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Foreword

The environmental assets of the Coorong, Lower Lakes and Murray Mouth (CLLAMM) region in South Australia are currently under threat as a result of ongoing changes in the hydrological regime of the River Murray, at the end of the Murray-Darling Basin. While a number of initiatives are underway to halt or reverse this environmental decline, rehabilitation efforts are hampered by the lack of knowledge about the links between flows and ecological responses in the system.

The CLLAMM program is a collaborative research effort that aims to produce a decision-support framework for environmental flow management for the CLLAMM region. This involves research to understand the links between the key ecosystem drivers for the region (such as water level and salinity) and key ecological processes (generation of bird habitat, fish recruitment, etc). A second step involves the development of tools to predict how ecological communities will respond to manipulations of the "management levers" for environmental flows in the region. These levers include flow releases from upstream reservoirs, the Lower Lakes barrages, and the Upper South-East Drainage scheme, and dredging of the Murray Mouth. The framework aims to evaluate the environmental trade-offs for different scenarios of manipulation of management levers, as well as different future climate scenarios for the Murray-Darling Basin.

One of the most challenging tasks in the development of the framework is predicting the response of ecological communities to future changes in environmental conditions in the CLLAMM region. The CLLAMMecology Research Cluster is a partnership between CSIRO, the University of Adelaide, Flinders University and SARDI Aquatic Sciences that is supported through CSIRO's Flagship Collaboration Fund. CLLAMMecology brings together a range in skills in theoretical and applied ecology with the aim to produce a new generation of ecological response models for the CLLAMM region.

This report is part of a series summarising the output from the CLLAMMecology Research Cluster. Previous reports and additional information about the program can be found at http://www.csiro.au/partnerships/CLLAMMecologyCluster.html

Table of Contents

Acknowledgements

This research was supported by the CSIRO Flagship Collaboration Fund and represents a collaboration between CSIRO, the University of Adelaide, Flinders University and SARDI Aquatic Sciences.

We also acknowledge the contribution of several other funding agencies to the CLLAMM program and the CLLAMMecology Research Cluster, including Land and Water Australia, the Fisheries Research and Development Corporation, SA Water, the Murray Darling Basin Commission's (now the Murrray-Darling Basin Authority) Living Murray program and the SA Murray-Darling Basin Natural Resources Management Board. Other research partners include Geoscience Australia, the WA Centre for Water Research, and the Flinders Research Centre for Coastal and Catchment Environments. The objectives of this program have been endorsed by the SA Department for Environment and Heritage, SA Department of Water, Land and Biodiversity Conservation, SA Murray-Darling Basin NRM Board and Murray-Darling Basin Commission.

We are grateful to Russel Seaman and M. Miles (South Australian Department for Environment and Heritage) for providing aerial photos, bathymetry and habitat maps for the Coorong and regions, and Yuki Tunn (Map Land, DEH) for providing the SPOT5 imagery. Thanks to Maylene Loo, Brian Deegan, Alec Rolston and Rebecca Lester for sharing their knowledge about the Coorong**.** We would also like to thank Pramod Aryal for help with writing model scripts.

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Executive Summary

The Coorong is a 2-3 km wide lagoon running parallel to the coast for approximately 100 km from the Murray Mouth. It provides an important habitat for a wide range of bird species, and in particular has been listed as a Ramsar wetland due to its exceptional importance for migratory waterbirds. Over 85 species of water birds and waders, and 68 fish species, have been reported in the region. In large part, the regions uniqueness is due to the diversity of habitats located in a small area, in particular the salinity gradient, which under natural conditions ranges from almost fresh to estuarine through to hypersaline. Understanding the distribution, spatial extent and connectivity of these habitats is crucial for successful conservation and management of the region, particularly under the severely altered flow regimes currently being experienced, which have resulted in lower than normal water levels and extreme hypersalinity in the South Lagoon.

Regional habitat maps

As part of the Coorong, Lower Lakes and Murray Mouth Research Cluster (CLLAMMecology), we developed comprehensive maps of a variety of habitat attributes in the Coorong in the early to mid 2000's. This mapping included surrounding vegetation assemblages and wetlands, subtidal sediment characteristics, and bathymetry. We used a variety of data sources, including pre-existing mapping conducted by the South Australian Department for Environment and Heritage, aerial photography, satellite imagery, in situ field surveys of benthic habitats and sediments, and topographic surveys. In situ sampling focussed on the 12 reference sites selected for intensive study by the broader CLLAMMecology research team, producing detailed habitat maps of an area ~2 km wide extending across the lagoon from the eastern to the western shore. However, mapping efforts based on existing data sources and remote sensing also produced maps of the entire Coorong and its surrounds.

At a broad scale, a total of 5,755 ha was mapped using remote sensing, with about half the mapped area in the lagoon (49.9%), 34.7% on the peninsula, 13% on the mainland, and less than three percent on islands. The terrestrial and wetland habitat categories covered 34.9 and 65.1 percent, respectively, of the mapped area. A total of 19 landforms and 17 wetland types were identified in the reference sites. Twenty four wetland habitats and 14 terrestrial habitat types were reported from these reference sites. The Coorong and surrounding region were classified into ten broad habitat categories including agricultural and pastoral land. The habitat maps generated through the current study provide a reference for the available habitats in the area, and baseline information for making future predictions on habitats based on the major ecological drivers of the system: water level and salinity. They also facilitate estimations on the likely occurrence of species or ecosystems in the region, and can be used to help determine the likely ecological effects of management decisions on water flow over the barrages.

Coorong Digital Elevation Model

A range of data sources were also combined with predictive modelling to develop an accurate and comprehensive Digital Elevation Model (DEM) of the Coorong and surrounds. While a relatively good data set on bathymetry is available from the South Australian Water Corporation for the North Lagoon, and there is an existing DEM for terrestrial areas of South Australia, which includes the area surrounding the Coorong, there is limited bathymetric data available for the South Lagoon. The few field data on depth in the South Lagoon were used to develop a predictive model of bathymetry using remote sensing data, in order to generate a comprehensive bathymetry, although the predictive ability of the model was poor for regions south of Jack Point, where turbidity was high. This and the bathymetry data from the North

Lagoon, as well as the SA regional DEM, were then merged into a seamless DEM of bathymetry and topography for the Coorong, allowing prediction of the extent of different habitats based on depth at different water levels.

Benthic habitat maps

We also generated sediment and benthic habitat maps for the Coorong. Sediment characteristics were obtained at a number of points at each of the sites from field sampling, and modelling was then used to predict characteristics along the two lagoons, based on distance from the Murray Mouth, the underwater topography, distance to shore, and also salinity, amongst other variables. We found three main depositional areas along the Coorong, where sediments are fine and organically-enriched: (1) the middle channel of the lagoons, (2) the constriction between the North and South Lagoons, and (3) the western (seaward) shore of the North Lagoon, particularly south of Long Point.

Mudflats

The status of the Coorong wetlands as migratory bird habitat has been due primarily to the opportunities they provide for large numbers of birds to feed in a highly productive estuarine and lagoonal environment. A significant proportion of this foraging occurs on the large tracts of mudflat found throughout the Coorong. The productivity of the mudflats varies along the length of the Coorong, dependent primarily on water quality (particularly salinity), nutrient inputs, sedimentary structure, and the duration, frequency and extent of inundation. Resident macroinvertebrate populations and aquatic vegetation such *Ruppia* species are both an indicator of productivity in the mudflats and a food source for fish and birds.

High resolution topographic/bathymetric models for the 12 CLLAMMecology reference sites, confirm the importance of the South Lagoon in terms of mudflat habitat, as it contains some 61% of available mudflat, as measured in the reference sites. All mudflats should be highly productive if the necessary physical, chemical and biological conditions existed. Across all 12 reference sites the 0 m to 0.5 mAHD elevation range is most significant as it contains approximately 43% of all available mudflat area. The second most important elevation class is -0.5 m to 0 mAHD, containing approximately 40% of total available mudflat area. This suggests that manipulations of water level should be kept within this range. Ideally, the most important elevation range is 0.2 m to 0.4 mAHD, as manipulations in this range accomplish wetting and drying of the maximum area of mudflat. If water levels can be maintained at close to optimal levels, then natural high-frequency, wind-driven oscillations in water levels will inundate large areas of mudflat.

Dynamic habitat model

By combining the bathymetry data described above with the outputs of a CSIRO hydrodynamic model detailing hourly water level and salinity along the Coorong for a given flow scenario, we were able to develop dynamic habitat models for key bird and fish species. The first spatial model predicts the location and extent of mudflats, defined as soft sediment areas that are either emersed or covered by no more than 12 cm of water, where most waterbird foraging occurs. Mudflat availability varied spatially and temporarily along the Coorong, and is influenced by tide, wind, rainfall and evaporation, some of which are dependent on the distance from the Murray Mouth and are affected by seasonal variation. The modelling of mudflats at different water levels suggests that an average water level of 0.12 mAHD gives the maximum average mudflat area in the three reference sites examined in detail (Barker Knoll, Noonameena and Salt Creek), with the majority of the mudflats located on the eastern shores. Out of seven key fish species examined, four (Yelloweye Mullet, Smallmouth Hardyhead, Greenback Flounder and Tamar River Goby), demonstrated a significant relationship with salinity. Among the three different salinity gradient scenarios examined, a salinity range from 5 to 90 g/L along the Lagoon was found to be the best in terms of the suitability of the entire Lagoon for these four key species, as well as for supporting other important biological communities including both macrophytes and infauna. The extent of habitat available for each of these species depends on the salinity gradient present, which varies considerably over time.

Potential applications for the design of environmental flow strategies for the Coorong

This study has developed a set of tools that will help managers design better intervention strategies for the rehabilitation of the Coorong region. These tools allow managers for the first time to explicitly incorporate spatial considerations in the design of environmental flow strategies for the Coorong, such as where mudflats will be located under different management interventions. Similarly, it is now possible to quantify the habitat that could be gained or lost under different management intervention for a range of key wading bird and estuarine fish species. Another important legacy of the project is to have collated and synthesised a large amount of spatial information about the Coorong region, which can now be used for a variety of other purposes in addition to the design of environmental flow strategies. Of particular importance, is the finding that the South Lagoon appears to have substantially more mudflat habitat than the North Lagoon, making it more important that management startegies address the need to maintain such habitats in this region in a productive state.

1. Introduction

The Coorong is a 2-3 km wide lagoon, separated from the Southern Ocean by a barrier dune, and running parallel to the coast for approximately 100 km from the Murray Mouth. Historically, it was permanently connected to both the freshwater Lower Lakes and the ocean, however, in recent times these connections have been threatened and even severed. In the 1940's, a series of barrages were constructed between the Lower Lakes and the Murray estuary and Coorong, in order to prevent saltwater incursion into freshwaters used for human consumption and irrigation. While freshwater continued to flow over the barrages, increasing abstraction upstream and reduced rainfall has meant that these flows have declined precipitously, and have frequently stopped, especially since the mid 1990's (e.g. Geddes 2005). As a consequence, less freshwater has been available to the Coorong and Murray estuary. This reduction has resulted in closure of the Murray Mouth, which is now only kept open by dredging, reduced water levels in the Coorong, and increased salinity, to the point where the southern end of the Coorong now has salinities in excess of six times those of seawater (e.g. Noell *et al.* 2009).

These physical changes in the Coorong have had major implications for the flora and fauna that help make the Coorong a unique environmental asset. Historically, it has provided an important habitat for a wide range of bird species, and it is listed as a Ramsar wetland due to its exceptional importance for migratory waterbirds, which were estimated to number in excess of 234,543 in 1982 (Wilson 2001). Over 85 species of water birds and waders, and 68 fish species, have been reported in the region. These, in turn, rely on a rich assemblage of macro-invertebrates, as well as extensive stands of macrophytes, to provide them with the abundant food resources that make the region so attractive to them. However, increasing salinity has meant that many of these food resources have declined greatly in abundance (e.g. Rolston and Dittman 2009), and as a consequence, bird numbers have also declined (e.g. Rogers and Paton 2009). Fish also are suffering from reduced food availability, as well as directly from increased salinity, which is beyond their osmoregulatory ability to cope with (e.g. Noell *et al.* 2009).

With limited freshwater resources available, it is necessary to optimise its use for generating environmental flows and to understand what other management interventions could be considered to maintain as much of the biological diversity and ecological integrity of the Coorong as possible. As such, the Coorong Lower Lakes and Murray Mouth research cluster (CLLAMMecology), has conducted an extensive research project to examine the habitat characteristics, assemblages of key species including birds, fish and macro-invertebrates, productivity and biogeochemical cycling of the Coorong. The overall goal is to develop an integrated ecosystem model that can be used to predict the future ecological state of the Coorong under a range of defined flow scenarios.

In this report, we develop a dynamic GIS-based habitat model of the Coorong, that can be used to predict the availability of habitats for key bird and fish species under any pre-defined flow scenario. This model uses output from the CSIRO 1-dimensional hydrodynamic model of the Coorong, which produces hourly outputs of water level and salinity along the length of the two lagoons (Webster 2007). Both models also utilise a seamless digital elevation model that we developed from a number of data sources, and describe here. The model for birds predicts the extent of mudflats available at different water depths in each of 12 reference sites that are the subject of detailed study by the broader CLLAMMecology team, although only results for 3 sites (Barker Knoll in the north, Noonameena mid-way down the North Lagoon, and Salt Creek at the southern end of the South Lagoon) are presented for brevity. It also builds upon more detailed mapping of topography at each of the reference sites, as well as sediment mapping. The model for fish primarily links the probability of occurrence for a range of species to salinity, based on data collected by Noell *et al.* (2009).

Chapter 2 of this report builds on existing work by the South Australian Department for Environment and Heritage (Seaman 2003) to produce a broad-scale habitat map of the area surrounding the Coorong. This exercise focuses on mapping different vegetation and wetland types, using a combination of remote sensing data and field verification. Chapter 3 develops a single seamless digital elevation model of the region from a number of data sources, and uses predictive modelling to fill the existing data gaps. This model underpins the dynamic habitat model, as a knowledge of bathymetry is required to determine the extent of mudflat available at different water levels. Chapter 4 then focuses on fine scale mapping of benthic and near-shore habitats and sediment characteristics at each of the 12 reference sites. Chapter 5 examines the geomorphology of the mudflats at these reference sites in more detail, allowing centimetre scale prediction of water depth in the vertical scale at different water levels. This level of accuracy is important, as most wading birds have a very specific foraging niche with respect to water depth, with few foraging in water > 20 cm deep (Rogers and Paton 2009). Finally, Chapter 6 presents the dynamic habitat model, and details how habitat availability changes under different conditions using a flow scenario based on actual water inputs to the Murray Darling Basin over the last 112 years.

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2. Habitat Mapping of the Coorong and Surrounds

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2.1. Executive Summary

The Coorong Lagoon and surrounding areas provide exceptional habitat for a wide range of bird and fish species. Over 68 fish species and 85 species of water birds and waders have been reported in the region. Unique biological diversity has rendered the region as one of high conservation value, which has been recognised through its listing as a wetland of national, as well as international, importance.

Understanding the distribution, spatial extent and connectivity of habitats has been widely accepted as a crucial step for successful conservation and management of biological diversity. Habitat mapping has become a popular tool for identification, characterisation and visualisation of different habitats. Habitat maps are also very useful as a monitoring tool for detecting change in habitats and evaluating human impacts or the effects of climate change, and for assessing the ecological values of the region.

The South Australian Department for Environment and Heritage (DEH) developed a GIS based habitat map for the areas surrounding the Coorong and Lower Lakes in 2003, mainly focused on the state of the wetlands. This map does not include benthic habitats along the Coorong or characterisation of physical environmental parameters. In order to complement the DEH habitat map, the Dynamic Habitat Project under the CLLAMMecology Research Cluster aimed to map the benthic habitats and areas surrounding the Coorong. This habitat mapping exercise focussed primarily on the 12 representative sites across the Coorong selected for detailed study by the CLLAMMecology Research cluster, and this information was extrapolated to map habitats across the entire region through classification of LANDSAT5 Thematic Mapper imagery.

A habitat classification scheme with 12 attributes encompassing a range of geographical, physical, chemical and biological characteristics for each habitat was used. Apart from drawing on and improving information derived from existing habitat maps for the Coorong and Lower Lakes, the current habitat mapping program incorporated a range of other data sources. These included remotely sensed imagery such as satellite data and high resolution aerial photography, and field data collected as part of the CLLAMM project.

A total of 5,755 ha was mapped, with about half the mapped area in the lagoon (49.9%), 34.7% on the peninsula, 13% on the mainland, and less than three percent on islands. The terrestrial and wetland habitat categories covered 34.9 and 65.1 percent, respectively, of the mapped area. A total of 19 landforms and 17 wetland types were identified in the reference sites. Twenty four wetland habitats and 14 terrestrial habitat types were reported from these reference sites. The Coorong and

surrounding region were classified into ten broad habitat categories including agricultural and pastoral land.

The habitat maps generated through the current study provide a reference for the available habitats in the area, and baseline information for making future predictions on habitats based on the major ecological drivers of the system: water level and salinity. They also facilitate estimations on the likely occurrence of species or ecosystems in the region, and can be used to help determine the likely ecological effects of management decisions on water flow over the barrages.

2.2. Introduction

The Coorong Lagoon and surrounding areas provide exceptional habitat for a wide range of bird and fish species. In particular, the lagoon has been an indispensable habitat for many fish species for completing their life cycles as well as one of the most visited destinations for migratory shorebirds in Australia (Edyvane 1999). A total of 85 waterbirds species (Carpenter 1995) and 68 species of marine, estuarine and freshwater fish (Department for Environment and Heritage 2000) have been reported in the region. Unique biological diversity has rendered the region as one of high conservation value, which has been recognised through its listing as a wetland of national, as well as international, importance (Seaman 2003; Australian Nature Conservation Agency 1996)

A strong spatial gradient of habitat types exists along the length of the Coorong, defined by variations in physical environment and processes. Each habitat constitutes a unique combination of environmental conditions and interactions, which render the area suitable for habitation by different species and biological communities. In a general sense, habitats are distinguished by their physical, biological and chemical characteristics (Kostylev *et al.* 2001) and offer suitable areas for a species or group of species. These habitat variables are often viewed as environmental/ecological variables.

Understanding the distribution, spatial extent and connectivity of habitats has been widely accepted as a crucial step for successful conservation and management of biological diversity (Bowers 2008; Chong 2007). Habitat mapping has become a popular tool for identification, characterisation and visualisation of different habitats (Chust 2008; Lathrop 2006; Urbanski 2003). Habitat mapping aims to provide baseline information about the physical and biological features present in an area, and assists understanding of the interactions between them. Habitat maps are also very useful as a monitoring tool for detecting change in these features and evaluating human impacts or the effects of climate change, and for assessing the ecological values of the region.

The South Australian Department for Environment and Heritage (DEH) developed a GIS based habitat map for the areas surrounding the Coorong and Lower Lakes in 2003, mainly focused on the state of the wetlands, and mapped primarily through aerial photo interpretation (Seaman 2003). The mapping defines the spatial arrangement of primary vegetation assemblages and employs the standard DEH classifications for South Australia. However, this map does not include benthic habitats along the Coorong or characterisation of physical environmental parameters. In order to complement the DEH habitat map, the Dynamic Habitat Project under the CLLAMMecology Research Cluster aimed to map the benthic habitats and areas surrounding the Coorong. The current habitat mapping exercise focussed primarily on the 12 representative sites across the Coorong selected for detailed study by the cluster (Figure 2.1), and this information was extrapolated to map habitats across the entire region through classification of LANDSAT5 Thematic Mapper imagery.

The habitat maps generated through the current study provide a reference for the available habitats in the area, and baseline information for making future predictions on habitats based on the major ecological drivers of the system: water level and salinity. They also facilitate estimations on the likely occurrence of species or ecosystems in the region, and can be used to help determine the likely ecological effects of management decisions, such as how much water to release over the barrages and when.

2.3. Reference sites for habitat mapping in the Coorong

Twelve reference sites were identified between the Goolwa barrage in the North Lagoon and Salt Creek in the South Lagoon, representing habitats across the system (Figure 2.1). In addition to sites in the Goolwa and Mundoo channels, ten sites were located along the main channel of the Coorong extending south from the Murrary Mouth. The site at Goolwa Channel is placed between the Goolwa barrage and the Murray Mouth. Another site was established in Mundoo Channel about one kilometre west of the Mundoo barrage. Of the ten sites in the Coorong itself, six were in the North Lagoon between the Murray Mouth and Noonameena. These were: Barker Knoll, Ewe Island, Pelican Point, Mark Point, Long Point and Noonameena. The remaining four sites were located in the South Lagoon between Parnka Point and Salt Creek: Parnka Point, Villa dei Yumpa, Jack Point and Salt Creek. These sites were selected by the CLLAMMecology research cluster as being representative of the spatial gradient of habitats available in the lagoon, as well as suitable for sampling for the range of projects being undertaken by the cluster.

Each reference site was defined as a band approximately 1.5 km wide (except for the Mundoo Channel where the channel is narrow and bends sharply), centred on the actual site selected by the CLLAMMecology research cluster. As well as examining the aquatic habitats, adjacent terrestrial habitats were also mapped, with the sites being delineated by a road or natural landscape element on the eastern boundary and the Southern Ocean coast on the western boundary.

