. During this time a drop in temperature occurs as the climate transitions from an interglacial to pre-glacial phase. The gradual nature of the change is reflected in the intercalated bedding of facies.

The inferred palaeoenvironment is one of increasingly cold dry and windy conditions, with seasonally variable warmer periods suitable for biological activity, in freshwater wetland environments that are receiving aeolian sands from the coastal plain. This is supported by the grain population consisting of fine sands that are very well sorted and finely skewed. Such sands are able to be transported by strong persistent winds and can be finely laminated due to seasonal variation in wind speed and biological activity, (Boggs, 1987). This is clearly the case at SSP. The lack of pollens due to desiccation causing oxidation, is also is consistent with the increasingly cold temperatures causing a reduction in precipitation, sea level fall and ground water lowering.

The four primary points of evidence that support this interpretation are:

1. the predominance of fine sub-angual sands that are well sorted and finely skewed,
2. few minor lithic components,

3. laminated facies indicating seasonal variation in biological activity, and,
4. intercalated sequence showing the gradual change in climatic conditions.

Stratigraphic Unit 3, Pre-Marine Oxygen Isotope Stage 2, Tasmanian glacial advance

Climate correlation

Stratigraphic unit 3 is comprised of only one facies. Its lower age limit has not yet been established although its depth and consistent lithology suggests an environment of deposition that experienced a period of constant climatic conditions and energy levels. The geologic age (26,700 yr BP) corresponding to the upper section of the facies (around 76 cm depth in the core) coincides with the period of maximum dryness for the region which is inferred to be around 25,000 to 11,000 yr BP (Colhoun, 1982). The climatic conditions were predominantly cold, arid and windy.

Facies

From 96 to 66.5 cm the colour, grain size and organic content are consistent (see Figure A4.4). Analysis shows a well sorted grain population that is finely skewed (see Figure A4.7), consistently sub-rounded to sub- angular and mineral content is >99% quartz. All of these characteristics are consistent with aeolian transport and deposition process. Figure A4.7 shows the homogenous nature of the lithology of facies 10.

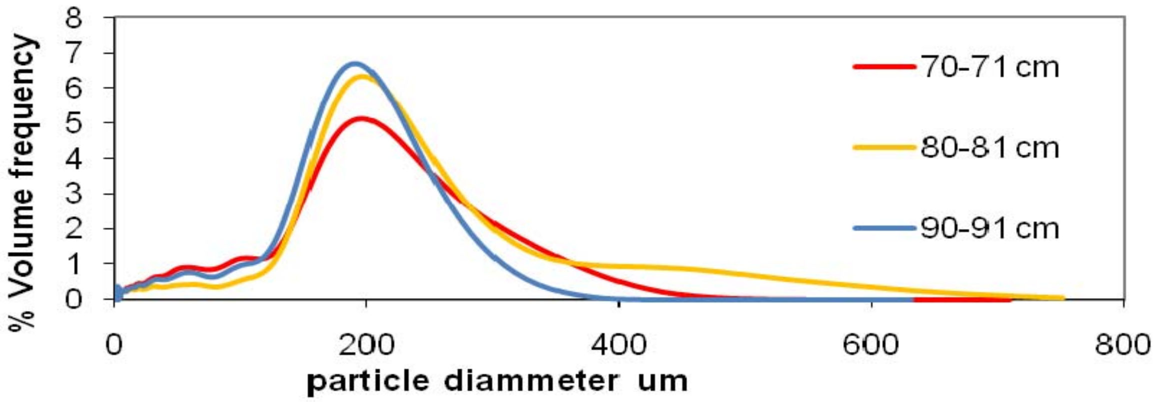

Figure A4.7 Particle distribution for samples in Stratigraphic Unit 3, facies 11. The distribution shows the homogenous nature of the oxidized peat.

Microfossil analysis showed the deposit to be barren of forams. Further, from the cores and other samples from the oxidized peat in Boullanger Bay, not one macrofossil indicating marine conditions such as shells or even fragments of shell were found. Not only does this support the aeolian deposition theory but also points toward fresh water wetland conditions. Although diatoms were rare and further work is required, the initial results indicate a community of slightly brackish to freshwater species.

Palaeoenvironmental interpretation

Four points of evidence point toward a constant environment of deposition in freshwater wetland. These include:

1. much lower than present sea levels,
2. high organic content of the sediment other than the quartz (>70%),

3. homogenous grain population,
4. presence of slightly brackish to freshwater diatom species.

The lack of marine microfossils, biological inclusions, or minor lithic components and the well sorted, finely skewed, fine sand, that show no variation throughout the deposit indicates that the process of deposition of the quartz grains was by aeolian transport. The consistent slight laminations indicate that wetlands occupied the deposits and seasonal biogenic production of organic silt was deposited also.

The Holocene sequence

The contact between the Pleistocene organic fine sand strata and the sand facies that overlies it is consistent with an erosional unconformity indicates a significant break in the geologic record (see Figure A4.4). Further interpretation of the break is pending the dating outcome for the more recent saltmarsh deposits. Notwithstanding the current lack of dating, evidence for the cause of the erosion point toward recent transgressive processes. The two remaining stratigraphic units are divided on the basis of the inferred processes of deposition that represent 2 phases of Holocene transgressive processes.

Stratigraphic Unit 4, Holocene transgressive sequence

Facies 12-13

Facies 12, 66.5 to 60 cm is an unconformable overlying sand layer that is coarser than the mean grain size of the oxidized peat (205 μm and 153 μm mean grain size respectively). The sand layer or sheet, contains frequent black oxidized peat clasts of up to 1 cm, that have been eroded from the surface of the deposit which now represents the flooding surface of the Last Marine Transgression.

Such clasts are termed rip up clasts and are indicative of erosion caused by tidal currents that are simultaneously transporting the sand grains from offshore deposits mobilized by the transgressing sea (Boggs, 1987). The clasts become finer upwards through the core, indicating reduced energy conditions consistent with water depth becoming shallower via sediment infill processes. Notably, 2-3 mm clasts are frequent in the surface saltmarsh peats, and erosion of the deposit is currently active with gravel sized clasts present on the exposed deposit in the upper intertidal zone. Black sand clasts are present throughout all cores from Robbins Passage Crossing to Sealers Springs Point, indicating that erosion of the deposit has been extensive and still actively occurring.

Microfossil evidence also points toward the sand sheet facies being tidally deposited. Foraminifera were abundant and dominated by *M. fusca.* This species has a broad ecological range from intertidal to subtidal environments but are usually only dominant intertidally (Hayward *et al.*, 1999). Several other types were located but not identified to the species level. *M. Fusca* was identified in facies 12 and in modern surface samples in the Brick Islands area.

The third point of evidence for a transgressive sand sheet deposited by recent rising sea level is the gradational contact from the sand facies to the modern saltmarsh peat (facies 13, 60-48 cm depth in core). Gradational contacts occur when changes in the depositional environment occur gradually (Boggs, 1987). In this case the transgressing sea has gradually deposited sediment on the tidal flat. When the tidal flat reaches an elevation of around the high water mark a saltmarsh will develop rapidly.

Extensive saltmarsh development requires relatively stable sea levels such as that of the recent Holocene stillstand (Davis, 1985). Evidence of the extent of the recent saltmarsh at Sealers Springs Point was identified in a series of pit cores that extended at least 25 m seaward of the current eroding edge. Well preserved vertical roots were identified down to pit 5 which is 15 m from the micro-cliffed edge and 39 cm above current MSL. The root formation was consistent with that of the growth habit of *Juncus krausii* which currently occurs on the marsh edge but is dominated by *Melalueca* stands. In other less eroded sites at Boullanger Bay *J. kraussii* and Melalueca co-exist in transitional areas between saltmarsh and the terrestrial margin and *J. kraussii* is dominant in the mid to upper marsh. In these locations the depth of the saltmarsh substrate is around 50 cm. If 50 cm were added to this point at SSP to represent the pre eroded marsh surface, the height would correlate well with the current surface height. This is clear evidence of recent rising sea level causing erosion and retreat of saltmarsh. Further evidence consistent with sea level rise is provided by the extensive dieback of *Melalueca* stands that fringe the marsh upland border and the apparent landward migration of saltmarsh species into this zone (see Section5.2.5. Changes in shoreline wetlands: vegetation and geomorphology).

Stratigraphic Unit 5

Facies 14-15

Core 3 at Sealers Springs Point shows a thin, wedge shaped sand sheet that overlies the saltmarsh facies and pinches out at the current edge of the saltmarsh before core 4 (see Figure A4.8). It too contains evidence of being tidally deposited and has pioneering seagrasses occurring at around pit 6 to pit 4. Because the saltmarsh facie (facies 13) is connected to the current saltmarsh edge it is clear that the current and past erosional processes of the modern saltmarsh are neither cyclical nor part of normal marsh evolution over time.