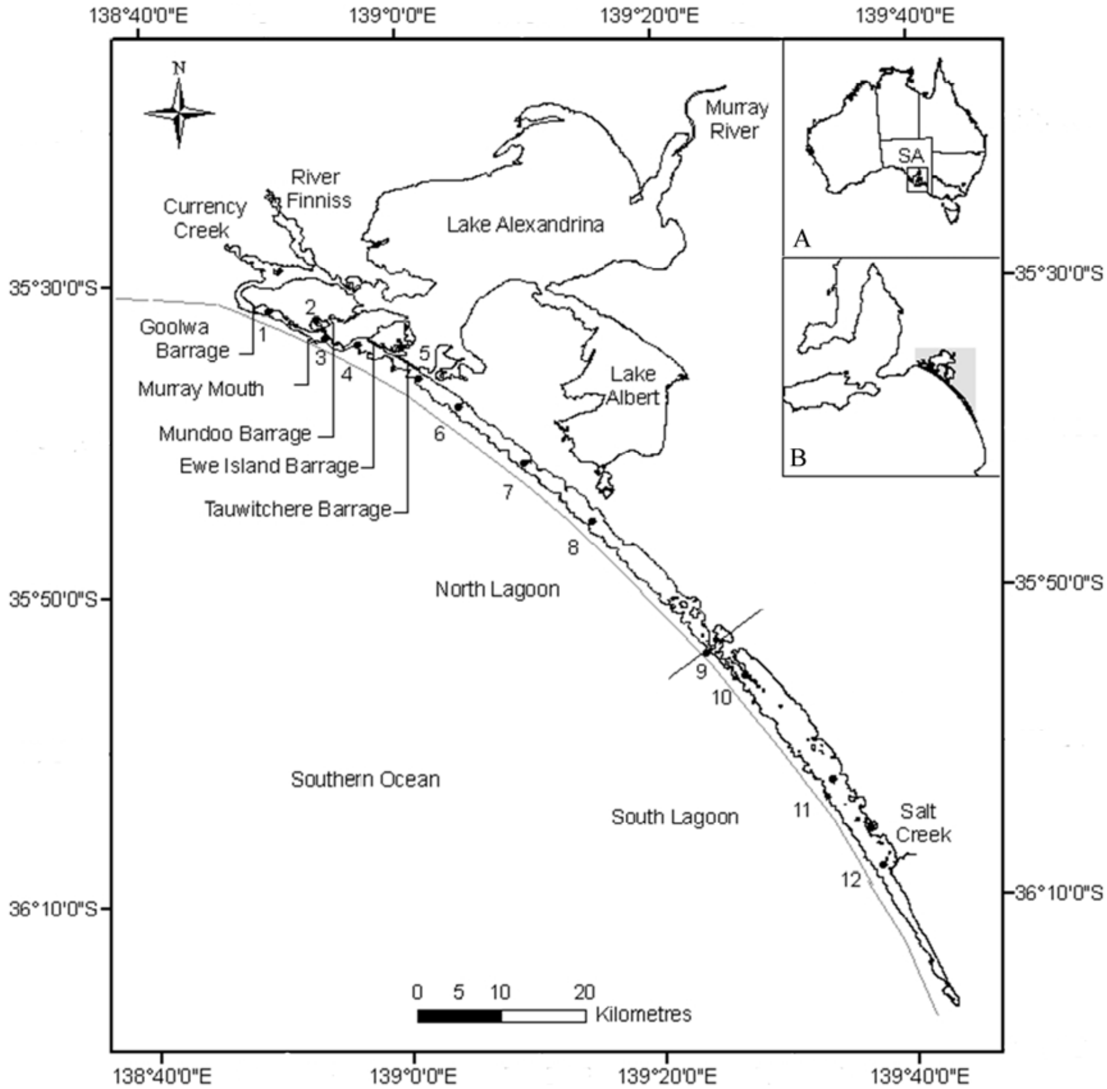

Figure 2.1. Locations of the reference sites in the Coorong Lagoon: 1 = Goolwa; 2 = Mundoo; 3 = Barker Knoll; 4 = Ewe Island; 5 = Pelican Point; 6 = Mark Point; 7 = Long Point; 8 = Noonameena (in the North Lagoon); 9 = Parnka Point; 10 = Villa dei Yumpa; 11 = Jack Point and 12 = Salt Creek (in the South Lagoon). The Australian map (A) shows the state boundaries and the study area in South Australia (SA) while the inset map (B) highlights the study area shown in the main map.

2.4. Habitat classification scheme

Previous habitat maps developed by DEH were based on 24 biological, physical and environmental attributes (Seaman 2003). Although the habitat classification system was very detailed and comprehensive, most of the attributes were missing for many habitat units. To minimize the missing data in the database and also to incorporate both wetlands and terrestrial habitats into the one habitat map, a habitat classification scheme with 12 attributes, encompassing a range of geographical, physical, chemical and biological characteristics for each habitat was used. These habitat attributes are described briefly in the following section.

2.4.1 Habitat zone

The Coorong and surrounds include mainland, island, peninsula and lagoon systems, and contain a huge diversity of wetland, terrestrial and benthic habitats within a small geographical domain. The zoning of habitats specifies their location within these landscapes. The mainland zone extends from the eastern shore of the lagoon inland.

Those areas that are separated from the mainland and form island habitats, such as Ewe Island and Hindmarsh Island, are found in the areas between the lakes and the lagoon. The lagoon includes the main channel and the shores delineated by the high water mark from the Murray Mouth to the South Lagoon, Goolwa Channel, Mundoo Channel and creeks flowing into the channel. The peninsula zone is the landmass separating the lagoon system and the Southern Ocean. The Murray Mouth divides the peninsula into two with the northern portion from Goolwa to the Murray Mouth being the Sir Richard Peninsula, while to the south the Younghusband Peninsula extends from the Murray Mouth to the end of the South Lagoon.

2.4.2 Habitat category

Habitats in the mainland and peninsula zones belong to two broad categories: terrestrial and wetland. These habitat categories are characterised by completely different ecosystems with different biological components and physical processes. In the Coorong, the prolonged drought of recent years may have rendered many areas unsuitable for classification as wetland compared to wetter times. Although wetland systems may include areas which are dry more often than wet (Aber 2007), connectivity to the lagoon or another water source, and substrate type, were taken into account when deciding whether an area should be categorised as a wetland or not. All areas within the lagoon system were identified as wetland systems. The ephemeral mudflats around the shores, and inland salt pans, were categorized as wetland habitat. Wetlands were further subdivided into wetland types, as described in section 2.4.4 below.

2.4.3 Landform

After identifying the habitat category, the habitats were classified into different landforms through examination of the dominant pattern of the land surface. Altogether 32 landforms were identified during the DEH habitat mapping of the Coorong and Lower Lakes (Seaman 2003). However, the list included ‘lagoon’ and ‘island’ as types of landform, which we have already used for defining habitat zones. To avoid repetition of the term, channel was redefined to designate the main body of the lagoon under water. Similarly, mudflat was not used as a category of landform rather we used this term to describe one of the wetland habitat types. A brief description of the landforms reported in the Coorong by Seaman (2003) is given in Appendix 2.1. In addition to these landforms, coastal swale and dune have been introduced to designate the undulating area adjacent to the shores and open dune without vegetative cover, respectively.

2.4.4 Wetland system

The wetland habitats were further classified into five major wetland systems based on the Cowardin system (Cowardin *et al.* 1979) as adopted by Seaman (2003) for the DEH habitat mapping. These wetland systems are: Marine, Estuarine, Riverine, Lacustrine and Palustrine (Aber 2007) (Table 2.1).

Table 2.1. Wetland system classification based on the Cowardin system (from Aber 2007).

Wetland System	Descriptions
Marine	Open ocean, continental shelf, including beaches, rocky shores, lagoons, and shallow coral reefs. Normal marine salinity to hypersaline water chemistry; minimal influence from rivers or estuaries. Where wave energy is low, mangroves, mudflats or sabkhas may be present.
Estuarine	Deepwater tidal habitats with a range of fresh-brackish-marine water chemistry and daily tidal cycles. Salt and brackish marshes, intertidal mudflats, mangrove swamps, bays, sounds, and coastal rivers. Drowned coasts, where supply of river sediment is insufficient to infill estuary basin.
Riverine	Freshwater, perennial streams comprised of the deepwater habitat contained within a channel. This restrictive system excludes floodplains adjacent to the channel as well as habitats with more than 0.5 g L^{-1} salinity.
Lacustrine	This system includes inland water bodies that are situated in topographic depressions, lack emergent trees and shrubs, have less than 30% vegetation cover, and occupy at least 8 ha. Includes lakes, larger ponds, sloughs, lochs, bayous, etc.
Palustrine	All non-tidal wetlands that are substantially covered with emergent vegetation - trees, shrubs, moss, etc. Most bogs, swamps, floodplains and marshes fall in this system, which also includes small bodies of open water (< 8 ha), as well as playas, mudflats and salt pans that may be devoid of vegetation much of the time. Water chemistry is normally fresh but may range to brackish and saline in semiarid and arid climates.

2.4.5 Water regime

In the wetland habitats, the water regime plays a key role in determining the biological communities present, and also influences physical and chemical processes. The DEH habitat mapping for the Coorong and Lower Lakes included water regime and tidal class as separate wetland habitat attributes adopted from Blackman *et al.* (1992) (Seaman 2003). The water regime characterises the frequency of flooding, and the tidal classes indicate the frequency and influence of oceanic tides upon the habitats (Blackman *et al.* 1992). The wetlands in the lagoons are not subjected to tidal influences except for the areas around the Murray Mouth, whereas the wetlands in the mainland and island zones are non-tidal and are subjected to flooding events. Hence, both water regime and tidal class were attributed under water regime in the habitat classification scheme used here. The frequencies of flooding events were recorded as semi-permanent, intermittent and seasonal. Within those areas subjected to tidal influences, subtidal signifies the wetland is under water all the time while intertidal signifies wetland areas located between the low and the high water mark.

2.4.6 Wetland type

The Directory of Important Wetlands in Australia (Environment Australia 2001) used 40 different wetland types to classify wetlands in Australia based on the Ramsar Convention under Article 1.1. This wetland classification was accepted by the Australia and New Zealand Environment and Conservation Council (ANZECC) Wetland Network in 1994 and has not been changed since (Environment Australia 2001). Under this scheme, wetlands are first classified into three major categories: marine and coastal, inland, and human made, with 12, 19 and 9 wetland types, respectively. Seaman (2003) added three more wetland types to the marine and coastal wetland category to include coastal dune shrubland, freshwater soak and estuarine stream channel, and one to the inland category for freshwater/brackish mud or sand flats, during mapping of wetlands in the Coorong and Lower Lakes. All these wetland types are listed in Table 2.2. These wetland types are identified by water regime, salinity, substrate type and vegetation type. The Coorong and Lower Lakes encompasses wetlands belonging to all three wetland categories. The wetlands along the lagoon system itself are all classified as marine and coastal wetlands.

Table 2.2. Wetland types for the Coorong and Lower Lakes adopted from Environment Australia (2001) and Seaman (2003).

Inland	Human Made
B1 Permanent rivers and streams + waterfalls	C1 Water storage areas, reservoirs, barrages, impoundment (>8ha)
B2 Seasonal irregular river and streams	C2 Ponds, farm, stock, tanks (<8ha)
B3 Inland deltas (permanent)	C3 Aquaculture
B4 Riverine floodplains	C4 Salt pans
B5 Permanent freshwater lakes (8ha, includes oxbow lakes)	C5 Excavations, gravel pits, borrow pits, mining
B6 Seasonal/intermittent freshwater lakes (>8ha), floodplain lakes	C6 Waste water treatment, settling ponds (Constructed/Artificial Wetlands?)
B7 Permanent saline/brackish lakes	C7 Irrigated land, canals, ditches
B8 Seasonal/intermittent saline lakes	C8 Seasonally flooded arable land, farm land
B9 Permanent freshwater ponds (<8 ha), marshes and swamps on inorganic soils, with emergent veg. Waterlogged for at least most of the growing season. Includes coves and open water enclosed with reeds	C9 Canals
B10 Seasonal/ intermittent freshwater ponds and marshes on inorganic soils includes potholes, seasonally flooded meadows, sedge marshes. Includes reed shorelines.	**Marine and Coastal Zone Wetlands**
B11 Permanent saline/brackish marshes	A1 Marine waters-permanent shallow waters less than six metres deep at low tide, includes sea bays and straits
B12 Seasonal saline marshes	A2 Sub tidal aquatic beds, includes kelp beds, seagrasses, tropical marine meadows
B13 Shrub swamps, shrub dominated freshwater marsh, sedges and Gahnia sedgeland	A3 Coral reefs
B14 Freshwater swamp forest, seasonally flooded forest, wooded swamps	A4 Rocky marine shores, includes rocky offshore islands, sea cliffs. Rocky estuarine shores.
B15 Peatlands, forest, shrub or open bogs	A5 Sand, shingle or pebble beaches, includes sand bars, spits, sandy islets
B16 Alpine	A6 Estuarine waters, permanent waters of estuaries and estuarine systems of deltas
B17 Freshwater springs, rock pools	A7 Intertidal mud, sand or salt flats and algae.
B18 Geothermal wetlands	A8 Intertidal marshes, including saltmarshes, salt meadows, saltings, raised salt marshes, tidal brackish and freshwater marshes and vegetated shorelines.
B19 Inland Karst.	A9 Intertidal forested wetlands, includes mangrove swamps, nipa swamps, tidal freshwater swamp forest
B20 Freshwater/brackish mud or sand flats.	A10 Brackish to saline lagoons and marshes with one or more relatively narrow connections to the sea
	A11 Freshwater lagoons and marshes in the coastal zone. Reedbeds and vegetated bed sediments.
	A12 Non tidal freshwater forested wetlands
	A13 Coastal dune shrubland
	A14 Freshwater soaks <.8ha within the coastal zone
	A15 Estuarine stream channel

2.4.7 Habitat type

The lagoon is comprised exclusively of wetland habitats, while the mainland and peninsula zones contain a mix of terrestrial and wetland habitats. Land cover (vegetation, cover density and land condition) distinguishes different habitat types in the terrestrial system, whereas the substrate and /or submerged vegetation types primarily define the habitat types in the wetland and benthic systems. A list of habitat types used in this habitat mapping is given in Table 2.3. Patchy bare mud has been used to identify a wetland habitat type in the shallower areas adjacent to the main channel which contains sparse Polychaetes and *Ruppia*.

Table 2.3. Habitat types in the Coorong.

Wetland Habitat types	Terrestrial Habitat types
Bare Mud	Dense *Myoporum*
Bare Mud with Polychaetes	Coastal Vegetation
Bare Mud with *Ruppia*	Open Coastal Vegetation
Bare Sand	Patchy Coastal Vegetation
Bare Sand and Grit	Dense Dune Vegetation
Bare Sand Mud	Dune Vegetation
Bare Sand Mud with Algae	Open Dune Vegetation
Bare Sand Mud with *Ruppia*	Patchy Dune Vegetation
Coastal Vegetation	Pasture
Dense *Melaleuca*	Patchy Pasture
Dense Samphire	Wet Grassland
Dense Sedge	Plantation
Dry Grassland	Bare Sand
Melaleuca	Unvegetated Sand Dune
Mud Flat	
Open Coastal Vegetation	
Open Samphire	
Patchy Coastal Vegetation	
Patchy *Melaleuca*	
Patchy Bare Mud	
Patchy Samphire	
Rocky Outcrop	
Samphire	
Very Soft Mud	

2.4.8 Salinity

The salinity of the Coorong is controlled by freshwater flow over the barrages and from Salt Creek, and incursions of sea water from the Murray Mouth, as well as evaporation rates and connectivity between the North and South Lagoons (Webster 2007). Due to extreme drought conditions, freshwater flow over the barrages has not occurred since 2005. As a consequence, the salinity of the entire system has increased substantially. The salinity of the South Lagoon is currently above 120 g/L, while salinity gradually decreases towards the Murray Mouth due to incursion of marine water.

Salinity is considered to be one of the major ecological drivers in the Coorong, and determines the quality of habitats for infauna and fish species. In the habitat classification used here, salinity has been incorporated as a water quality parameter that determines habitat condition in the subtidal and intertidal areas, as it impacts on the distribution of infauna, *Ruppia* and birds.

2.4.9 Vegetation

Dominant floral species occurring within each habitat unit were reported. Plant species present were identified from the habitat mapping database for the Coorong and the Lower Lakes (Seaman 2003) and also from the Coastal Saltmarsh and Mangrove Mapping database (Canty and Hille 2002). Dominant species were recorded for each of the available habitat units. If the habitat units were outside of the coverage area of the existing habitat mapping projects or information on flora or fauna was missing, colour aerial photos from 2003 were interpreted in conjunction with these habitat maps to assign flora to the habitat. For the benthic region of the Lagoon, information from an underwater video survey was used (section 2.5.1).

2.4.10 Cover percent

Cover percent records the percentage of area covered by the vegetation. It gives a relative indication of the abundance of the flora in a given habitat unit. Seaman (2003) adopted the cover/abundance classes as prescribed by Heard and Chanon (1997) for the Coorong and Lower Lakes DEH habitat mapping (Table 2.4). The three lowest cover classes were semi-quantitative (few, sparse and plentiful), and so we combined these into a single class of < 5% cover for consistency in the database.

Table 2.4. Cover or abundance classes for the Coorong habitat mapping (Modified from Heard and Channon 1997).

Description	Label
Limited cover, <5% area	<5%
Any number of individuals, covering 5-25%	5-25%
Any number of individuals, covering 25-50%	25-50%
Any number of individuals, covering 50-75%	50-75%
Any number of individuals, covering more than 75%	>75%

2.4.11 Habitat condition

The habitat condition summarizes the overall environmental and biological status of the habitat unit. It is subjectively assessed by taking into account the level of human interference, ecological condition, invasive species and habitat connectivity. The following six habitat condition categories were adopted from Seaman (2003) (Table 2.5).

Table 2.5. Habitat condition classes adopted from Seaman (2003).

Habitat Condition	Description
Pristine	Pristine, or nearly so; no obvious signs of disturbance. Indigenous flora dominant and abundant, 100 % ground cover. Structural diversity present if applicable and microhabitats present. Surrounding ecosystems intact with high connectivity. Habitat integrity is high. Reflects pre-European vegetation or natural landscape feature.
Excellent	Vegetation structure intact, disturbance affecting individual species and weeds are non- aggressive species limited to 5 - 20% coverage. Diverse species, stable fauna habitat, structural diversity present, if applicable. Habitat buffered by and linked to remnant vegetation with ecosystem stability. Microhabitats present.
Very Good	Vegetation structure altered, indigenous and exotics together, 20-50% weed invasion, obvious signs of disturbance (eg disturbance to vegetation structure caused by repeated fires, the presence of some more aggressive weeds, dieback and grazing). Core habitat areas exist buffered by remnant vegetation. Obvious signs of use by fauna, areas of structural diversity might exist with some microhabitats.
Good	Vegetation structure significantly altered by very obvious signs of multiple disturbances. Retains basic vegetation structure or ability to regenerate it (eg disturbance to vegetation structure caused by very frequent grazing). Presence of aggressive weeds at high density (50 - 70%). Core habitat areas exist that are buffered by scattered remnants. Species use of habitats is likely to be opportunistic. Structural diversity limited to isolated patches if at all, micro-habitat presence low.
Degraded	Basic vegetation structure severely impacted by disturbance. Scope for regeneration but not to a state approaching good condition without intensive management (eg disturbance to vegetation structure caused by cropping, grazing or clearance; the presence of very aggressive weeds, partial clearing, dieback and livestock grazing). Weed presence greater than 70%. Habitats are impacted by disturbances and are not connected with remnant buffers.
Completely degraded	The structure of the vegetation is no longer intact and the area is completely or almost completely without native species. Habitats do not exist, although areas might be used as opportunistic habitats or 'stepping stones' to desirable habitat areas. Weed presence aggressive and greater than 80%, monoculture can exist such as pasture.

Salinity level was considered for habitat condition in the intertidal and subtidal areas. The following four habitat condition classes were used based on the cumulative effect of the salinity level on macrophytes, infauna, fish and birds: very good (30-50 g/L), good (50-60 g/L), degraded (60-80 g/L) and completely degraded (>80 g/L) (CLLAMM 2008). It should be recognized that the habitat conditions at most reference sites would have been adversely and in some cases drastically affected by recent years of drought and low water levels in the Coorong.

Bare sand in the intertidal area, sand bars or in closed depressions, and coastal or dune vegetation with more than 50% cover were considered in good condition. However, inland bare sand, open dune or coastal and open samphires were considered in degraded condition. Exposed sand and patchy vegetation with degraded land were categorised as being in a completely degraded condition.

2.4.12 Area

The area of each habitat unit was calculated in ArcGIS 9.3 (Environmental Systems Research Institute 2008) and included in the habitat mapping database.

2.5. Methods

Apart from drawing on and improving information derived from existing habitat maps for the Coorong and Lower Lakes (Seaman 2003; Department for Environment and Heritage 2008), the current habitat mapping program incorporated a range of other data sources. These included remotely sensed imagery such as satellite data and high resolution aerial photography, and field data collected as part of the CLLAMM project. Aerial photographs have been widely used for delineating both terrestrial and benthic habitats and are usually complimented by ground verification (Barrett *et al.* 2001; Finkbeiner *et al.* 2001; Jordan *et al.* 2001). The current habitat mapping was based on aerial photography taken in 2003, the most recent high resolution imagery available for the region. The characterisation of each habitat unit and detailed information on all of the attributes was obtained from a combination of data sources including video survey, previous maps, expert knowledge of the area and field observation. In addition to a detailed habitat mapping of the key sites, a general habitat mapping of the entire region was undertaken using LANDSAT5 Thematic Mapper imagery. The datasets and techniques used are described in the following sections.

2.5.1 Available datasets

Habitat mapping for the Coorong and Lower Lakes from DEH

Habitat mapping of the Coorong and Lower Lakes (Figure 2.2.) was undertaken by DEH in 2002-2003 in two stages (Seaman 2003). The habitats around the Lower Lakes and creeks were classified in the first stage, which identified 518 habitat units covering a total area of 24,400 hectares. The second stage included areas in the Coorong National Park from the Murray Mouth to the southern Coorong National Park near Kingston. One hundred and ninety five distinct habitat units were identified covering 25,980 hectares in the second stage.