The Stratigraphy of the Holocene strata shows two sequences. Firstly, the unconformable transgressive sands overlying the Pleistocene deposit fine upwards to saltmarsh sandy silts. This is followed by a second period of transgression as evidenced by the wedge shaped surface sand sheet as the marsh is cut back and retreating landward. This assumes that the modern saltmarsh represents a period of stable sea levels.

Any further interpretation of the palaeoenvironment at SSP requires more detailed analysis of the biostratigraphic sequence using a multiproxy approach. Dating of the Holocene sequence is pending and will provide a better understanding of the processes that have occurred in the recent past. Most importantly, knowing the age of the onset and then breakup of the marsh could provide detail on the impact that human land use activities are having on the modern marshes stability in the past, present and future.

Stratigraphic assessments of all cores for SSP indicate a depositional Pleistocene lacustrine environment (see Figure A4.8).

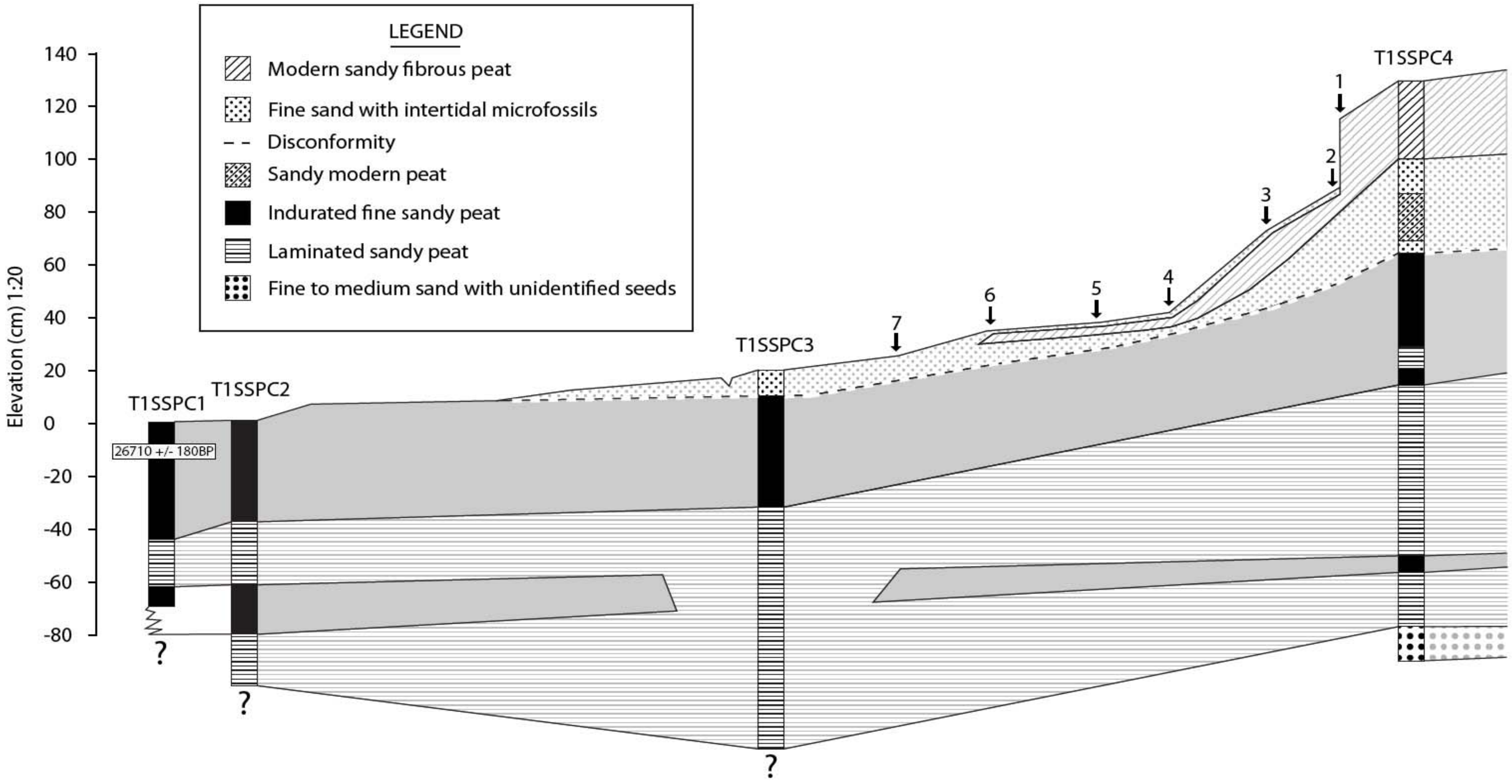

Figure A4.8 Stratigraphic diagram of Sealers Springs Point showing the location of cores and the sequence of stratigraphic units described in the text.