For the current study, we obtained the habitat map in the form of a shape file (ArcGIS file format for vector data). The spatial coverage of the habitat map was determined by collating and analysing existing spatial datasets at the 1:50,000 scale, and interpretation of aerial photos at the 1:40,000 scale (Seaman 2003). We observed a pronounced discrepancy between the DEH habitat maps and high resolution aerial photos (0.5 m) from 2003 (Figure 2.3). These differences are probably due to a range of factors including inconsistencies between data sources used to generate the DEH maps, changes in habitat distribution since the original data was collected, and data collection at different resolutions to that provided by the aerial photography. Nonetheless, as described above, the DEH habitat map provided a wide range of useful habitat information, which was extracted and augmented using other data sources.

Figure 2.2. Area covered by the Coorong and Lower Lakes habitat mapping project undertaken by DEH.

Figure 2.3. Example of DEH habitat map from Ewe Island on the peninsula side (red line) and the 2003 aerial photography, showing discrepancies between the two.

Coastal Salt-marsh and Mangrove mapping

Mapping of coastal salt-marsh and mangrove was carried out to identify the distribution, vegetation composition and ecological status of these habitat types within South Australia (Department for Environment and Heritage 2008; Seaman 2003). A GIS layer containing the coastal salt marsh and mangrove map covering the areas between the Murray Mouth and about five kilometres to the south of Salt Creek was obtained from DEH (Figure 2.4). This layer had 1,860 mapped units, each described by 23 attributes, including landform, estuarine and tidal class, vegetation (cover), integrity, description, area and length. However, 69 of these mapping units were outside the geographic scope of the project. This map also had very poor matching to the aerial photos taken in 2003 (Figure 2.5), which is probably the result of using a very high resolution for the photo or map interpretation, poor orthorectification of the aerial photography used for the original mapping, and changes in the distribution of some habitats. Nevertheless, the information on vegetation type was highly useful for the current habitat mapping of the Coorong region.

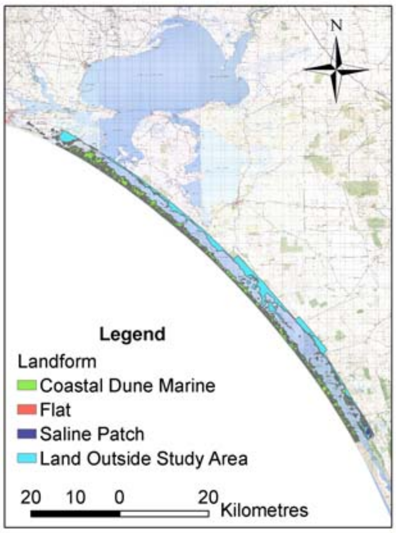

Figure 2.4. Area covered by the coastal salt-marsh and mangrove mapping project in the Coorong region.

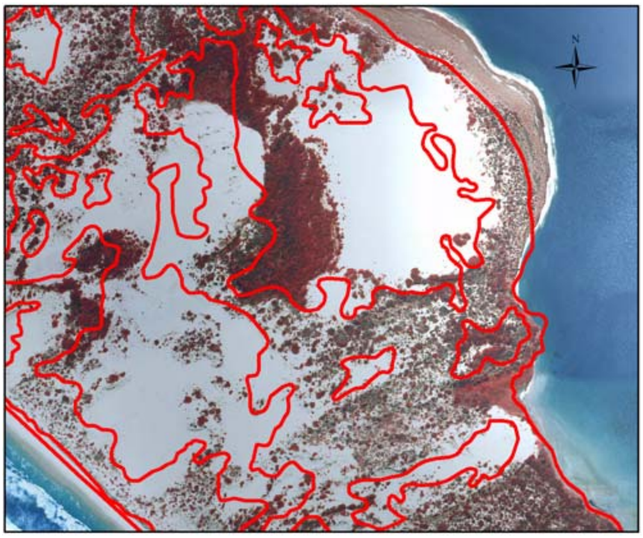

Figure 2.5. Example of the coastal salt-marsh and mangrove Map from Noonameena (red line) and the 2003 aerial photography, showing discrepancies between the two.

Aerial photographs

Orthorectified aerial photographs are an important tool for habitat mapping (Kendall *et al.* 2001). The most recent colour aerial photographs of the Coorong and region were taken in 2003. DEH supplied geo-referenced and orthorectified aerial photos of the Coorong and parts of the Lower Lakes to this project in the Enhanced Compressed Wavelet (ECW) 3-band RGB format (Figure 2.6). These aerial photos were used as the major tool for the current habitat mapping for the Coorong and formed the spatial reference base for the project. The resolution of the aerial photography is 0.5 m by 0.5 m, and ground features including terrestrial vegetation are easily identifiable in these photos. Extensive mapping of reference points along the length of the Coorong during fieldwork using differential GPS to an accuracy of <40 cm confirmed the high quality of spatial representation within this dataset.

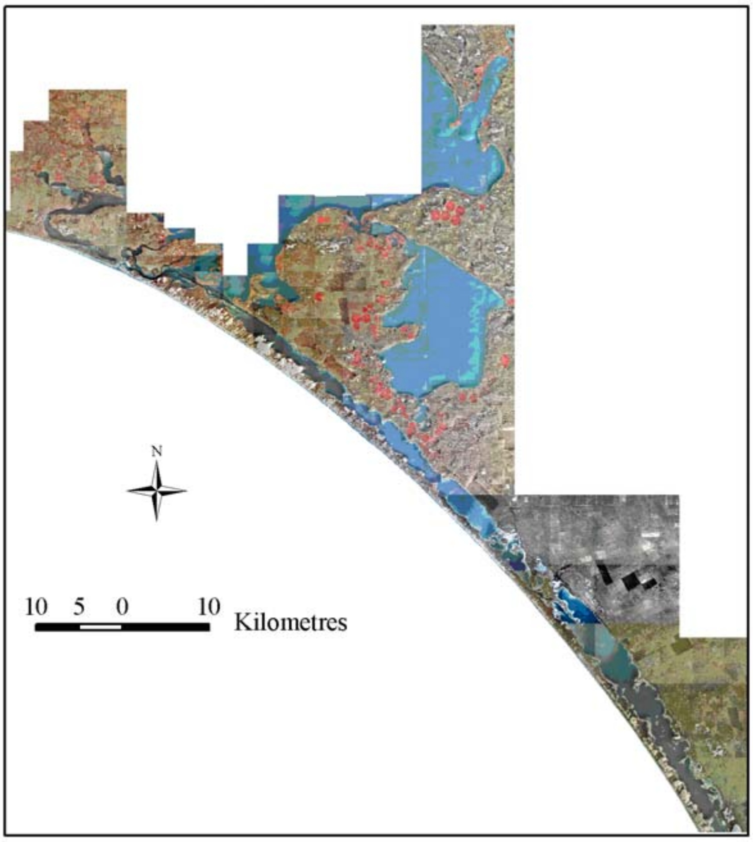

Figure 2.6. Aerial photographs for the Coorong region taken in 2003.

Satellite imagery

LANDSAT 5 Thematic Mapper (TM) imagery (mosaic) covering the CLLAMM region was purchased from MapLand, DEH. The LANDSAT5 mosaic was supplied by DEH resampled to 25 m, orthorectified and histogram matched. The imagery was collected by NASA's LANDSAT5 mission equipped with the Thematic Mapper (TM) multispectral sensor in 2004. The electromagnetic energy reflected from the earth's surface is captured by the sensors in seven different bands (1-7) at a resolution of 30 m. Each of these bands captures reflectance in a different range of wavelengths in the electromagnetic spectrum, with different land cover types having different reflectance signatures across the seven bands. For visualisation, a combination of bands is displayed in red, green and blue colour for differentiating different land covers, such as vegetation, rock and water. A false colour composite image of the LANDSAT5 imagery is shown in Figure 2.7. The digital information contained within the various bands of the multi-spectral imagery can be converted into land cover information and maps through application of a range of well accepted digital image classification techniques, as described in section 2.5.3 below.

Figure 2.7. LANDSAT5 imagery (bands 2, 3 and 4) for the Coorong, Lower Lakes and Murray Mouth.

Sediment sampling and underwater video survey

Sediment core samples were collected along three cross-lagoon transects from the subtidal areas at each of the 12 reference sites used for the study. These samples were analysed for sediment size fractions and organic matter content in the laboratory. The physical composition of cores from each site in terms of general sediment type and accompanying floral or faunal communities (if any) were noted to aid in identifying habitat types.

Underwater video surveys were undertaken to complement the habitat type information collected from the core samples. The video survey equipment comprised a Morph Cam underwater video camera that was mounted on a small towable platform that kept it at a 30^0 angle to the bottom. A boat was used to tow the equipment and travelled along the same transects used for the core sampling, with footage collected from all areas > ~0.4-0.5 m depth. While the video survey was undertaken, the footage of the bottom surface was observed live on the screen and any changes in the lagoon bed were recorded manually. The digital footage was subjected to further analysis in the laboratory, which involved scoring of successive image frames to record the presence or absence of underwater vegetation and other notable characteristics. A GPS mounted on the boat was used to record the geographic location for observed habitat transitions. An example of the video survey footage from the North Lagoon is shown in Figure 2.8. The South Lagoon was too shallow to use the boat and hence video surveys were not carried out beyond Noonameena.

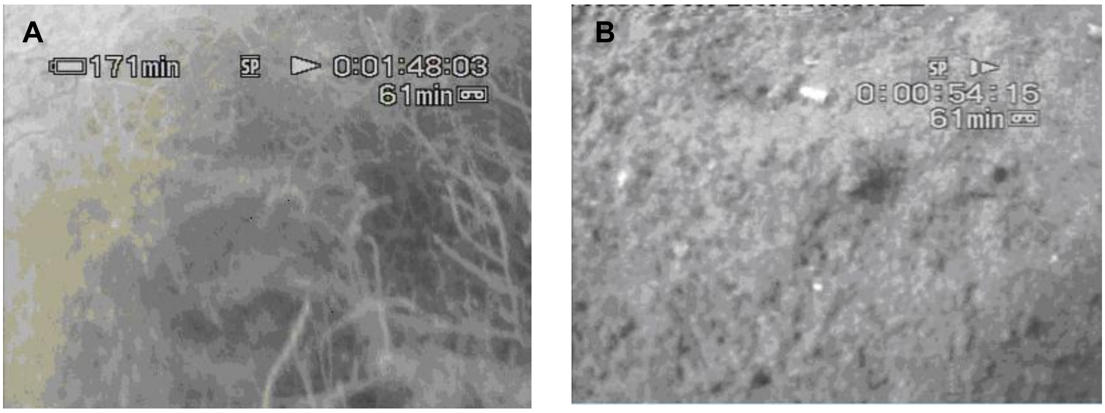

Figure 2.8. Video footage from Mark Point (A) and Goolwa Channel (B) taken during the underwater video survey.

Other data

Salinity data was acquired during fish sampling conducted at 10 locations between Goolwa and Salt Creek in June 2008. The data were interpolated in ArcGIS using Inverse Distance Weighting (IDW) (Environmental Systems Research Institute 2008) to obtain salinity at the 12 representative sites. While, seasonal variations in salinity were evident between summer and winter along the lagoon, they were not sufficiently large to change our conclusions. In the North Lagoon slightly lower salinity (< 10 g/L) was recorded in the winter whereas salinity difference could be as high as 30 g/L in the South Lagoon between summer and winter.

2.5.2 Habitat digitization and interpretation

Habitat maps of the Coorong and surrounds were created by digitizing distinctive units from the geo-referenced aerial photographs taken in 2003. Each of the habitat units was visually interpreted based on standard aerial photo interpretation techniques employing colour, appearance, texture, shape, etc. The minimum mapping unit was not set beforehand and instead we sought to map all habitat types identified within the reference sites. The digitization was performed at a scale of 1:1,000 to 1:1,500 in order to expedite the process without compromising the accuracy of the maps. A finer scale of interpretation may enhance the map accuracy at the expense of greater time for digitization (Kendall *et al.* 2001). Firstly, a distinctive area with identical appearance in the photographs was digitized on screen using ArcGIS Editor (Environmental Systems Research Institute 2008). Secondly, the attributes as per the habitat classification scheme were assigned for each habitat unit. The substrate data for the sub-tidal habitat in the benthic system were based on the video survey data and their visual interpretation. The coastal salt-marsh and mangrove map and DEH habitat map were used to derive information on vegetation and cover/abundance. For those habitat units that matched the DEH habitat maps, the habitat attributes were also collated from that dataset. A special case related to the distributions of polychaete worm mounds in the sub-tidal areas, which were interpreted through local knowledge of the areas.

2.5.3 Imagery classification

For selecting appropriate bands for classification of LANDSAT5 imagery, correlations among the bands were analysed (Table 2.6). The thermal infrared band (band 6) is not considered in this analysis as it is mostly used to determine surface temperatures, and is not generally used for terrestrial vegetation classification (Sader *et al.* 2001; Trisurat *et al.* 2000). High correlations can reduce the effectiveness of the image classification process (Lillesand and Kiefer 2000). The correlation matrix showed that band 1 was highly correlated to bands 2 and 3, and moderately correlated to bands 4, 5 and 7. Band 4 was relatively poorly correlated to bands 1 and 2 and moderately correlated to bands 5 and 7, whereas bands 5 and 7 were relatively highly correlated. Bands 1, 4 and 7 were thus chosen for unsupervised classification based on the criterion of minimum band correlation.

Table 2.6. Correlations between the individual bands of LANDSAT imagery (excluding thermal band 6).

Layer	1	2	3	4	5	7
1	1					
2	0.94	1				
3	0.91	0.90	1			
4	0.55	0.48	0.70	1		
5	0.48	0.41	0.71	0.81	1	
7	0.51	0.45	0.73	0.76	0.98	1

2.5.4 Map validation and accuracy testing

The habitat maps for the 12 reference sites produced by digitizing aerial photos were printed out and taken to the sites for field verification. Those habitats that were not interpreted accurately from the aerial photos were visited, identified and revised in the habitat map database.

To assess the accuracy of the broader scale classified maps, 159 points, mostly on the eastern shores of the Coorong and covering all subtidal, intertidal and terrestrial habitat classes, were randomly selected and classified based on interpretation of the aerial photos. The interpreted classes were validated during field observation and assigned to the appropriate habitat classes for accurate assessment of the maps.

2.6. Results

2.6.1 Habitat maps of the reference sites

The habitat maps of the 12 reference sites were analysed for each category of the habitat classification scheme. The following sections summarise the findings from the habitat classification in the Coorong.

Habitat zone

The distribution of habitat zones for all reference sites in the Coorong is provided in Table 2.7. The reference sites were located between the mainland and the peninsula, except for Mundoo Channel (between Hindmarsh and Ewe islands), Barker Knoll (between the peninsula and Hindmarsh/Ewe islands) and Ewe Island (between the peninsula and Ewe Island). All reference sites in the South Lagoon contained small islands. 49.9% of the total area mapped was in the lagoon, 34.7% on the peninsula, 13% on the mainland and less than three percent was on islands.

Table 2.7. Habitat zone distribution in the reference sites.

SN	Reference site	Habitat zone (Area, ha)				
		Island	Lagoon	Mainland	Peninsula	Total
1	Goolwa Channel		129.66	44.74	116.52	290.93
2	Mundoo Channel	10.33	37.94	17.93		66.20
3	Barker Knoll	22.55	97.29	15.69	70.28	205.81
4	Ewe Island	27.28	203.13		223.96	454.37
5	Pelican Point		182.90	27.79	315.43	526.13
6	Mark Point		236.91	24.09	250.60	511.60
7	Long Point		252.97	47.57	170.47	471.01
8	Noonameena		334.73	12.74	151.32	498.78
9	Parnka Point		64.95	450.65	110.37	625.97
10	Villa dei Yumpa	50.13	462.57	8.20	175.69	696.59
11	Jack Point	7.51	417.43	45.45	234.65	705.05
12	Salt Creek	17.32	452.42	53.48	179.60	702.81
	Total Area	135.13	2872.91	748.34	1998.88	5755.26
	Area Percent	**2.35**	**49.92**	**13.00**	**34.73**	**100.00**

Habitat category

The reference sites were classified into terrestrial and wetland habitat categories. These habitat categories comprised 34.9 and 65.1%, respectively, of the mapped area (Table 2.8). Approximately three quarters of the wetland category was located within the lagoon system while the remaining quarter was located in the mainland, peninsula and island habitat zones.

Table 2.8. Habitat category distribution in the reference sites.

SN	Reference site	Habitat category (Area, ha)	
		Terrestrial	Wetland
1	Goolwa Channel	109.41	181.52
2	Mundoo Channel	5.02	61.19
3	Barker Knoll	73.46	132.35
4	Ewe Island	212.03	242.34
5	Pelican Point	305.52	220.60
6	Mark Point	265.97	245.63
7	Long Point	192.54	278.47
8	Noonameena	154.28	344.50
9	Parnka Point	71.14	554.83
10	Villa dei Yumpa	183.00	513.60
11	Jack Point	259.29	445.76
12	Salt Creek	176.28	526.53
	Total Area	2007.93	3747.33
	Area Percent	**34.89**	**65.11**

Landform

A total of 18 landforms were identified in the reference sites (Table 2.9). Dune, channel and floodplain were major landforms constituting 43.7, 24.7 and 8.1% of the total area, respectively. The dune landform without vegetation was dominant in the peninsula, whereas channel was the predominant landform of the lagoon system. The floodplains (including ephemeral mudflats) were found adjacent to the eastern shore of the lagoon, primarily in the mainland or island habitat zones.

Table 2.9. Landform distribution in the reference sites.

SN	Landform	Reference sites (Area, ha)												
		Goolwa Channel	Mundoo Channel	Barker Knoll	Ewe Island	Pelican Point	Mark Point	Long Point	Noona-meena	Parnka Point	Villa dei Yumpa	Jack Point	Salt Creek	Total
1	Beach	14.92	2.70	14.85			15.97	4.04	32.01	49.93	66.27		8.63	209.33
2	Channel	126.33	31.58	87.65	187.50	127.56	210.47	220.72	302.72	36.38	420.49	322.40	440.33	2514.12
3	Closed Depression				1.42			4.73			4.81			10.96
4	Coastal Swale	1.57	1.10	0.07	1.42	11.02	8.20	4.24	2.21	11.51	7.46		13.24	62.04
5	Consolidated Dune			7.71	173.20	32.62	6.55	20.36	14.35		47.86	87.41	28.85	418.89
6	Cove			0.60										0.60
7	Dune	94.07		56.73	38.83	271.80	235.85	145.87	130.84	71.14	87.26	141.72	147.43	1421.55
8	Flat	14.44		0.56		1.11		25.78	7.93		47.83	29.88		127.53
9	Floodplain	37.32	26.28	37.58	36.06	26.68	23.64	16.58	4.74	163.24	4.12	28.33	59.05	463.63
10	Rocky Outcrop				15.63		10.47					26.57	3.46	56.13
11	Rocky Shore							28.21						28.21
12	Salt Lake									203.87				203.87
13	Sand bar					32.61								32.61
14	Sandy Beach									89.91		68.46		158.37
15	Shoreline		3.67			22.73	0.25	0.48	2.83					29.96
16	Stream Channel	1.37	0.88	0.06	0.30								1.83	4.43
17	Undulating Plain								1.15		8.15			9.30
18	Vegetated Island										2.30			2.30

Wetland system

The areas in the wetland category were further classified into five major wetland systems using the classification scheme of Seaman (2003) for wetland mapping of the Coorong and Lower Lakes region. The distribution of these wetland systems within the reference sites is given in Table 2.10. Estuarine wetland was the dominant wetland system, comprising more than 80% of the total wetland area. Palustrine wetlands constituted about one sixth of the area and were commonly located adjoining the main channel. Less than two percent of the area along the coast was classified as marine wetland. The areas classified as lacustrine and riverine wetlands were negligible.

Table 2.10. Distribution of wetland system in the reference sites.

SN	Reference site	Wetland system (Area, Hectare)				
		Marine	Estuarine	Palustrine	Riverine	Lacustrine
1	Goolwa Channel	11.59	140.85	28.60		0.48
2	Mundoo Channel		38.66	21.69		0.84
3	Barker Knoll	3.41	99.15	29.79		
4	Ewe Island		205.68	36.66		
5	Pelican Point		194.94	24.32	1.35	
6	Mark Point		245.63			
7	Long Point		268.93	9.54		
8	Noonameena		337.56	6.95		
9	Parnka Point	21.36	155.57	377.90		
10	Villa dei Yumpa	24.18	477.14	12.27		
11	Jack Point		433.68	12.08		
12	Salt Creek		473.06	51.65		1.83
	Total Area	60.55	3070.84	611.45	1.35	3.14
	Area Percent	**1.62**	**81.95**	**16.32**	**0.04**	**0.08**

Water regime

The wetlands in the reference sites were classified into five water regime categories based on the water condition and the frequency of inundation. The distribution of these water regime categories is given in Table 2.11. The lagoon system consisted of the subtidal and intertidal water regimes, comprising about 67.2 and 9.7% of the wetlands in the reference sites respectively. Some areas switched between these categories, depending on the water level in the Coorong. About a quarter of the wetland areas were seasonally inundated. The ocean coastlines were the classic example of intertidal areas and were classified as tidal regions under water regime.

Table 2.11. Distribution of water regimes in the Reference Sites.

SN	Reference site	Water regime (Area, Hectare)				
		Subtidal	Intertidal	Tidal	Semi - Permanent	Seasonal
1	Goolwa Channel	126.33	3.33	11.59		40.26
2	Mundoo Channel	32.42	6.60			22.17
3	Barker Knoll	87.65	11.44	3.41		29.84
4	Ewe Island	180.22	23.74		1.63	36.76
5	Pelican Point	127.56	57.71			35.33
6	Mark Point	220.94	15.97			8.72
7	Long Point	220.72	32.25			25.50
8	Noonameena	302.72	32.97			8.82
9	Parnka Point	36.38	28.58	21.36		468.52
10	Villa dei Yumpa	420.49	42.09	24.18		26.84
11	Jack Point	322.40	95.03			28.33
12	Salt Creek	440.33	12.09		1.83	72.29
	Total Area	2518.15	361.79	60.55	3.45	803.39
	Area Percent	**67.20**	**9.65**	**1.62**	**0.09**	**21.44**

Wetland type

Of 44 wetland types mentioned in Seaman (2003), 17 were observed in the 12 reference sites. Although Seaman (2003) defined coastal dune shrubland as a new marine and coastal wetland type, we classified it as terrestrial. The distribution of all 17 wetland types in these reference sites is presented in Table 2.12. Subtidal aquatic bed (A2) was the dominant wetland type occupying about two-thirds of the wetland in the study area. The second most commonly observed wetland type was seasonal saline marshes (B12) followed by intertidal mud, sand or salt flats (A7). These two wetland types covered more than 10 and 7 percent of the total wetland, respectively (Figure 2.9).

Table 2.12. Distribution of wetland types in the reference sites.

Wetland type	Reference site (Area, Hectare)											
	Goolwa Channel	**Mundoo Channel**	**Barker Knoll**	**Ewe Island**	**Pelican Point**	**Mark Point**	**Long Point**	**Noona-meena**	**Parnka Point**	**Villa dei Yumpa**	**Jack Point**	**Salt Creek**
A2	126.33	31.58	87.65	180.22	127.56	210.47	220.72	302.72	36.38	420.49	322.40	440.33
A4				15.63		10.47					26.57	3.46
A5	3.33		1.81		32.61	0.16	0.63		89.91	42.09		
A7	11.59	7.03	13.05	7.28	22.73	15.81	32.25	32.01	49.93	24.18	68.46	8.63
A8	11.18		1.72	11.71	12.03	8.72	7.33	8.00		2.30	16.25	3.32
A9		9.53	0.07									
A15		0.88	0.66	0.29								
B1												1.83
B2	0.48											
B8									204.57	4.81		
B12	27.71	12.16	27.40	17.41	24.32		17.54	1.78	174.04	19.73		68.80
B13					1.35							
B14											11.79	
B15				8.36								
B20	0.89											
C4				1.43							0.29	0.17

NB: See Table 2.2 for definitions of wetland types.

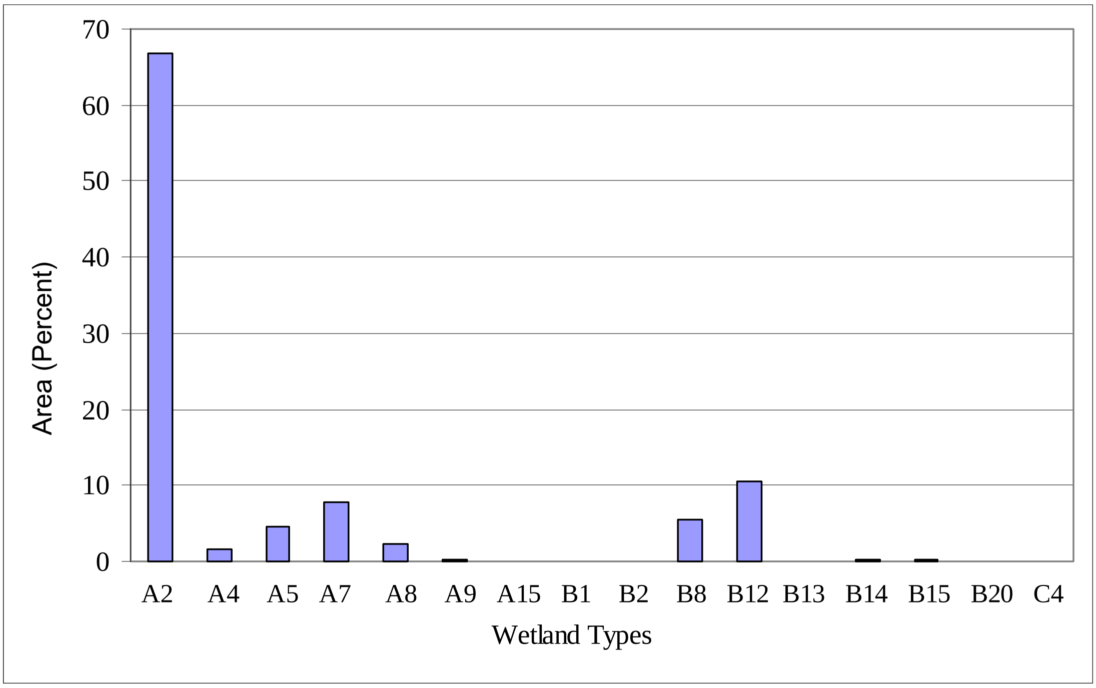

Figure 2.9. Total area covered by the wetland types in the reference sites (See Table 2.2 for definitions of wetland types).

Habitat types

The habitat types in the wetland and terrestrial habitat categories are given in Figures 2.10 and 2.11, respectively. The first eight wetland habitat types (listed in Table 2.3) were found in the subtidal areas within the main channel of the lagoon. Bare mud was predominant in the deep channel throughout the lagoon, whereas the adjacent shallower areas were characterised by the presence of polychaetes, fine filamentous algae and *Ruppia*. Shallow areas between the channel and shores were interspersed with polychaetes (0.1-1.5 m^2) on the bare mud in the North Lagoon. Polychaetes were mainly reported in the bare mud in shallower water at Mark Point.

Bare sand was commonly found in the intertidal areas and also in the salt pan/lake areas. Samphire was found along both shorelines across the lagoon. However, the cover density varied in different locations and was classified into four habitat types: dense samphire (>75% cover), samphire (50-75% cover), patchy samphire (25-50% cover) and open samphire (<25% cover). Coastal vegetation was reported mainly on the floodplain areas on the eastern coast of the lagoon. In the open and patchy coastal vegetation areas, the ground surface was mostly covered by small grasses. Some grasslands without overstorey vegetation were reported from four reference sites. Areas of dense and patchy *Melaleuca* were found in the Mundoo Channel site. Extensive areas of sand dunes were exposed on the peninsula between the lagoon and the Southern Ocean. However, the consolidated dunes were covered by dune vegetation from dense to patchy cover densities in all reference sites except for Mundoo Channel. A few patches of coastal vegetation were observed on the mainland on the eastern coast of the lagoon. Pasture lands were reported from the North Lagoon reference sites. The habitat maps and some photos are given in Appendix 2.2 and 2.3, respectively.

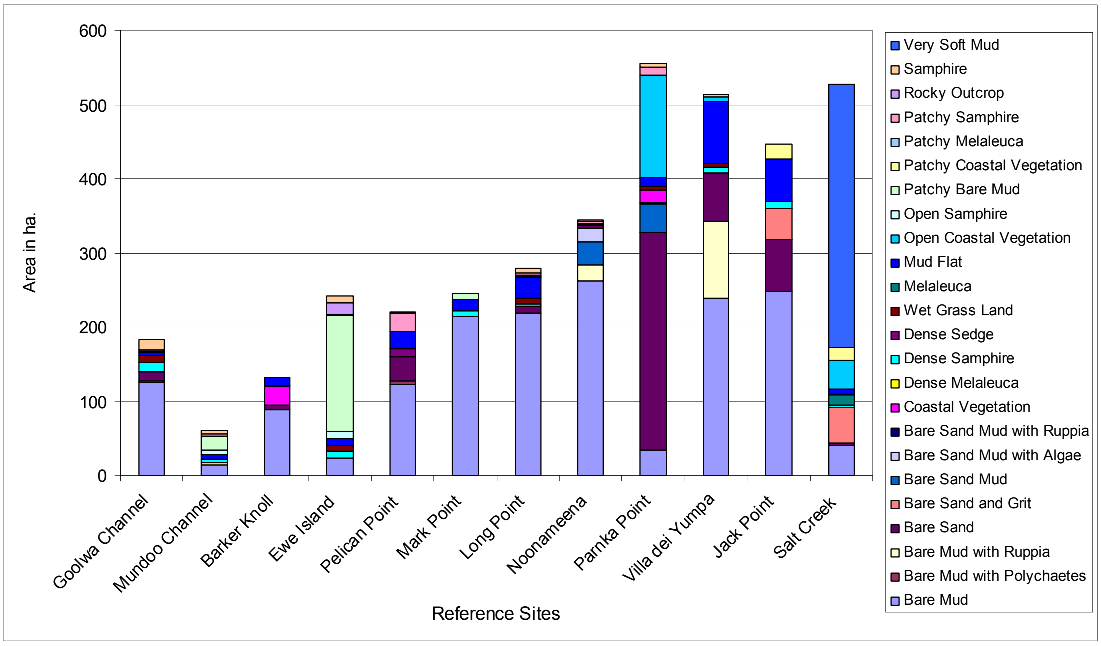

Figure 2.10. Area and habitat types in the wetland category.

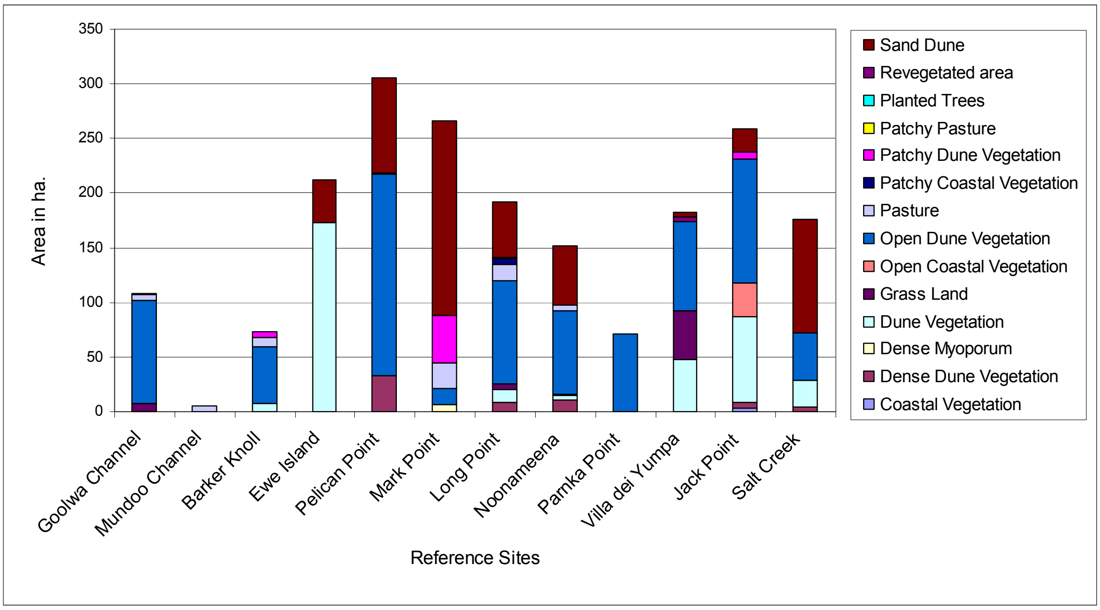

Figure 2.11. Area and habitat types in the terrestrial category.

Salinity

Salinity levels at the reference sites were derived through interpolating the salinity data collected across the lagoon in June 2008 (Table 2.13). Between Goolwa and Ewe Island, the salinity range was 30-40 g/L, increasing to 40-50 g/L between Pelican Point and Mark Point. At Parnka Point, the barrier between the North and South Lagoon, the salinity rose to more than 110 g/L. The salinity range remained constant between Parnka Point and Jack Point at 110-120 g/L. In the area south of Jack Point, the salinity level reached more than 120 g/L. It should be recognised that the water levels in the Coorong are highest in June and salinity levels are considerably higher in summer, particularly in the South Lagoon.

Table 2.13. Salinity level at the reference sites in the Coorong in June 2008.

Reference sites	Salinity (g/L) (Area, Hectare)					
	30-40	40-50	50-60	70-80	110-120	120-130
Goolwa Channel	129.66					
Mundoo Channel	36.13					
Barker Knoll	88.31					
Ewe Island	196.14					
Pelican Point		127.56				
Mark Point		220.94				
Long Point			220.72			
Noonameena				302.72		
Parnka Point					36.38	
Villa dei Yumpa					420.49	
Jack Point						348.97
Salt Creek						443.78
Total Area	450.24	348.50	220.72	302.72	456.86	792.75
Area Percent	17.51	13.55	8.58	11.77	17.76	30.82

Vegetation

Samphire dominated by *Sarcocornia* and *Halosarcia* was commonly observed along shorelines on both sides of the lagoon adjacent to the intertidal sand on the coastal swale and floodplain landforms. In the mainland area, samphire or grasslands were gradually replaced by coastal vegetation composed of *Myoporum*, *Casuarina*, *Acacia*, saltbush and *Melaleuca*. In the peninsula, inland dune areas had dune vegetation associations dominated by *Olearia asillaris*, *Acacia longifolia* and *Leucopogon parviflorus*. A dense patch of mallee association of *Eucalyptus diversifolia* and *Melaleuca* was found at the Salt Creek reference site.

In patchy or open vegetation, the ground cover mainly included introduced grasses (less than 0.5 m tall) such as Paspalum (*Paspalum distichum*), Kikuyu (*Pennisetum clandestinum*) and Couch (*Cynadon dactylon*). However, grasses composed of reed species (*Phragmites australis* and *Typha domingensis*) were also reported at the Goolwa Channel site.

In the subtidal areas, the mud sediments in shallower water were colonized by *Ruppia tuberosa* at Noonameena, Parnka Point and Villa dei Yumpa. As this species typically grows on ephemeral mudflats (Paton 2005) this suggests that these areas are exposed for part of the year. Fine filamentous algae were observed at Noonameena.

Cover

Table 2.14 presents the ground cover percent for the habitat types characterised by vegetation in both wetland and terrestrial habitat categories. The highest area (32.5%) was found under 25-50% cover. Only one percent of the areas had less than 5% cover.

Table 2.14. Cover percentages for Reference Sites in the Coorong.

Reference site	Cover percent (Area, ha)				
	<5%	**<25%**	**25-50%**	**50-75%**	**>75%**
Goolwa Channel	1.84		95.22		49.93
Mundoo Channel	0.26	2.77	6.14	10.44	7.10
Barker Knoll		5.33	52.14	32.37	1.79
Ewe Island		0.74	18.92	182.66	8.36
Pelican Point			185.43	56.93	13.74
Mark Point		43.57	14.33	7.07	31.57
Long Point		11.59	95.48	38.67	17.74
Noonameena		7.44	77.86	5.57	19.07
Parnka Point		208.50		31.02	5.66
Villa dei Yumpa			138.37	49.41	12.02
Jack Point	6.21	7.51	155.21	81.76	14.38
Salt Creek	17.32	43.50		37.49	46.15
Total Area	23.79	330.95	743.88	533.39	177.57
Area Percent	**1.04**	**14.45**	**32.47**	**23.28**	**7.75**

Habitat condition

Although there were six habitat condition categories used by Seaman (2003), the first two categories, pristine and extremely good, were not reported as this region has experienced a high level of anthropogenic interference, invasion of introducedspecies and high salinity levels. Habitat conditions in the 12 reference sites in the Coorong are given in Table 2.15.

Table 2.15. Habitat conditions in the Coorong.

Reference site	Habitat conditions (Area, Hectare)			
	Very good	Good	Degraded	Completely Degraded
Goolwa Channel	131.03	43.91	115.09	
Mundoo Channel	42.07	14.48	6.90	2.77
Barker Knoll	97.94	44.42	61.04	1.84
Ewe Island	204.86	191.02	18.92	39.57
Pelican Point	150.29	103.68	185.03	87.12
Mark Point	243.30	32.25	57.90	177.95
Long Point	28.21	267.73	115.61	59.37
Noonameena	42.25	11.17	445.19	
Parnka Point	12.66	125.35	451.59	36.38
Villa dei Yumpa		107.33	119.28	469.92
Jack Point	5.65	158.96	168.94	371.23
Salt Creek	13.23	29.40	112.29	547.89
Total	971.48	1129.69	1857.79	1794.04
Area Percent	**16.89**	**19.64**	**32.29**	**31.18**

2.6.2 Habitat classification

Maximum likelihood classification of LANDSAT5 TM imagery

Figure 2.12 illustrates the habitat maps generated by applying maximum likelihood classification to LANDSAT5 bands 1, 4 and 7. The blue colour represents areas under water in the Lower Lakes and the subtidal areas in the Coorong, and is mostly characterised by bare mud substrate. Intertidal sand areas were found around the Murray Mouth and mostly on the eastern shore adjacent to the subtidal areas. Sand dunes in the peninsula and the inland sand flats/built areas were classified into separate classes. However, some misclassification between intertidal sand and inland sand flat was unavoidable and these areas could not be reliably distinguished.

Both coastal and dune vegetation were classified as shrublands, whereas the dense vegetation dominated by mallee or *Myoporum* was classified as woodland. Reed grasses around Lake Alexandrina were also accurately represented in the map. Pasture and grassland (small) were also classified into one class because of the spectral signature overlap between them in the iso-cluster classification. Open lands in exposed condition with no vegetation, and also the land not used for agriculture, were categorised into one class in the maps.

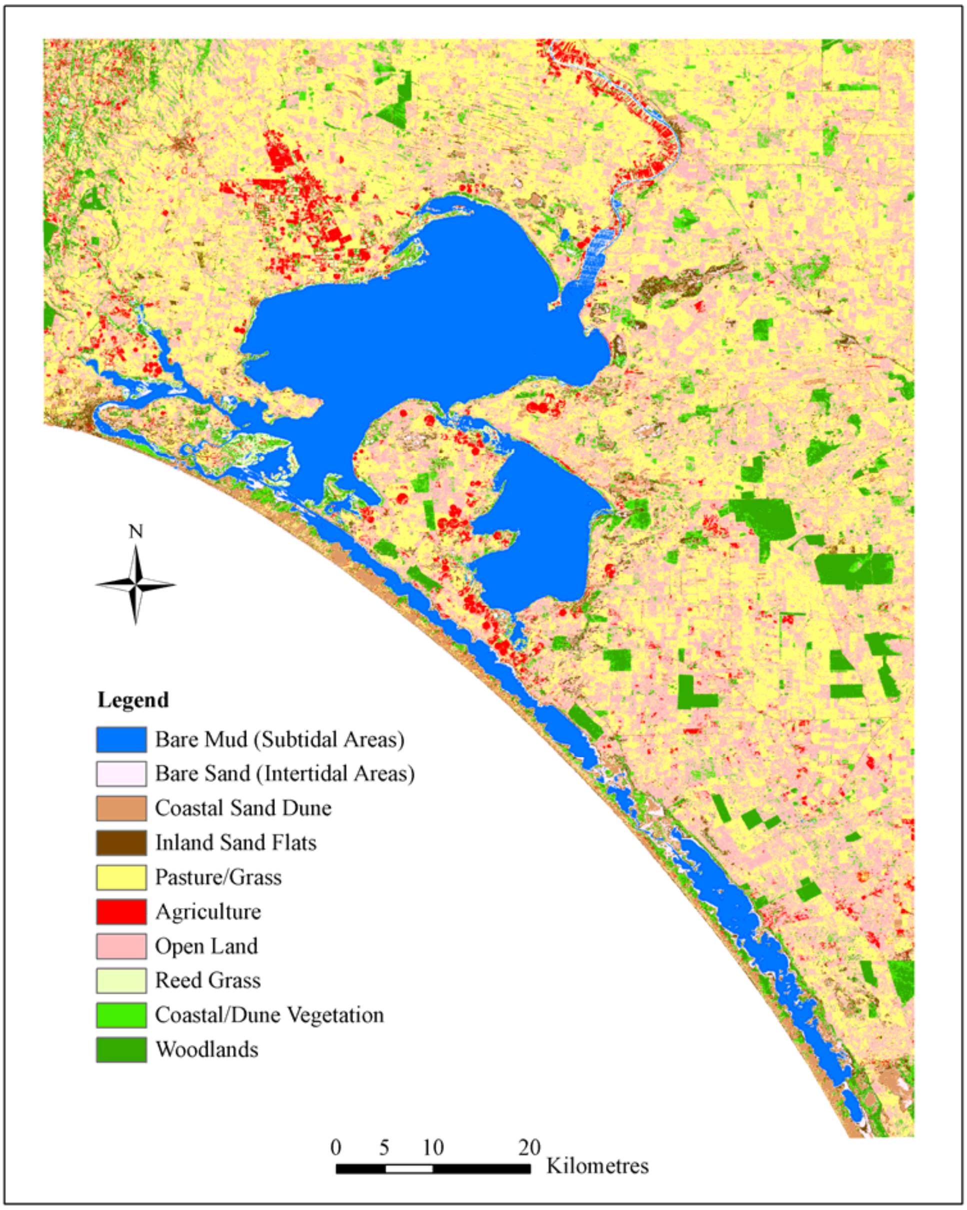

Figure 2.12. Habitat classification using LANDSAT5 bands 1, 4 and 7.

Validation of the classified map

The accuracy of the habitat classifications derived from the raw LANDSAT5 TM bands was assessed using 159 validation points with known landuse/habitat. The accuracies for each class as well as for the overall map are given in Table 2.16. The classification derived from LANDSAT5 bands 1, 4 and 7 correctly classified 83% of the validation points. The lowest accuracy was found for the inland sand flats. In most cases these were classified as intertidal sand or coastal sand dune, which was clearly due to their similar geomorphologic characteristics, leading to similarity in their reflectance.

Table 2.16. Accuracy assessment results for the classification maps.