Brick Islands site

The Brick Islands site is between Sealers Springs Point and Robbins Passage Crossing and has extensive salt marsh with well developed tidal creeks and clear and consistent vegetation zones. The oxidised peat outcrops in the main tidal creek in the salt marsh and across the intertidal sand flat (see Figure A4.9).

A transect was surveyed for elevation from the marsh upland border out onto the intertidal sand flats to the tidal creek where the black deposit (Pleistocene peat) outcrops. One core of 103 cm was retrieved from the low marsh and the elevation of the oxidized peat within the core was tied to that of the tidal creek. The aim of this exercise was to identify the similarity or difference of the deposit to the outcrops at the other sites by comparing its lithology and heights. The primary objective was to contribute to lines of evidence regarding to the environmental history of the whole study area by comparing the processes that occurred at SSP to the stratigraphic record at Brick Islands. The results show similar processes of deposition where modern salt marsh overlies transgressive intertidal sands that, in turn, lie unconformably over the black deposit, see Figure A4.10.

A) Google Earth image of Brick Islands core location and tidal creek (T1BI).

B) Core location and proximity to deposit outcrop.

C) Deposit outcrop at the end of T1BI.

Figure A4.9. Brick Islands Site overview showing the core and tidal creek deposit locations.

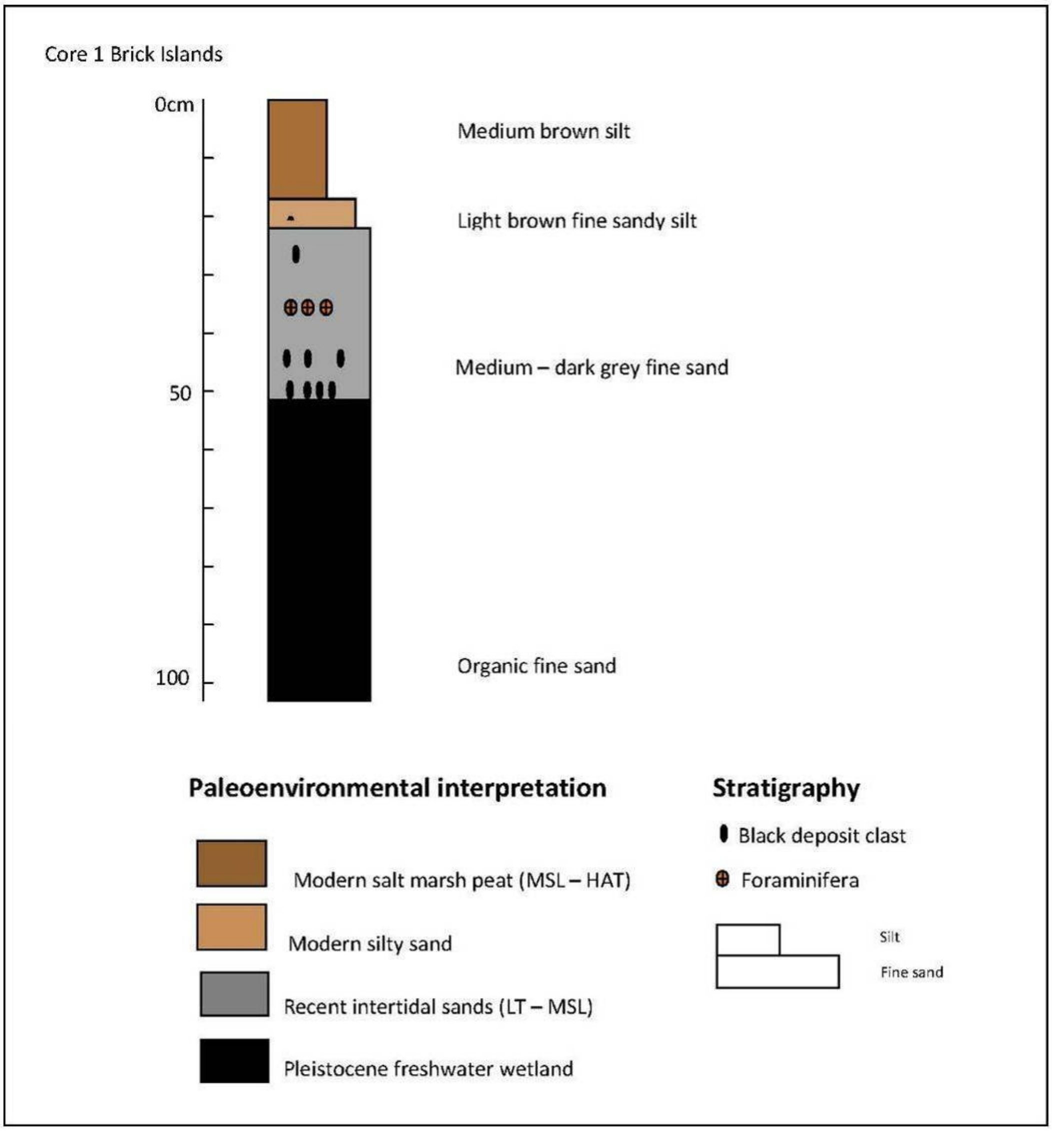

Figure A4.10 Core diagram with palaeoenvironmental interpretation for Core 1 Brick Islands

The elevation profile below (Figure A4.11) shows that the oxidized peat deposit is extensive and underlies the modern intertidal sands and saltmarsh in this area.

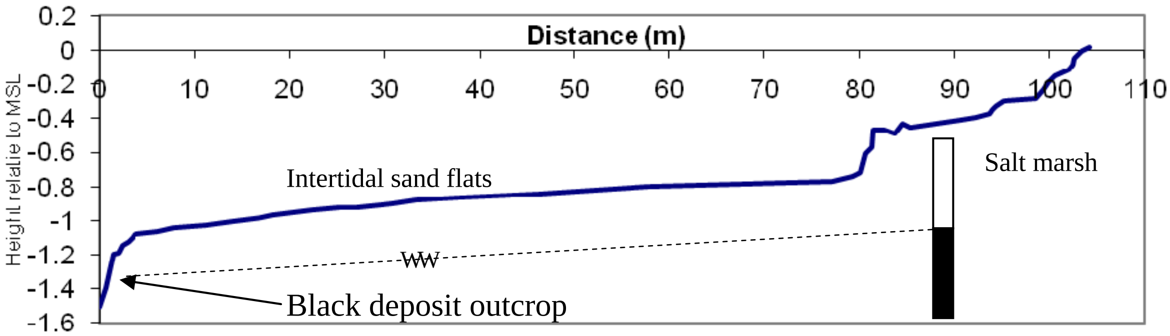

Figure A4.11 Transect profile showing the core location and the depth at which the oxidized peat occurs beneath the marsh and where it outcrops at the tidal creek.

To further test the hypothesis of Boullanger Bay being filled with sediment during the late Pleistocene, a comparison of the lithological characteristics of the oxidized peat deposit was undertaken for each of the main study sites. The results show remarkable similarity in grain size, sorting and skewness, see Figure A4.12.

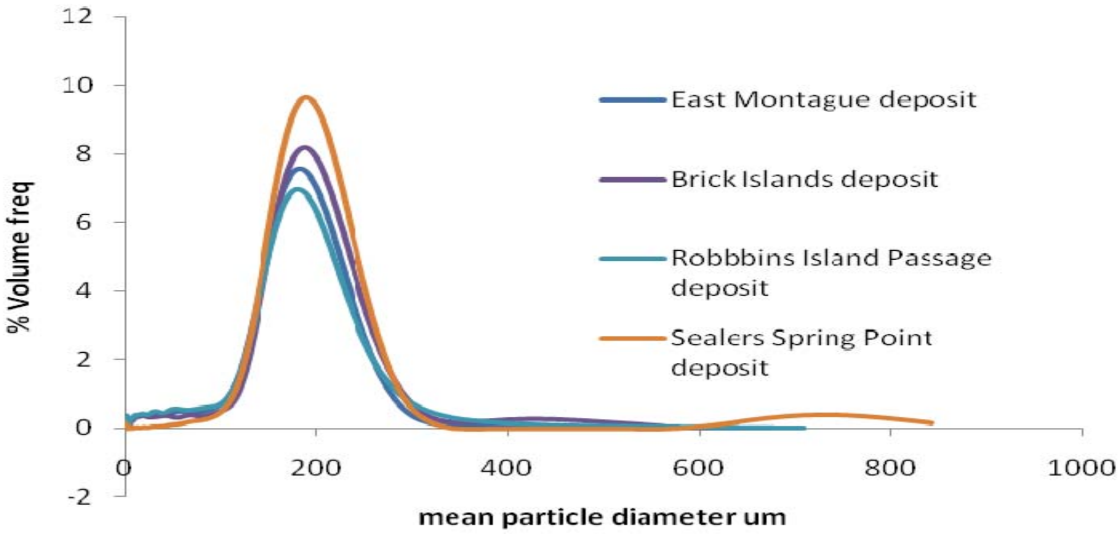

Figure A4.12 Particle size distribution of samples from an oxidised peat exposure at each site.