Habitat Class	Number of validation points	Number of points classified correctly	Percent of accuracy
Bare mud (Subtidal Areas)	17	16	94.12%
Bare Sand (Intertidal areas)	21	17	80.95%
Pasture/Grass Land	19	12	63.16%
Agriculture	7	7	100.00%
Coastal Sand Dunes	25	23	92.00%
Woodlands	22	21	95.45%
Open Land	20	18	90.00%
Reed Grass	2	2	100.00%
Inland Sand Flats	10	3	30.00%
Coastal/Dune Vegetation	16	13	81.25%
Total	159	132	83.01%

2.7. Discussion

The habitat mapping carried out for the current study involved both terrestrial and wetland areas, including benthic habitats, in the 12 reference sites across the Coorong and surrounding area. A specific habitat classification scheme with eight physical, two biological and one chemical (water quality) parameters was used to give a simple and clear delineation of unique habitats in the terrestrial and benthic environment. All 24 attributes used in the DEH habitat maps for the wetlands in the Coorong region could not be used because of the lack of detailed information for each habitat unit, and a simpler classification scheme was therefore more appropriate. However, the habitat maps generated from this study, at both the local (reference site) scale and regional (CLLAMM) scale have been created within a GIS database which allows future updates and also inclusion of additional parameters or further detail on an existing attribute.

Among the wetland habitats, mudflats and samphire are the most significant from an ecological perspective as they offer suitable foraging ground for wader species (Edyvane 1999). These habitats were mostly reported along the eastern (landward) shoreline of the Coorong, and are frequently inundated so offer suitable habitat for macro-invertebrates, hence their value as bird habitat. For many shorebird species, mudflats deeper than 12 cm at any point in time are generally not accessible (Rogers, pers. comm) and cannot be used for foraging. Since there is no or limited tidal influence along much of lagoon, longer term changes in water level and wind action play a major role in inundating these areas. The maintenance of water levels in the lagoon, particularly in the summer, requires inflow over the barrages. Lack of such discharge for the past five years has resulted in increased exposure of extensive mudflat areas, particularly in summer, which in turn are becoming unsuitable for colonisation by macro-invertebrates as they dry out, and this is directly affecting shorebirds through decreased availability of prey (CLLAMM 2008).

The lack of freshwater flow into the lagoon has also resulted in extreme hypersaline conditions in the South Lagoon, creating unfavourable habitats for many organisms. The dramatic rise in salinity has already had a profound impact on the ecosystems of the region by apparently eliminating some important key species like *Ruppia megacarpa* from the system, while others (e.g. *R. tuberosa* and Smallmouth

Hardyhead) are now found only in the North Lagoon whereas they were previously found in the South Lagoon (CLLAMM 2008).

The habitats in the broader Coorong and Lower Lakes region were classified by using a combination of unsupervised isoclassification and supervised maximum likelihood classification using three original bands 1, 4 and 7 of the LANDSAT5 imagery. The Coorong and surrounding region were classified into ten broad habitat categories including agricultural and pastoral land.

The subtidal areas were perfectly differentiated by this classification, as found by Talukdar (2004). However, inland sand flats and intertidal sand flats/bare sand were often misclassified because of similar reflectance from bare sand surface on both areas.

Due to the limitations of LANDSAT5 in capturing reflectance from the underwater surface and also the moderate spatial resolution of 25 m, the terrestrial and wetland habitats were not represented in great detail in these maps. The use of imagery with high spatial and spectral resolution will enhance the ability to identify more variations on the ground, enabling the extraction of habitat maps at finer scales.

2.8. Summary and conclusions

This habitat mapping was accomplished at 12 reference sites, covering the Coorong system from Goolwa Channel to Salt Creek. A great diversity of habitats was reported, with 24 wetland habitats and 14 terrestrial habitats in these sites. Among the wetland habitats, mudflats and samphire are vital for wader species However, the habitats for fish and birds were subjected to extremely high salinity and unprecedented low water levels primarily due to lack of fresh water flows through the barrages, thus reducing their availability and quality.

The habitats in the Coorong are shaped and maintained by the fresh-water flow into the system, which sustains the water level, as well as salinity gradient, supporting the high biodiversity of the region. The relationships between the key bird and fish species and their physical environment in terms of water level and salinity have been explored by the CLLAMMecology Research Cluster. However, the biological interrelationships are not yet sufficiently well known as to allow us to confidently predict how changes in the abundance of one species will affect others. The response of a species to changing habitat conditions together with the quantification of the impacts of the species on other members of biological communities would be very helpful in predicting the future states of ecosystems in the Coorong.

This mapping was done in a GIS platform by compiling all attributes for each habitat type and the resultant GIS database allows to easily share and query information about the habitat in the Coorong. In addition, new fields for habitat attributes could be easily incorporated into the database to make it more comprehensive.

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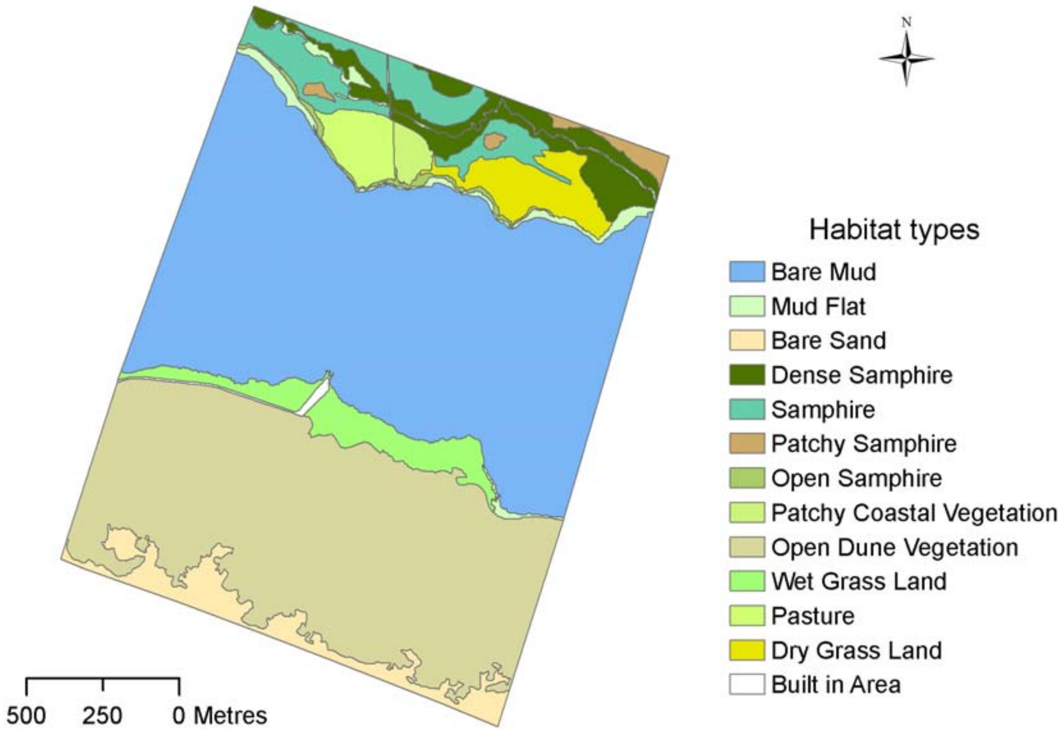
2.10. Appendices

Appendix 2.1: A brief description of landforms reported in the Coorong (From Seaman 2003).

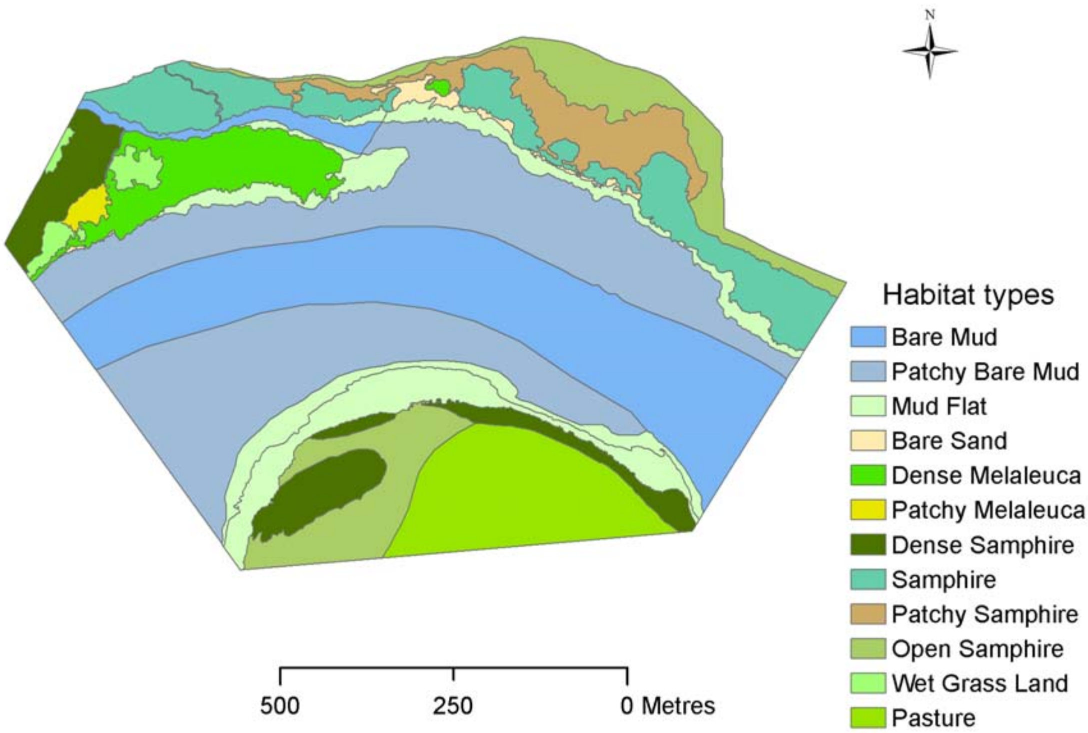
1. Beach: Short, low, very wide slope, gently or moderately inclined, built up or eroded by waves, forming the shore of a lake or sea.
2. *Channel: Main body of the lagoon under water and other subtidal areas.
3. Closed depression: Landform element that stands below all points in the adjacent terrain.
4. Consolidated dune/dune: Moderately inclined to very steep ridge or hillock built up by the wind. This element may comprise dune crest and dune slope. May also be consolidated due to the stabilising effects of vegetation.
5. Cove: Body of water, depth six metres or less bounded by land on three sides. Water is connected permanently by a narrow or wide opening to a larger water body.
6. Flat: A planar landform element that is neither a crest nor a depression and is level or very gently inclined (<3% slope).
7. Floodplain: Alluvial plain characterised by frequent active erosion and aggradations by channelled or over-bank stream flow. Unless otherwise specified, frequently active is to mean that flow has an average recurrence interval of 50 years or less.
8. Rock outcrop: Any exposed area of rock that is inferred to be continuous with underlying bedrock on a large, very gently inclined or level landform.
9. Rocky shore: Shorelines adjacent to a water body having an aerial cover of bedrock, stones and boulders alone or in combination with 75% or more of the surface cover. The vegetative cover is less than 30%.
10. Salt lake: Lake containing a concentration of mineral salts, predominantly sodium chloride in solution as well as magnesium and calcium sulphate.
11. Sand bar: Elongated, gently to moderately inclined low ridge containing coarse grains, built up by water movement.
12. Sandy beach: Short, low, very wide slope, gently or moderately inclined, built up or eroded by waves, forming the shore of a lake or sea. Composed of coarse grains.
13. Shoreline: Extensive, low, very wide slope, gently or moderately inclined, built up or eroded by waves, forming the shore of a lake or sea. Composed of a combination of one or more of the following: coarse grain sands, mud flat, rocky reef and rocky shore.
14. Stream channel: Linear, generally sinuous open depression, in parts eroded, excavated, built up and aggraded by channel stream flow.
15. Undulating plain: Large very gently inclined or level landform of unspecified geomorphological agent or mode of activity.
16. Vegetated island: Sediments built up over time through water movement forming landform with low relief consolidated by stabilising effects of vegetation.

*Landform with modified description during this study.

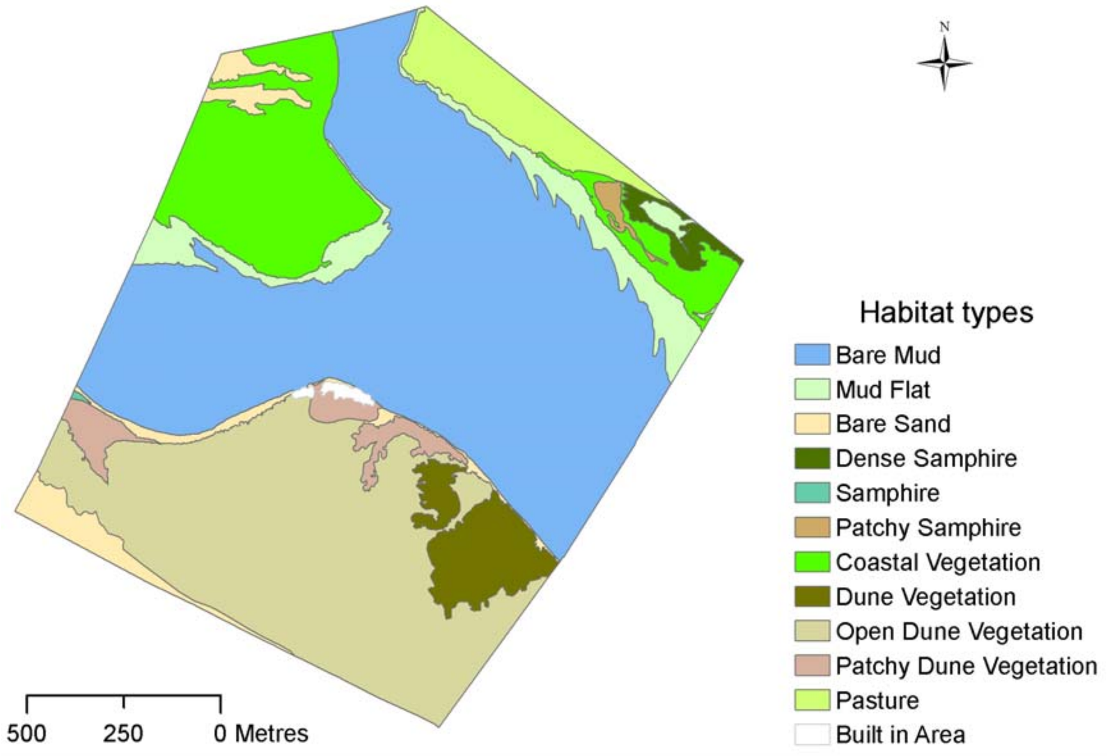
Appendix 2.2: Habitat maps for the reference sites in the Coorong.



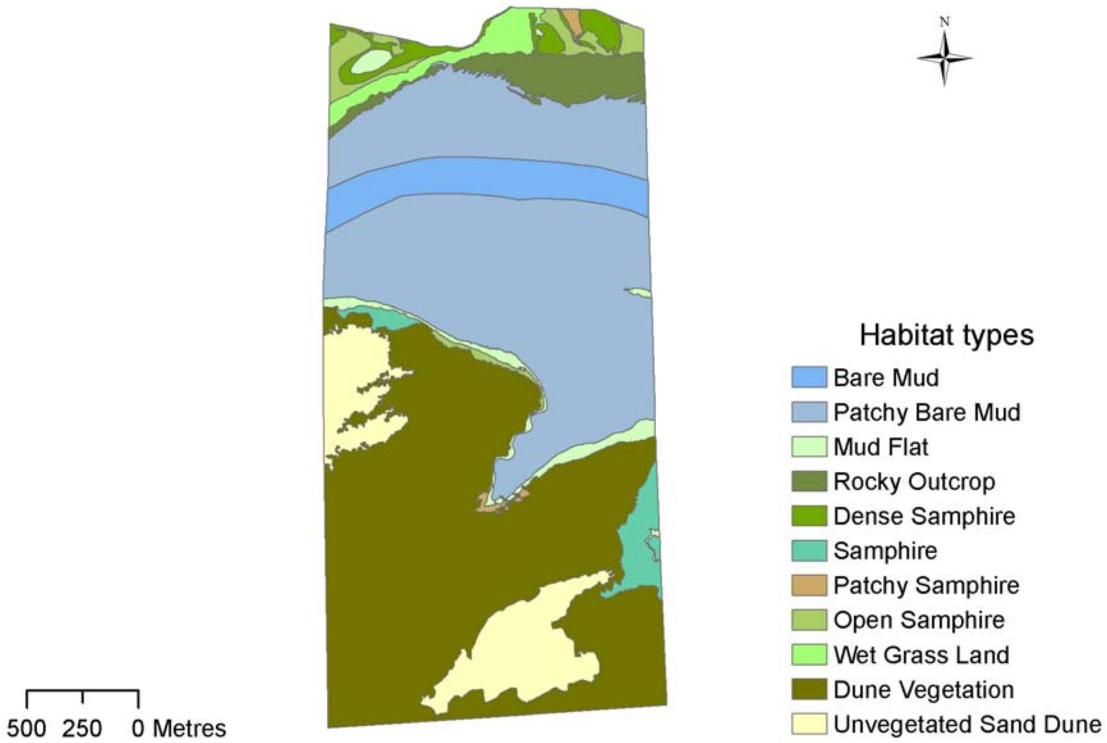
Habitat types at Goolwa Channel



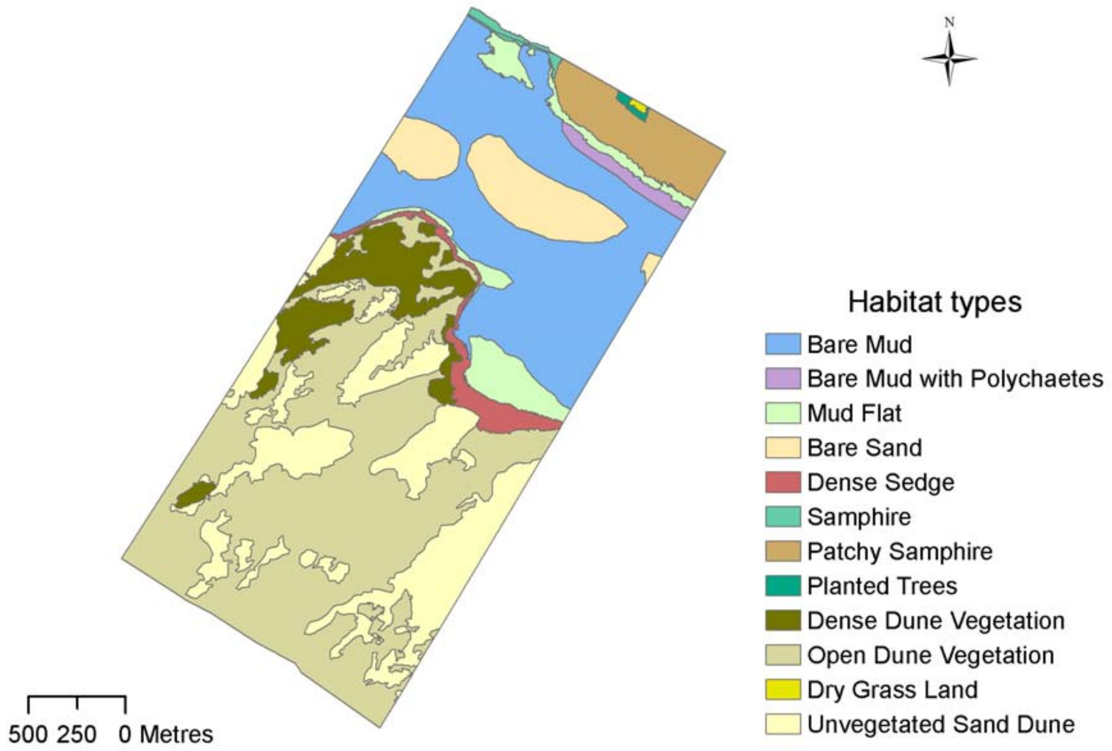
Habitat types at Mundoo Channel



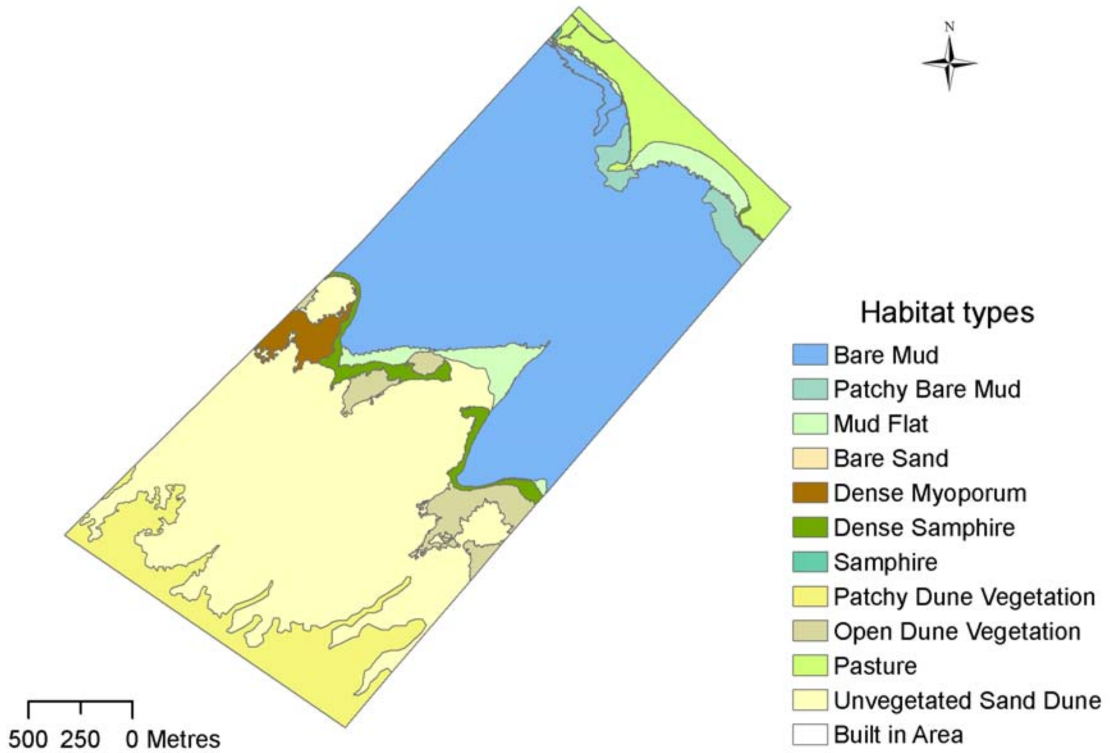
Habitat types at Barker Knoll



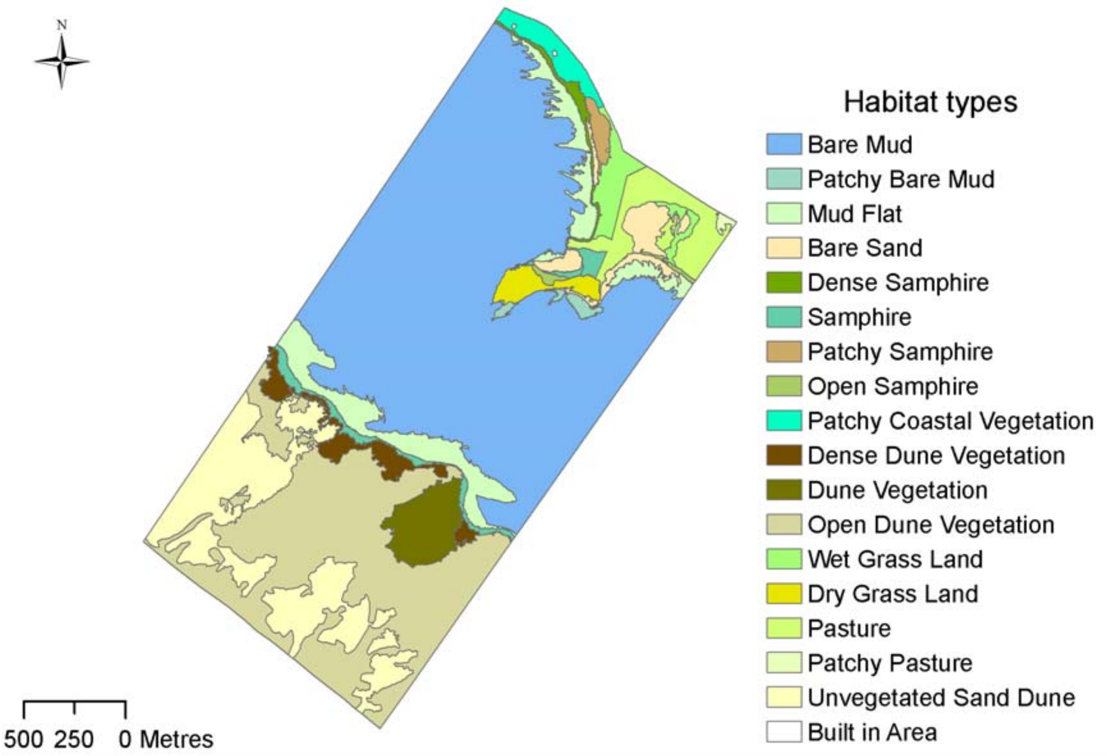
Habitat types at Ewe Island



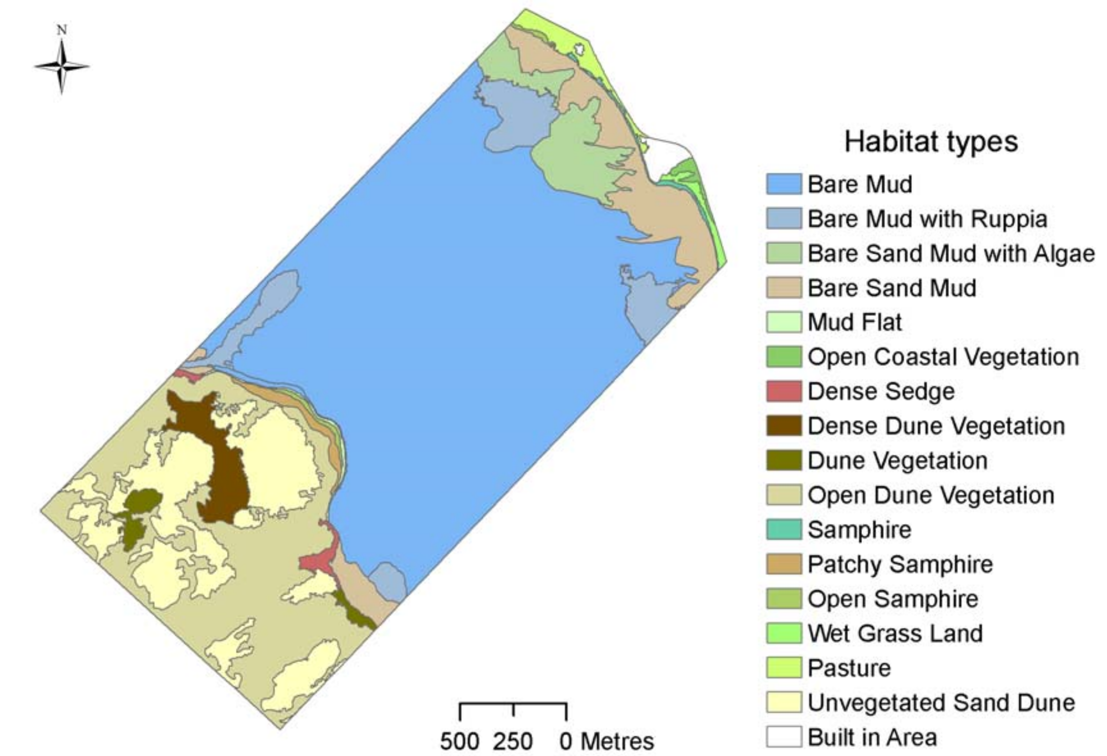
Habitat types at Pelican Point



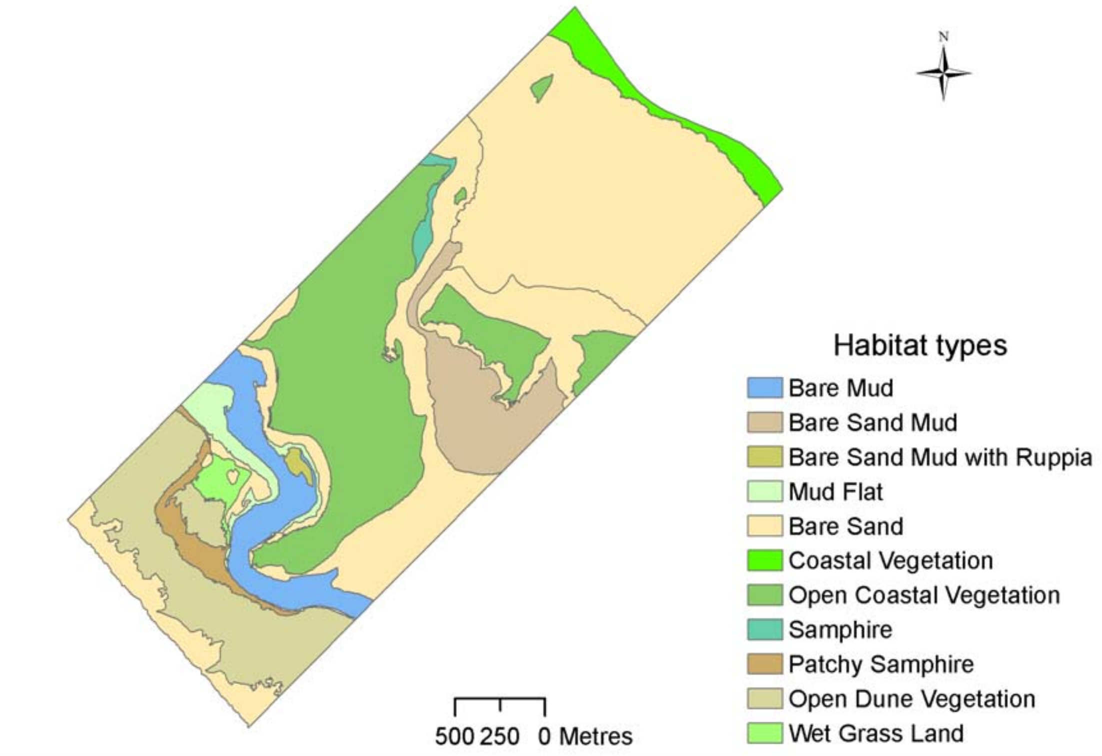
Habitat types at Mark Point



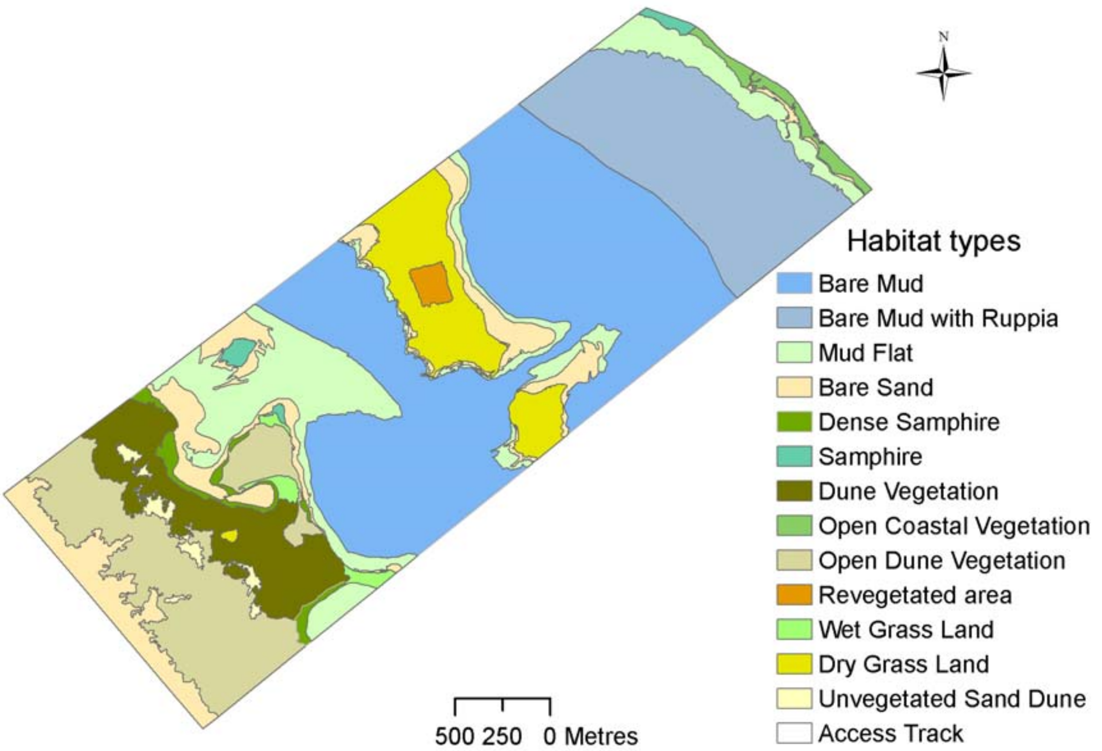
Habitat types at Long Point



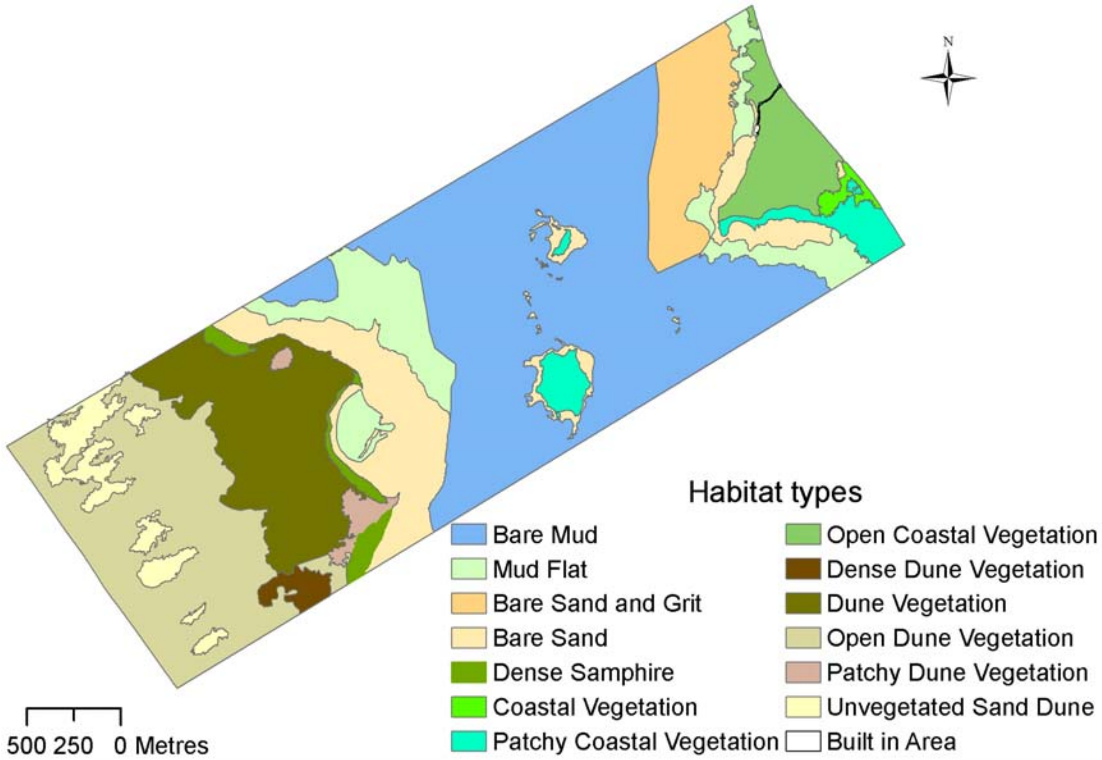
Habitat types at Noonameena



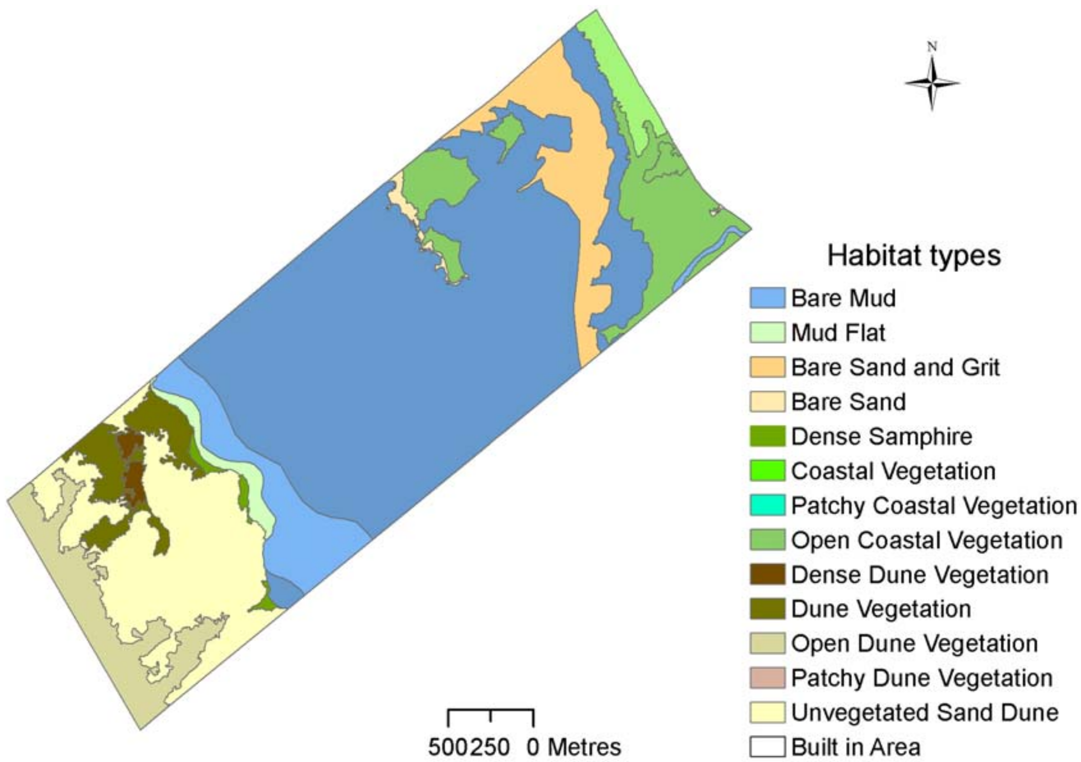
Habitat types at Parnka Point



Habitat types at Villa dei Yumpa



Habitat types at Jack Point



Habitat types at Salt Creek

Appendix 2.3: Some photos of the habitats in the Coorong.

Cleared Land (Salt Creek)

Mudflat (Villa dei Yumpa)

Samphire

Sedge bushes

Coastal Vegetation *Myoporum* and Tea Tree

Rocky Shore (Jack Point)

Coastal vegetation: *Myoporum*, iceplant, sedge, foxtails and salt bush

Open degraded area (Villa dei Yumpa)

Samphire and Rocky Outcrop (Noonemeena)

Rocky surface (Long Point)

Grassland taken up by Samphire

Large coastal vegetation

3. Digital Elevation Model of the Coorong and Surrounds

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3.1. Executive Summary

An accurate and comprehensive Digital Elevation Model (DEM) is considered a primary dataset for developing habitat models of the Coorong and its surrounding areas. A seamless merger of topographic and bathymetric data would provide a dataset which would be helpful for the better understanding of the ecology of the region. The Dynamic Habitat Project under the CLLAMMecology Research Cluster aims to generate a seamless DEM for the Coorong and surrounding areas by collating the existing topographic and bathymetric datasets. However, the bathymetric datasets for the South Lagoon and the areas around the Murray Mouth are not available. Although the Department of Water, Land and Biodiversity Conservation (DWLBC) have recently used airborne LIDAR for collecting topographic data around the South Lagoon, this did not include bathymetry and only became available in late October 2008, and thus could not be used in this project. To achieve the project's aim of a seamless merged bathymetric and topographic dataset, firstly we modelled the bathymetry for the Murray Mouth and the South Lagoon using satellite data, survey data collected during fieldwork, and the existing bathymetric data for the Coorong and; secondly, the derived DEMs from the bathymetric data were integrated with the DEM of South Australia to derive a seamless DEM for the region.

Generalized Additive Modelling, a non-parametric method, was used to model the relationship between depth and reflectance signatures captured in LANDSAT5 and SPOT5 imagery. For modelling bathymetry for the Murray Mouth, all ten bands (seven from LANDSAT5 and three from SPOT5) were used as predictors, whereas only LANDSAT5 (seven bands) was used for the South Lagoon due to the SPOT5 image for this region not overlapping areas with known bathymetry that could be used to develop the model. Model selection was accomplished by applying both forward and backward selection procedures, followed by a comparison of prediction errors for a small subset of candidate models. For the Murray Mouth, a 4 variable model with SPOT5 bands 2 and 3 and LANDSAT5 bands 3 and 5 was selected to predict bathymetry. For the South Lagoon, a 6 variable model was selected with LANDSAT5 bands 1-6. The predicted bathymetry for the Murray Mouth worked well in capturing the trend along the main channel and in the near-shore areas. The South Lagoon model gave good predictions between Parnka Point and Jack Point. However, the depth for the southern quarter of the South Lagoon was underestimated, which could be directly attributed to poor reflectance because of turbid water.

A seamless DEM for the Coorong and surrounds was derived by merging the bathymetry for the North Lagoon and Lakes, and the predicted bathymetry for the

Murray Mouth and the South Lagoon with the DEM for South Australia. However, the bathymetry models for the Murray Mouth and the South Lagoon were not perfect and could be improved in a number of ways. In future, the availability of more comprehensive ground survey data for these regions will provide an opportunity for further improvement in the errors and uncertainty in these models. The seamless DEM for the Coorong and surrounds will be very useful for modelling habitat availability for birds, fish and macro-invertebrates at different water levels in the Coorong and will help in making decisions for sustainable management of the region.

3.2. Introduction

The Coorong, Lower Lakes and Murray Mouth region offers unique coastal habitats for a wide variety of macro-invertebrate, fish and bird species (MDBC 2006; Geddes 2005; Geddes 2004) (Figure 3.1). The availability of mudflat habitats, in particular, is dependent on periodic inundation caused by either fresh water flow through the barrages or incursion of sea water through the Murray Mouth. An accurate and comprehensive Digital Elevation Model (DEM) is considered a primary dataset for developing habitat models of the Coorong and its surrounds (CLLAMM 2007). A high resolution DEM of the Lagoon and the adjoining topography is required to model the changes in habitat availability in terms of spatial distribution and extent at various water levels. Specifically, the DEM will be highly useful for predicting the availability of mudflat habitat for shore birds at different depths as a function of water levels.

The Coorong, Lower Lakes and Murray Mouth (CLLAMM) Research Cluster is taking a holistic approach to exploring implications of major ecological drivers like water and salinity levels at the ecosystem level, through understanding the interrelationships between physical processes and the biological communities (CLLAMM 2007). Understanding of the physical processes is a prerequisite for better ecological management of the region, and requires a seamless merger of topographic and bathymetric data (Gesch and Wilson 2001). One aim of the Dynamic Habitat Project under the CLLAMMecology Research Cluster is to produce a seamless DEM for the Coorong and surrounding areas by collating the existing topographic and bathymetric datasets. The available datasets include the 3 second DEM for South Australia (SA) and interpolated bathymetry for the Lower Lakes and the Northern Lagoon of the Coorong. However, bathymetric datasets for the South Lagoon and the areas around the Murray Mouth are not available. Shallow waters and numerous limestone reefs in the South Lagoon, in particular, have prevented standard bathymetric data collection using a boat with depth sounder. In late 2008, the South Australian Department of Water, Land and Biodiversity Conservation (DWLBC) developed a DEM for the Lower Lakes and the Coorong from airborne (topographic) LIDAR (Light Detection and Ranging) data under the “Imagery Baseline Data Program for the SA NRM Planning, Monitoring and Evaluation Project”. Although the DEM has high resolution (2m by 2m), the dataset excluded all areas covered in water, as free surface water interferes with the LIDAR signal (DWLBC 2009). Thus this data set could be used to improve the terrestrial component of the DEM presented here, but was not used as it only became available in early 2009, after the project was completed. To achieve the project’s aim of a seamless merged bathymetric and topographic dataset, firstly we modelled the bathymetry for the Murray Mouth and the South Lagoon using satellite data, survey data collected during fieldwork, and the existing bathymetric data for the Coorong and; secondly, the derived DEMs from the bathymetric data were integrated with the DEM of SA to get a seamless DEM for the region.