The similar lithology of the samples collected from outcrops of the deposit at each location indicates that the palaeoenvironment of deposition was remarkably similar for each. Further evidence was sought to ascertain its depth relative to current mean sea level. For Brick Islands three black deposit outcrops were measured for elevation. The three elevations were, -1.19 m, -1.07 m and -1.10 m relative to MSL (see Table 0.1). At Robbins Passage Crossing, the deposit in the main tidal channel was -1.75 m relative to MSL. These heights indicate remarkable consistency in the heights and given the other stratigraphic evidence, this strongly suggests that they are of a similar age and origin. Furthermore, the remote sensing imagery (see Figure 4.12, Figure 4.13 and Figure 4.14) shows that the deposit occurs at least from the high tide mark around Sealers Spring Point to the edge of the main tidal channel of Welcome Inlet. The same types of exposures were identified at Brick Islands and East Montague in the field, and so the breadth of evidence provided here indicates similar geographic distribution across the broader area.

Robbins Passage crossing site

The stratigraphic profile at Robbins Passage crossing (wadeway) is typical of an infill sequence (see Figure A4.13). Grain size analysis of each facies shows a slight fining upward sequence although all facies except the modern saltmarsh is dominated by the 150 μm fraction. Only at the base of the core from 145 to 123 cm depth are there quartz grains over 250 μm, making up 16% of the total sediment volume. Larger clasts of 7 mm of mud stone are also present. The >210 μm fraction is also greatest in this facies compared with those above it. The next facies at 123 cm depth is defined by a gradual contact, of slight colour change, and an absence of mud stone clasts. It consists of well sorted subrounded to subangual grains, dominated by the >150 μm fraction with very small inclusions of around 2 mm of the black deposit. Above it, at 18 cm depth is a sharp contact with the overlying light brown sandy peat, and then a gradual contact at 11 cm to the fine sandy peat of the saltmarsh to the surface.

Foraminifera were abundant in all samples and the upper two saltmarsh peat facies from 0 cm to 18 cm, were dominated by *Trochammina inflata. T. inflata* is known to occur at greater than 80% relative abundance from around mean sea level to mean high tide on saltmarshes, (Hayward *et al*., 1999, Morrison, 2005). *Quinqueflora seminula* occurred most frequently from 20 to 92 cm depth. This species is dominant from low tide to around mean sea level (Hayward *et al*., 1999). Another shift in species composition occurred at 92 cm depth where other species were evident, but not identified to the species level except for one, *Textularia earlandi*.

At 139 cm, *Q. seminula* occurred infrequently but the number of *T. earlandi* increased. The ecological range of *T. earlandi* is shallow sub tidal to low tidal positions, within brackish to slightly brackish locations of muddy lower reaches of estuaries, and inner to middle parts of harbours and tidal inlets (Hayward *et al*., 1999). Further taxonomic work of unclassified species and further numerical analysis of the relative abundance of *Q. seminula* and other species is required. However, these results identify sufficient change in species assemblages to show a change in the tidal frame from sub tidal to mean high tide, upwards through the core (see Figure A4.13). Further work is necessary to fully describe these changes, but the current evidence supports an estuarine infill sequence model.

Between Robbins Island Passage and Brick Islands coring was attempted with the Russian Peat Corer but only 45 cm of saltmarsh was retrieved. Refusal occurred at the contact between the saltmarsh deposits and a fine sand facies of similar lithology. Further pits were dug with a shovel in the main tidal creek close to the cores. These revealed the same sequence as C1RIR with no evidence of the oxidized peat. At this site a longer Holocene record of sea level change is evident.