Digital Elevation Models are generated from various sources of data including digital photogrammetry, airborne or terrestrial laser scanning, aerial photographs and satellite data (Buckley 2004). Although satellite data have found extensive application in the study of terrestrial environments, limited research has been carried out to explore the use of these data in aquatic environments (Nelson *et al*. 2003).

Nonetheless, these data have been used for mapping topography underwater (Lafon *et al*. 2002) by establishing a relationship between spatial reflectance and water parameters including depth (Gordon and Brown 1973), turbidity, and bottom colour (Lee *et al*. 1998; Maritorena 1996). In particular, Lafon *et al*. (1998) demonstrated a strong relation between reflectance from the water surface and depth.

The availability of bathymetric data for most of the North Lagoon, and the satellite imagery for the region, provided essential ingredients for modelling bathymetry for the Murray Mouth and the South Lagoon. Therefore, we attempted to derive bathymetric data for these areas to supplement the DEM for the region by modelling the satellite reflectance data and the bathymetric data in the surrounding areas. A popular non-parametric technique, Generalized Additive Modelling (GAM – Hastie and Tibshirani 1990) was used for establishing a relationship between depth and surface reflectance captured in the different bands of satellite imagery as explanatory variables. Details of the available datasets and methodology for deriving the bathymetry and the seamless integration of the DEMs are given in the following sections.

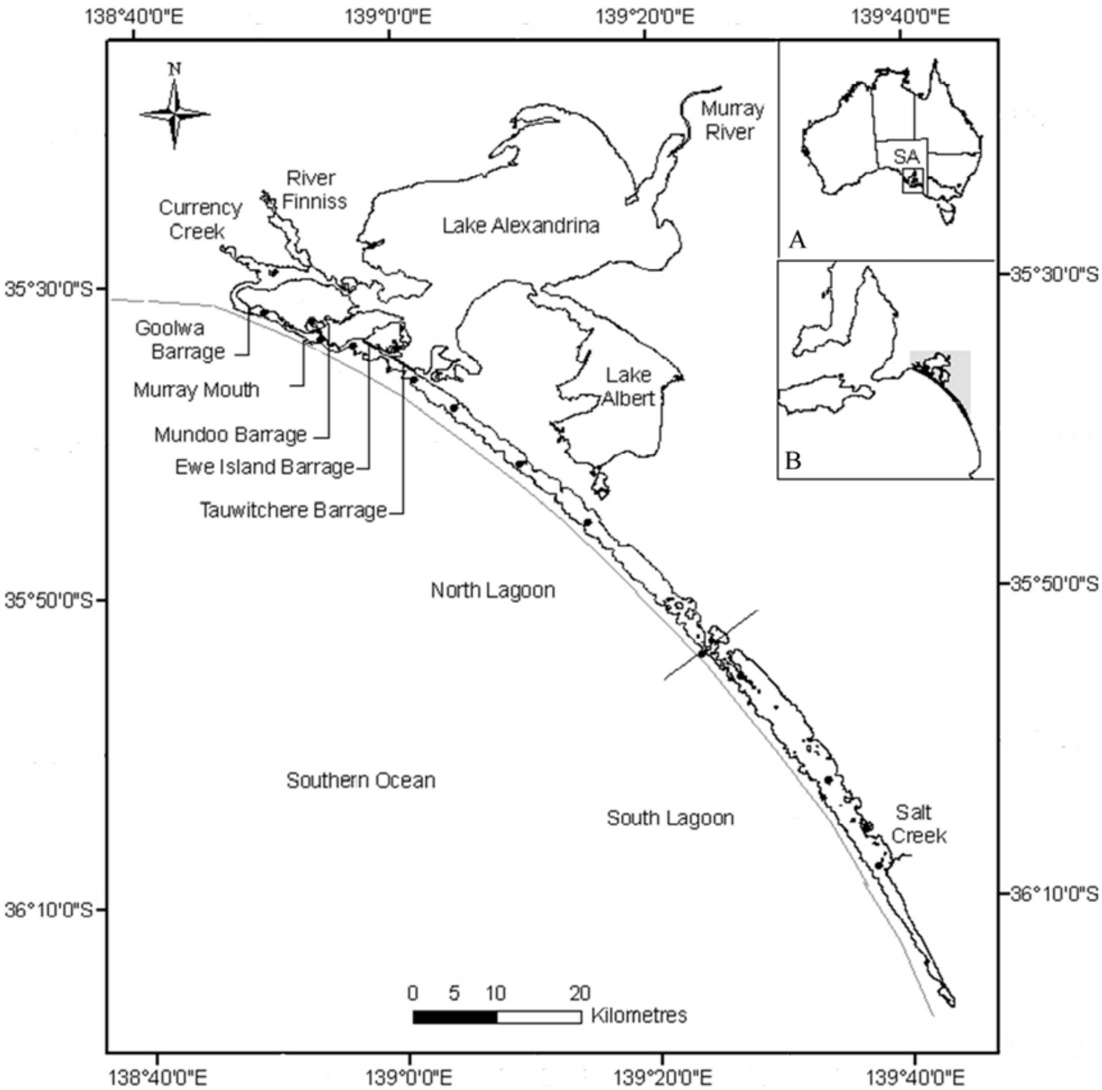

Figure 3.1. Coorong (North Lagoon and South Lagoon), Lower Lakes (Lake Alexandrina and Lake Albert) and Murray Mouth region with major locations and the barrages. The Australian map (A) shows the state boundaries and the study area in South Australia (SA) while the inset map (B) highlights the study area shown in the main map.

3.3. Available datasets and methodology

3.3.1 Available topographic and bathymetric data for the region

DEM for South Australia

A DEM for South Australia derived from NASA's Shuttle Radar Topography Mission (SRTM) project was obtained from the Spatial Information Services group (SIS) of the Department of Primary Industries of South Australia (PIRSA). Each grid cell in the model represents approximately 83 m^2 (3 arc seconds of latitude/longitude), and the vertical resolution or elevation for each cell is to the nearest one metre with reference to the Australian Height Datum (AHD). This model contains many areas without elevation data and the SIS of PIRSA are trying to improve the model by incorporating elevation data obtained from other sources. While the dataset has reasonable matching with the topographic data for the state (SIS 2005), a number of problems exist. Water bodies are not represented by their true elevation, the coastlines are not perfectly precise in the model (NASA 2005), and very flat areas tend to display the influence of striping as an artefact of the radar altimetry. The DEM for the Coorong and surrounding areas including the Lower Lakes, derived from the SRTM dataset, is shown in Figure 3.2.

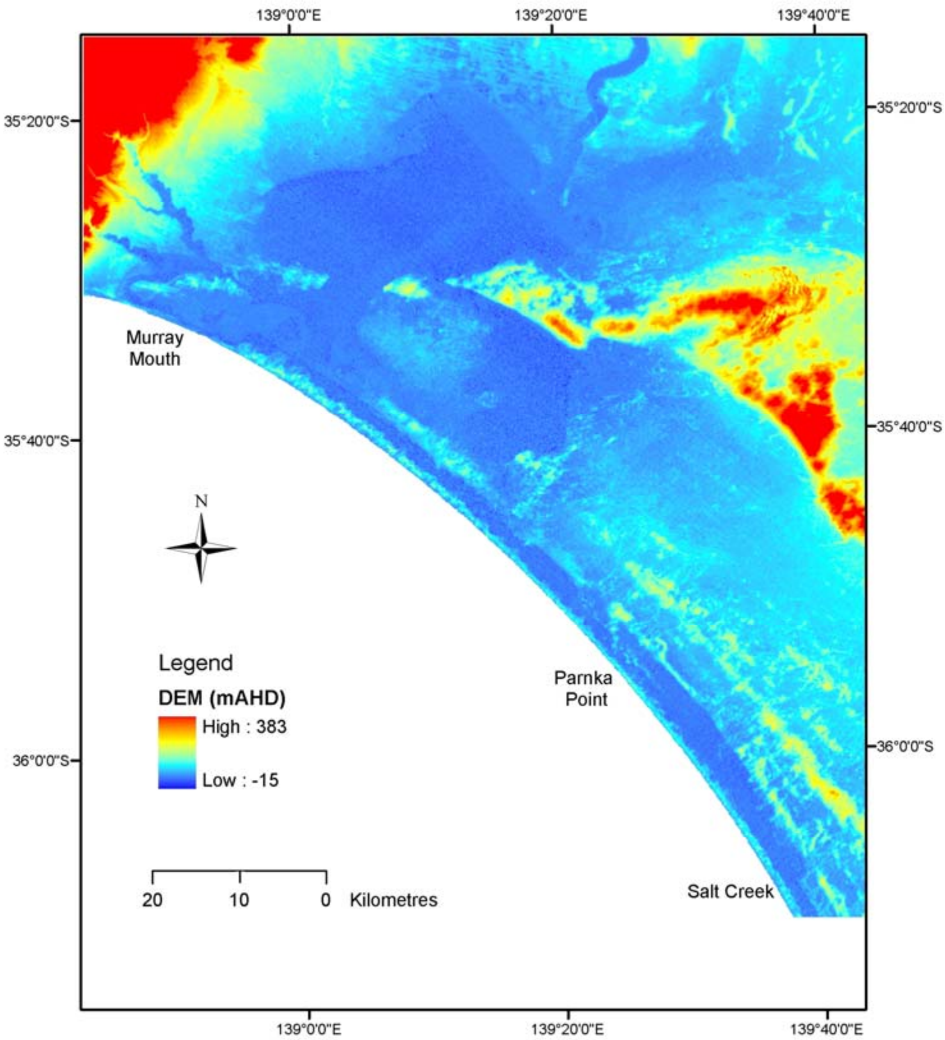

Figure 3.2. Digital Elevation Model derived from NASA's STRM project for the Coorong and surrounding areas.

Bathymetry for the Lower Lakes and the Coorong

The South Australian Water Corporation (SA Water) collected depth data for the Lower Lakes, including Lakes Alexandrina and Albert and the northern part of the Coorong, in order to derive a bathymetry for the region. The data was provided as point data at varying resolutions in AutoCAD DXF format. Metadata for the dataset is not available. However, Miles (2006) had prepared a note about the data collection procedure and accuracy of the bathymetric dataset. This note contains the following information about the dataset:

- The Lakes and the North Coorong were surveyed using an echo-sounder and GPS mounted on a small boat in May 2004.
- The spacing of transects was narrow around Hindmarsh Island and the Coorong as compared to the spacing in the Lakes.
- The eco-sounder was not used for surveying areas less than one metre deep.
- To compliment the echo-sounder data in shallow areas, the shoreline around the Lakes was delineated from aerial photographs and assigned the same value as the average water level of the Lakes.

The echo-sounder data and the shoreline contour data were processed in a Terramodel HDMS (Hydrographic Data Management System) and used to generate an interpolated bathymetry with the geographic coordinate system in decimal degrees of latitude and longitude, and vertical datum referenced to Australian Height Datum (AHD), for the Lakes and the North Lagoon. Except for a few rectangular blocks in Lake Albert that had a resolution of 5 m^2, the Lakes had 100 m^2 resolution. The North Lagoon had a resolution of 25 m^2 in the area between the Murray Mouth and Mark Point, and 50 m^2 between Mark Point and Parnka Point (Figure 3.1). The Goolwa Channel had a resolution of 10 m^2. The vertical accuracy of the original depth data collected by the echo-sounder is believed to be +/- 10 cm (Miles 2006). However, the accuracy of the boat position, the effects of motion on the depth and position readings, and the effects of tidal variation on the interpolated bathymetry, are not known.

Depth data for the Coorong

A dataset containing depth data along 51 transects with 486 points across the lagoon was obtained from CSIRO Land and Water. This data was originally collected by SA Water. Approximately half of these transects are in the South Lagoon with 241 points. The data collection procedure and accuracy of the dataset is not known. However, this dataset has been used for hydrodynamic modelling in the South Lagoon (Webster 2007).

3.3.2 Satellite Imagery

LANDSAT5 Imagery

LANDSAT5 imagery (mosaic) collected during 2004 using the Thematic Mapper (TM) sensor, and covering the CLLAMM region, was purchased from the MapLand section of the SA Department for Environment and Heritage (DEH). The imagery was already georeferenced to the Geocentric Datum of Australia 1994 (GDA 94). Electromagnetic energy reflected from the earth's surface is captured by the sensor in seven different bands at a resolution of 25 m^2. Each band corresponds to a specific range of wavelengths in the electromagnetic spectrum, and thus captures different reflectance from the target surfaces. For visualisation, combinations of bands are often used in Red, Green and Blue colours for differentiating land cover types, whether vegetation, rock or water. Reflectance from the water surface is sensed primarily in the visible spectrum (band 1 to band 3) of LANDSAT TM imagery. In the near and mid infrared regions (bands 4, 5 and 7), water mostly absorbs incident energy and thus provides minimal reflectance. Band 6 represents the thermal infrared, and is uniquely heat sensitive (Short 2008). LANDSAT data have been used in numerous studies to derive information on a range of parameters in aquatic and marine environments, including water quality (turbidity, chlorophyll, water chemistry, etc), water depth, presence of submerged vegetation and algal blooms, and others.

SPOT5 Imagery

Five pansharpened SPOT5 images encompassing the Coorong were obtained from MapLand, DEH. These images had been georeferenced to the same coordinate system as the LANDSAT5 imagery. The SPOT5 images were collected in 2004 by the high resolution geometry (HRG) optical sensor mounted on the satellite. Pansharpening is carried out to enhance the spatial resolution of the multispectral images, without altering the spectral information, through blending the lower resolution multispectral bands with a higher resolution panchromatic image over the same area (Pohl and Van Genderen 1998). Because of the high resolution and wide area coverage (up to 60 x 120 km), SPOT5 imagery is widely used in environmental monitoring, oil and mineral exploration, and urban and water resources planning (SIC 2008).

3.3.3 Methodology

Input data preparation

The bathymetric data, and the reflectance values or spectral digital numbers (DNs) from the satellite images for the areas on either side of the Murray Mouth and Mundoo Channel, were used for DEM modelling for the Murray Mouth area. Firstly, a geospatial framework with a consistent horizontal coordinate system was ensured by re-projecting the bathymetry dataset referenced to GDA 94, in line with the other datasets. The elevation data were already referenced to AHD. Secondly, the LANDSAT5 and SPOT5 datasets were converted from the raster format into vector format as point shape files, with the values for each pixel being allocated to a single point at the centre of the pixel. The reflectance point values in the seven bands of LANDSAT5 data were extracted for the region and joined together in ArcGIS. The point spectral data for the SPOT5 bands were at 2.5 m spacing and the LANDSAT5 spectral point data had 25 m spacing. Hence, the nearest spectral point in the SPOT5 data was joined to the LANDSAT5 data. Finally, the spectral point data were joined to the closest depth data point in the bathymetry dataset. The final dataset had 6067 points with 10 reflectance values and corresponding depth. For modelling and validation purposes, the dataset was randomly divided into a “training” dataset and a “testing” or validation dataset comprising 80 and 20 percent of the original dataset, respectively.

A separate model was developed for the South Lagoon using the reflectance of data from the areas adjacent to Parnka Point, assuming that these areas would have similar reflectance to the South Lagoon. The same procedure was used to derive the dataset as in the case of the Murray Mouth. However, the reflectance data from the SPOT5 imagery could not be used in the model because the areas used for the model development and the South Lagoon were covered by two separate SPOT5 images from different dates that showed very different reflectance. The dataset for the South Lagoon had 12977 points with depth data and seven predictor variables derived from the spectral values from the seven bands of the LANDSAT5 imagery. The data were again randomly divided into training (80%) and testing (20%) datasets, with 10381 and 2596 points for model development and validation purposes, respectively.

Modelling technique: Generalized Additive Model (GAM)

A Generalized Additive Model (GAM) fits a smooth non-parametric relationship between the response variable and the explanatory variable(s) (Crawley 2002).

Unlike parametric methods, where the shape of the curve fitted is defined a-priori, the shape of the non-parametric function is defined entirely by the data (Lehmann 1998). A general GAM formula for predicting a response variable y at location i with predictive variables x_{ij} is given as Equation 3.1.

$$g(y_i) = \beta_0 + \sum_{i=1,\, j=1}^{n} S_j(x_{ij}) \qquad (3.1)$$

where g is a link function, y_i is the response variable, β_0 is the intercept and S_j is a spline smoother for the predictor variable x_{ij}.

The GAM model was applied to the data using the mgcv package in the R software package (Wood and Augustin 2002), with the data being modelled as following a Gaussian distribution with the identity link function. A spline smoother was used for estimating the smooth relationship between the response and predictor variables. The model applied a penalized regression spline to guarantee a smooth fit by imposing a penalty to avoid overfitting (Wood and Augustin 2002). The smoothness of each fit is described by the estimated degrees of freedom for each predictor variable, which is chosen by minimizing the Generalized Cross Validation (GCV) score (Wood 2008). The package provides a summary of the model, which includes estimated degrees of freedom and the statistical significance of each predictor variable, adjusted R^2, deviance explained by the model, and the GCV values. Models with higher values of adjusted R^2 and deviance, and lower values of GCV, are considered to provide a better fit to the data. Since there is no automatic model selection function in the mgcv package, Wood and Augustin (2002) recommended using backward selection by manually deleting variables with degrees of freedom close to 1, a 95% confidence region that included zero everywhere in the parameter space, or that reduce the GCV score.

The reflectance values from the LANDSAT5 and SPOT5 imagery were used as explanatory variables for predicting bathymetry in the Murray Mouth region according to Equation 3.2.

$$g(Depth) = \beta_0 + S_1(1s_1) + S_2(ls_2) + S_3(ls_3) + S_4(ls_4) + S_5(ls_5) + S_6(ls_6) + S_7(ls_7) + S_7(sp_1) + S_8(sp_2) + S_9(sp_3) \qquad (3.2)$$

where *g* is the identity link function, and *ln* and *sp* represent the reflectance values for the respective bands in the LANDSAT5 and SPOT5 imageries.

For the South Lagoon bathymetry modelling, the spectral values from the seven bands of the LANDSAT5 imagery were used as explanatory variables in the model.

Model selection and validation

Although Wood and Augustin (2002) recommended the backward selection method for implementing GAM in the mgcv package, the forward selection approach has frequently been used in ecology for generating a model with the least number of significant variables which could explain almost the same variance as the model with all predictors(Blanchet *et al*. 2008). However, traditional forward selection based purely on adding variables until no additional variable is regarded as statistically significant is well known for producing a model with an excessive number of predictor variables. Hence, in implementing forward selection, we use the procedure developed by Blanchet *et al*. (2008), whereby an additional stopping criterion is specified. This criterion is that the adjusted R^2 should not exceed that of the global model with all possible predictor variables. Both the forward and backward approaches are applied to the data for conclusive model selection. These selection methods are briefly described below.

Forward selection: Initially, a model with all possible predictor variables was fitted to obtain the global adjusted R^2, and to avoid inflation of the Type I error rate (Blanchet *et al*. 2008). We then used this value as one of the stopping criteria during model selection. Variable entry into the model was based on the F statistic, providing that $p<0.05$ and that the variable did not have degrees of freedom close to 1 or a 95% confidence region that included zero everywhere in the parameter space (Wood and Augustin 2002). This was repeated in a stepwise fashion until either no additional variables met the entry criteria, or the global adjusted R^2 was reached.

Backward selection: Backward selection is implemented in the opposite fashion to forward section. We started with the global model and then eliminated terms in a stepwise fashion. The variable with the lowest F value was first eliminated, providing it had a $p>0.05$. This was repeated in a stepwise fashion until no additional variables met the exit criteria.

The prediction accuracy of the 'best fit' model derived through each variable selection procedure was assessed by comparing the predicted and the measured values in the validation dataset. The root mean square error, a commonly used measure of vertical accuracy for United States Geological Survey (USGS) DEMs (Wechsler 2003) was used to assess the prediction accuracy of the model (Equation 4.3). The model with the highest prediction accuracy would have a low root mean square error. Based on the prediction accuracy, and model comparison using analysis of deviance, the best model was selected and applied to the data for predicting bathymetry in the Coorong.

$$\text{Root Mean Square Error} = \sqrt{\sum_{i=1}^{N}(P_i - M_i)^2} \qquad (3.3)$$

where N is the number of measured data, P is the predicted value and M is the measured data.