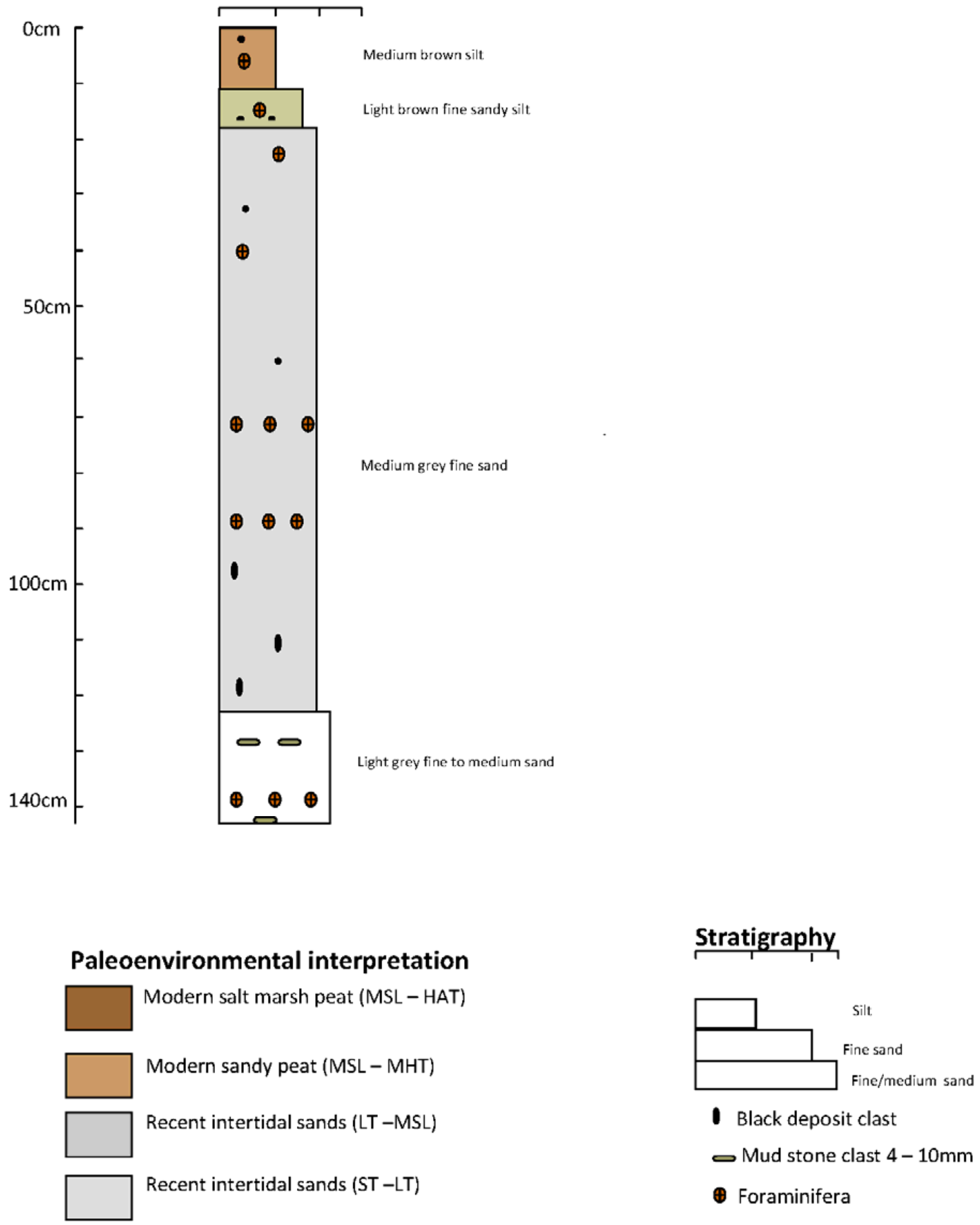

Figure A4.13 Stratigraphic diagram of core 1 at Robbins Island Road marshes showing a facies sequence that fines upward through the core. This is typical of an estuarine infill sequence.

4. Discussion and conclusion

A geomorphic history for Robbins Passage and Boullanger Bay spanning nearly 40,000 years has been reconstructed from the sedimentary record investigated in this study. The ability to obtain this history has in part been helped by the exposure of a well preserved oxidized peat formation now occupying the intertidal zone at sites across the study area. Examination and comparison of the lithological features of the oxidized peat in detail at Sealers Springs Point and the other sites has shown that the same processes of deposition have occurred across the area, and have created a platform formation on which the current intertidal sands lie. This was supported by the remote sensing results that show connectivity between exposures (see Figure 4.14). Although the freshwater wetlands in which the peat developed were extensive, they were not present at all locations.

The lenticular nature of the peat deposits is indicative of freshwater wetlands that have formed in the swales between sand dunes. These sands were transported and deposited into Boullanger Bay and adjacent areas from around 37,000 yr BP to around 27,600 yr BP when sea levels were around 30 m lower than present. Despite the cool, dry, windy conditions prevalent at this time, the climate was still moist enough to support wetland communities. Although there is a gap in the sedimentary record after 27,600 yr BP, sometime after this the climate cooled further (probably toward the last glacial maximum period at approximately 20,000 yr BP) and sea levels and the water table dropped along with a reduction in precipitation. These conditions probably caused the peats to dry out, thus causing them to oxidize.

Almost all of the sands at the study sites were fine, well sorted, subangual sands of > 99% quartz. The most likely processes responsible for the deposition of such a grain population are those of aeolian transport. Further evidence of processes after 26,700 yr BP may be inferred from the younger Pleistocene dunes overlying the oxidized peat at several locations around Sealers Springs Point. These dunes are presently eroding. It is most likely that the present intertidal zone was also covered by such dunes deposited as sea levels began to rise at the end of the last glacial period that ended around 18,000 yr BP. Those that covered the present intertidal zone have been progressively cut back to approximately their current position by the Last Marine Transgression (i.e. as the sea level rose after the last glacial period until it reached a stillstand about 6,000 yr BP).

The preservation of the Pleistocene organic peat in the intertidal zone is partially due to the resistance to erosive forces shown by the mixture of the fine grained organic sediment and compacted fine quartz grains that it coats and binds together. *In situ* the peat behaves as an indurated mass, in that it has cement like qualities of resistance to deformation. However, when dried in the laboratory the peat completely disaggregates to a powdery form with little force applied. Therefore, its preservation in the intertidal zone is a consequence of its repeated inundation by the tide that provides moisture and maintains its cohesion and resistance to mass break up. However, there is extensive evidence of surface erosion from the cores. In tidal creeks and outcropping at the sea ward edge of saltmarshes, and in some places at Sealers Springs Point rip up clasts and other eroded sediment is evident in the water column. This means that exposure of the Pleistocene peat at the surface, whether on the intertidal flats or along the shoreline, is conclusive proof that that location is currently more eroded than it has been since the peat was originally deposited. The dating suggests that this was about 26,000 years ago or more.

Rip up clasts of the oxidized peat occur throughout all cores, which suggests that it was eroded from the surface by tidal current action and redeposited with the transgressing sands when sea levels were rising after the last glacial period that ended around 18,000 yr BP. However, it is most likely that these sands and eroded clasts were deposited after 6,000 years BP, as MSL reached its present position and stabilized. The processes of erosion that are evident today may well mark the beginning of another transgressive phase. This is further supported by the die back of *Melalueca* along the terrestrial edge, particularly at Sealers Springs Point. Further, the stratigraphic record provides quantitative evidence of the degree to which the saltmarsh has receded at this location.

Recent saltmarsh deposits detected in pit cores, out to 15 m, beyond the current saltmarsh edge are now overlain by the thin transgressive sand sheet and pioneering seagrasses. Comparison of the elevation of *J. kraussii* macrofossils in these deposits with the surface elevation of intact *J. kraussii* communities in modern saltmarsh, showed a 50 cm difference. If 50 cm were added to the eroded surface it would be the same height as the current marsh edge. Similar saltmarsh sediment deposits in the tidal sand flats were identified at Brick Islands. Further investigation of these should enable quantification of the sea level rise for the time period over which the saltmarshes were deposited.

In conclusion, it is clear that the oxidized peat has been fundamental to the evolution of the Circular Head foreshore region in that it has acted as a platform and effectively created shallow water conditions. Such conditions have facilitated deposition of reworked marine sediment by the recent transgressing sea and created the broad intertidal sand flats. In turn this has created relatively gentle wave action reaching the landward edge and has allowed the development of salt marshes. According to Eisma (1997) mesotidal deposits only occur where there is shallow coastal water, an open coast or open connection to tides, and sediment available for building the tidal flats. Clearly this is the case at Boullanger Bay and it is likely that broad area of available intertidal habitat is a consequence of the interaction of these processes as sea levels began to rise during the last marine transgression and the subsequent relative sea level stillstand of the Holocene. These processes are still occurring and it is likely that they will continue, under the current rate of sea level rise. This is evidenced by the apparent resistance to erosion and mass breakup of the oxidized peat, other than surface erosion typical of transgressive tidal current action.