Seamless DEM for the Coorong and surroundings

A seamless DEM was created for the Coorong and the surrounding area by using DEMs originating from the above three different sources. The bathymetric point data for the Lakes and the North Lagoon were separated based on their resolution and subsequently converted into a raster DEM using the point to raster conversion tool in ArcGIS 9.3 (Environmental Systems Research Institute 2008). The resultant DEMs with different resolutions were resampled to 25 m^2 resolution using the bilinear resampling method in ArcGIS 9.3. DEMs for the Lower Lakes and the North Lagoon were then mosaiced into a new DEM. The DEMs for the Murray Mouth and the South Lagoon derived from the GAMs were joined to the DEM for the North Lagoon and the Lower Lakes to produce a complete DEM for the Coorong, Lower Lakes and Murray Mouth (CLLAMM). For the merger of all DEMs, a procedure for developing a seamless DEM from the topographic and bathymetric data for Tampa Bay in the USA was followed (Gesch and Wilson 2001). The DEMs derived from the bathymetric data were integrated into one raster with a 25 m^2 grid cell resolution. A buffer zone of 600 m around the bathymetric DEM was extracted from the SRTM DEM and converted from grid to point data with location attributes (XY) and elevation value (Z). The bathymetric points along the shorelines above 0 mAHD were selected and combined with the topographic data. This new dataset contained the elevation data for the areas encompassing the interface between the shoreline and the land surface, and ensured a seamless merger of the elevations from the topographic and bathymetric datasets. For a smooth merger of the topographic and bathymetry data, a thin plate spline interpolation technique available in the Radial Basis Function of Geostastistical Analyst in ArcGIS 9.3 was used (Environmental Systems Research Institute 2008). Out of the 600 m buffer zone around the bathymetric DEM, a region 300 m out from the shoreline was cropped to avoid interpolation edge effects in the final bathymetry and mosaic with the bathymetric DEM. Finally, a seamless DEM for the region was derived by merging the resultant bathymetric DEM and SRTM DEM using the Mosaic function in ArcGIS.

3.4. Results

3.4.1 Generalized Additive Model implementation and prediction error analysis

Murray Mouth

The global model had an adjusted R^2 of 0.882. The model included 2 SPOT5 bands and all 7 LANDSAT5 bands as predictor variables (Table 3.1). Forward selection identified the "best" model that included 2 SPOT bands and all 7 LANDSAT5 bands, although only SPOT bands 2 and 3 explained >2% of the variation in depth (Table 3.1). The four-variable model explained most of the variance (87.7%). Adding the fifth and subsequent variables to the model resulted in very small increases in total variance explained. The predictive powers of all these models were evaluated by comparing the estimated and measured depths for the validation dataset. The best predictive power was given by the models with 4-7 variables. Applying the principle of parsimony, the model with four variables was chosen as the model had the least number of variables and explained more than 99% of the variance explained by the global model. This model was applied to predict the bathymetry of the Murray Mouth region.

Table 3.1. Statistics associated with forward selection for depth prediction in the Murray Mouth region.

Model Name	Variable added[1]	GCV[2] score	Adjusted R^2	Variance explained %	Root Mean Square Error
Model 1	sp2	0.811	0.68	68.4	0.87
Model 2	sp3	0.400	0.84	84.5	0.60
Model 3	ls1	0.362	0.86	86.0	0.58
Model 4	ls3	0.321	0.88	87.7	0.55
Model 5	ls5	0.314	0.88	88.0	0.55
Model 6	ls6	0.311	0.88	88.1	0.55
Model 7	ls7	0.310	0.88	88.2	0.55
Model 8	ls2	0.306	0.88	88.4	0.72
Model 9	ls4	0.306	0.88	88.4	0.70

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is sp2, model 2 is sp2 + sp3, etc). sp2 = SPOT5 imagery band 2; sp3 = SPOT5 imagery band 3; ls1 = LANDSAT5 band 1; ls2 = LANDSAT5 band 2; ls3 = LANDSAT5 band 3; ls4 = LANDSAT5 band 4; ls5 = LANDSAT5 band 5; ls6 = LANDSAT5 band 6; and ls7 = LANDSAT5 band 7. [2]GCV = Generalized Cross-Validation.

The relationships between depth and the explanatory variables for the four-variable model are illustrated in Figure 3.3. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region. SPOT5 band 2 was monotonically related to depth, with higher values indicative of greater depths. SPOT5 band 3 showed the opposite pattern. LANDSAT5 band 1 was negatively correlated to depth up to a value of 110, after which the relationship became more erratic with a greater confidence interval. LANDSAT5 band 3 showed a quadratic relationship with depth.

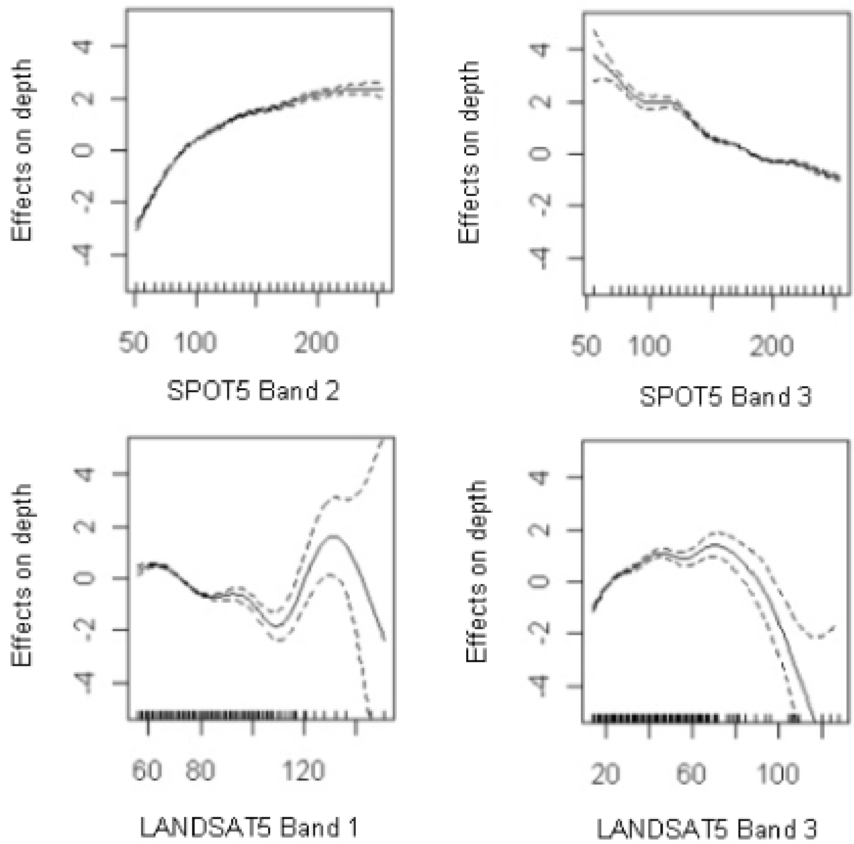

Figure 3.3. Response curves for predictor variables and depth for the final four-variable model for the Murray Mouth region. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

South Lagoon

The global model with all seven bands of LANDSAT5 had an adjusted R^2 of 0.757. Both the forward and backward variable selection methods identified a “best” model that included 6 LANDSAT5 bands, although only 3 of these explained >2% of the total variation in depth (Table 3.2).

Table 3.2. Model statistics for depth prediction in the South Lagoon.

Model Name	Variable added	GCV[2] score	Adjusted R^2	Variance explained %	Root Mean Square Error
Model 1	ls3	0.259	0.68	67.6	0.50
Model 2	ls2	0.222	0.72	72.4	0.46
Model 3	ls6	0.205	0.74	74.4	0.44
Model 4	ls5	0.200	0.75	75.2	0.44
Model 5	ls1	0.197	0.76	75.6	0.43
Model 6	ls4	0.196	0.76	75.8	0.43
Model 7	ls7	0.195	0.76	75.8	0.43

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is ls3, model 2 is ls3 + ls2, etc). ls1 = LANDSAT5 band 1; ls2 = LANDSAT5 band 2; ls3 = LANDSAT5 band 3; ls4 = LANDSAT5 band 4; ls5 = LANDSAT5 band 5; ls6 = LANDSAT5 band 6; and ls7 = LANDSAT5 band 7. [2]GCV = Generalized Cross-Validation.

Again, the predictive power of all models was evaluated by comparing the estimated and measured depths for the validation dataset. Model 3 with three predictor variable produced the lowest prediction errors in terms of the root mean square error, and thus the model was chosen for predicting the bathymetry of the South Lagoon.

The relationship between depth and each of the predictor variables in the final 3 variable model is shown in Figure 3.4. LANDSAT5 bands 2 and 3 showed a quadratic relationship with depth, and 6 had roughly monotonic influence.

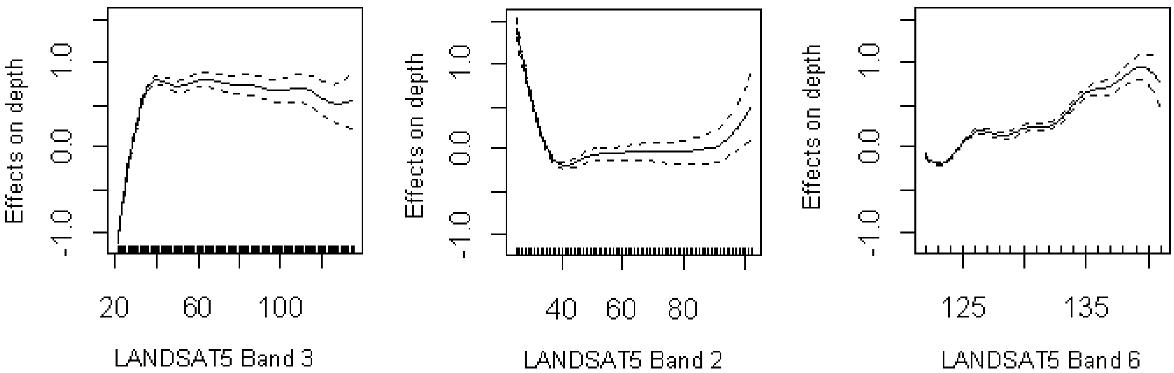

Figure 3.4. Response curves for predictor variables and depth for the final six-variable model for the South Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Figure 3.5 presents the relationship between predicted depth and measured depth in the South Lagoon between Parnka Point and Salt Creek. The predicted depths were very close to the measured depths between Parnka Point and Jack Point. However, the depths were underestimated further south towards Salt Creek. The summary statistics for the measured and predicted depths (Table 3.3) also demonstrate that the modelled depths were underestimated relative to the measured depths. Given that the model was developed using data from the North Lagoon near Parnka Point, this result makes sense, as water quality is known to deteriorate moving south from Parnka Point.

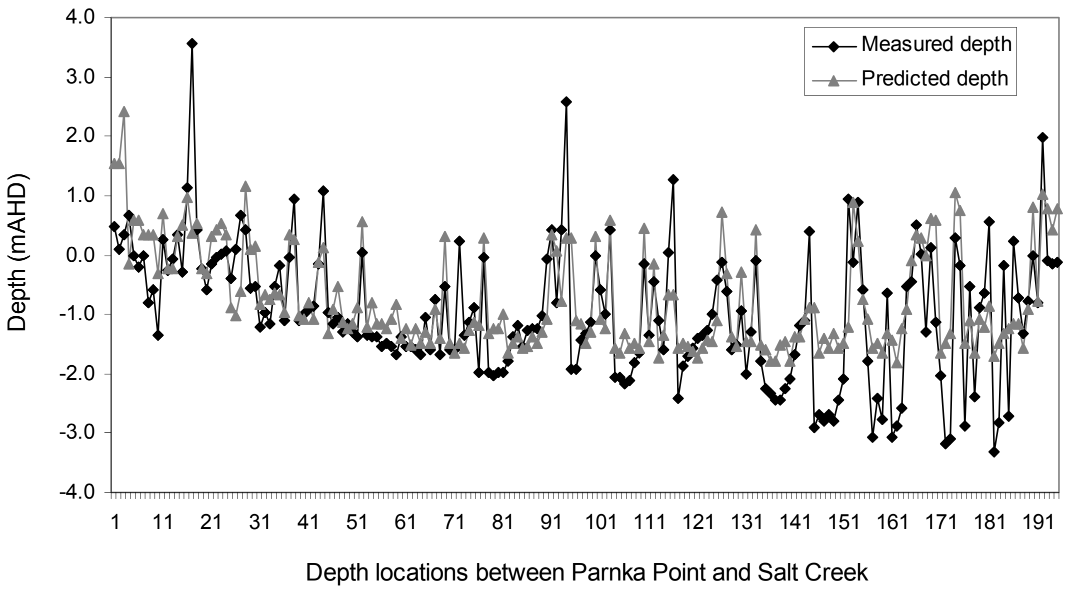

Figure 3.5. Predicted bathymetry for the South Lagoon compared to measured data.

Table 3.3. Summary statistics for the measured and associated predicted depths in the South Lagoon.

Depth	Mean	Standard Error	Median	Standard Deviation	Minimum	Maximum	Count
Measured	-0.98	0.08	-1.11	1.11	-3.33	3.56	195
Predicted	-0.74	0.06	-1.1	0.87	-1.81	2.41	195

DEM for the Murray Mouth and the South Lagoon

Model 4 was used to predict the bathymetry of the Murray Mouth region. A DEM for the Murray Mouth and surrounding region was then developed by converting the bathymetric data into a raster in ArcGIS 9.3. The predicted bathymetry for the Murray Mouth region was smoothed by applying a low pass filter using a 3X3 window (Figure 3.6), and then mosaiced into a DEM including the surrounding regions (Figure 3.7). The predicted bathymetry worked well in capturing the trend along the main channel and in the near-shore areas.

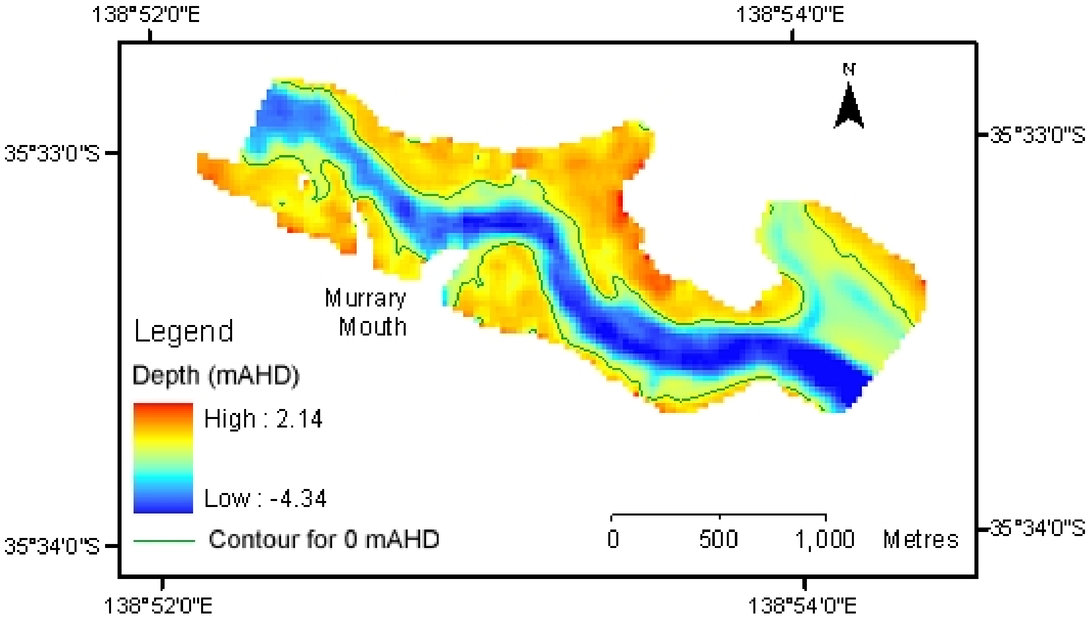

Figure 3.6. Predicted bathymetry for the Murray Mouth region derived from the final 4 variable model after smoothing by applying a low pass filter with a 3X3 window.

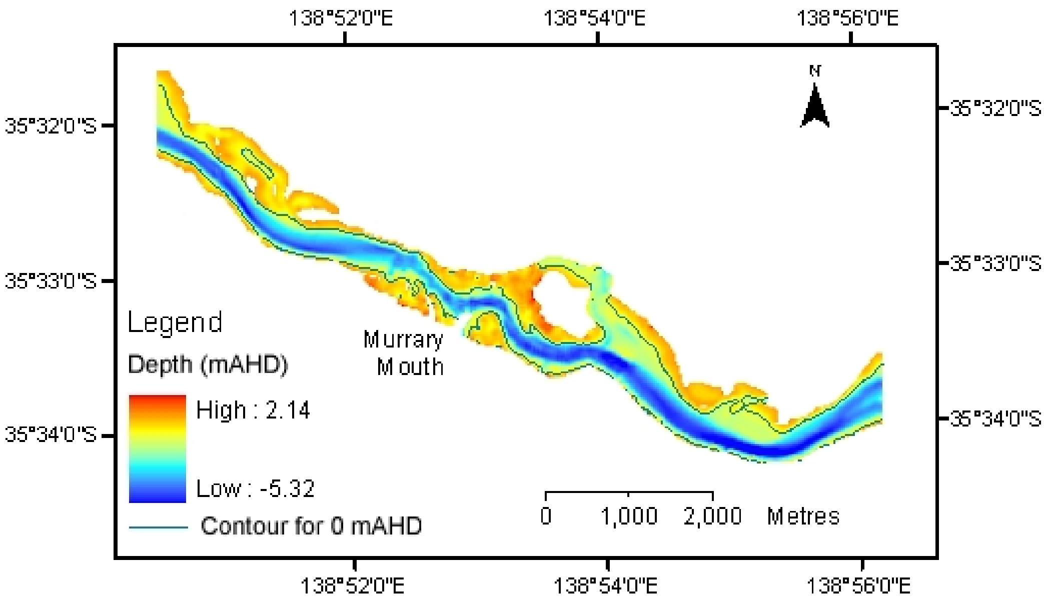

Figure 3.7. Mosaic of the bathymetry for the Murray Mouth and surroundings after smoothing by applying a low pass filter with a 3X3 window.

Figure 3.8 shows the bathymetry for the South Lagoon derived from the final 3 variable model, after smoothing the surface by applying a low pass filter with a 3X3 window.

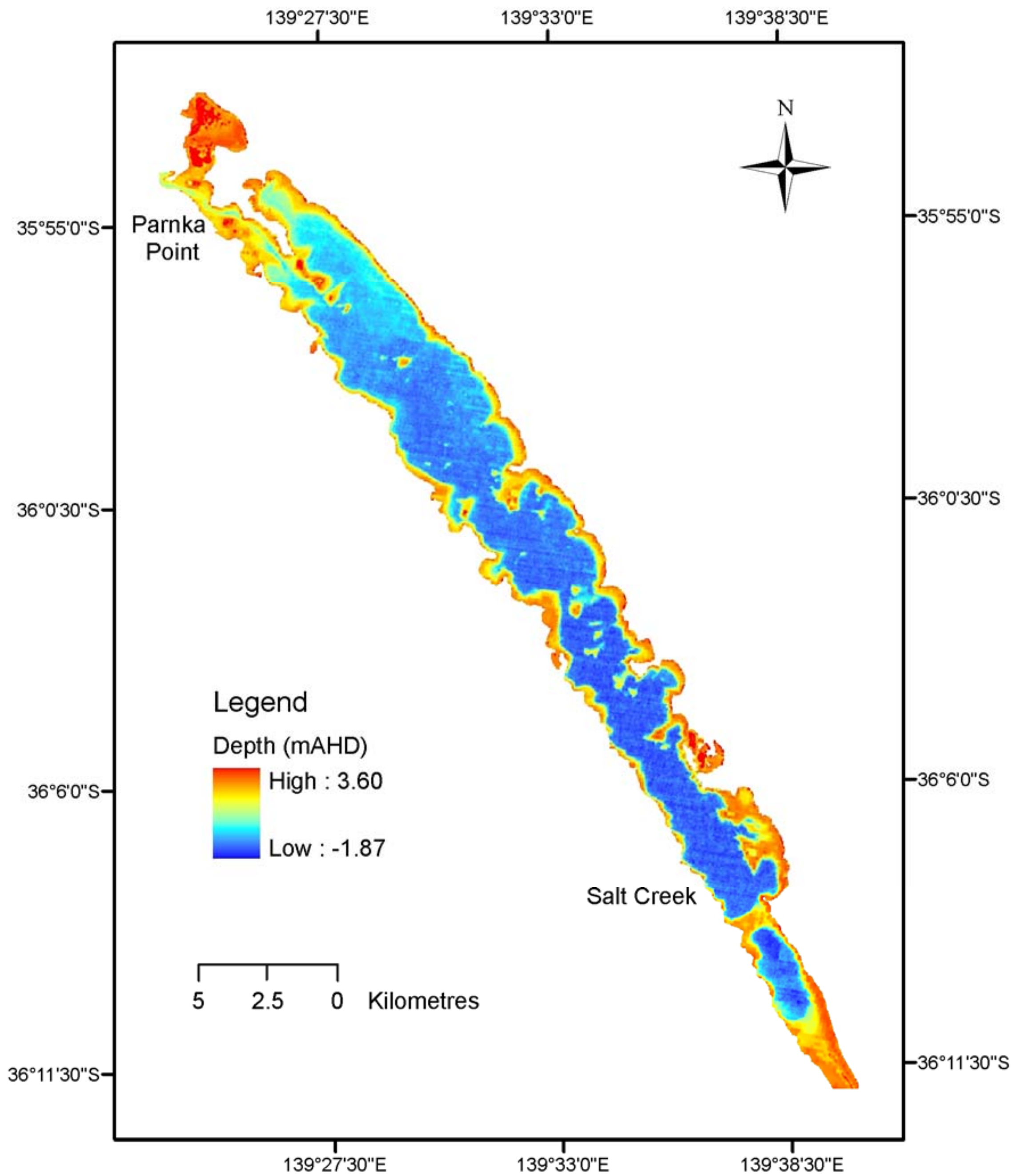

Figure 3.8. Predicted bathymetry for South Lagoon derived from the final 3 variable model after smoothing by applying a low pass filter with a 3X3 window.

3.4.2 Seamless bathymetry for the Coorong

Figure 3.9 presents an integrated bathymetry for the Coorong, Lower Lakes and Murray Mouth. This bathymetry was finally merged with the SRTM DEM to develop a seamless DEM for the CLLAMM region (Figure 3.10), by following the procedure described by Gesch and Wilson (2001).

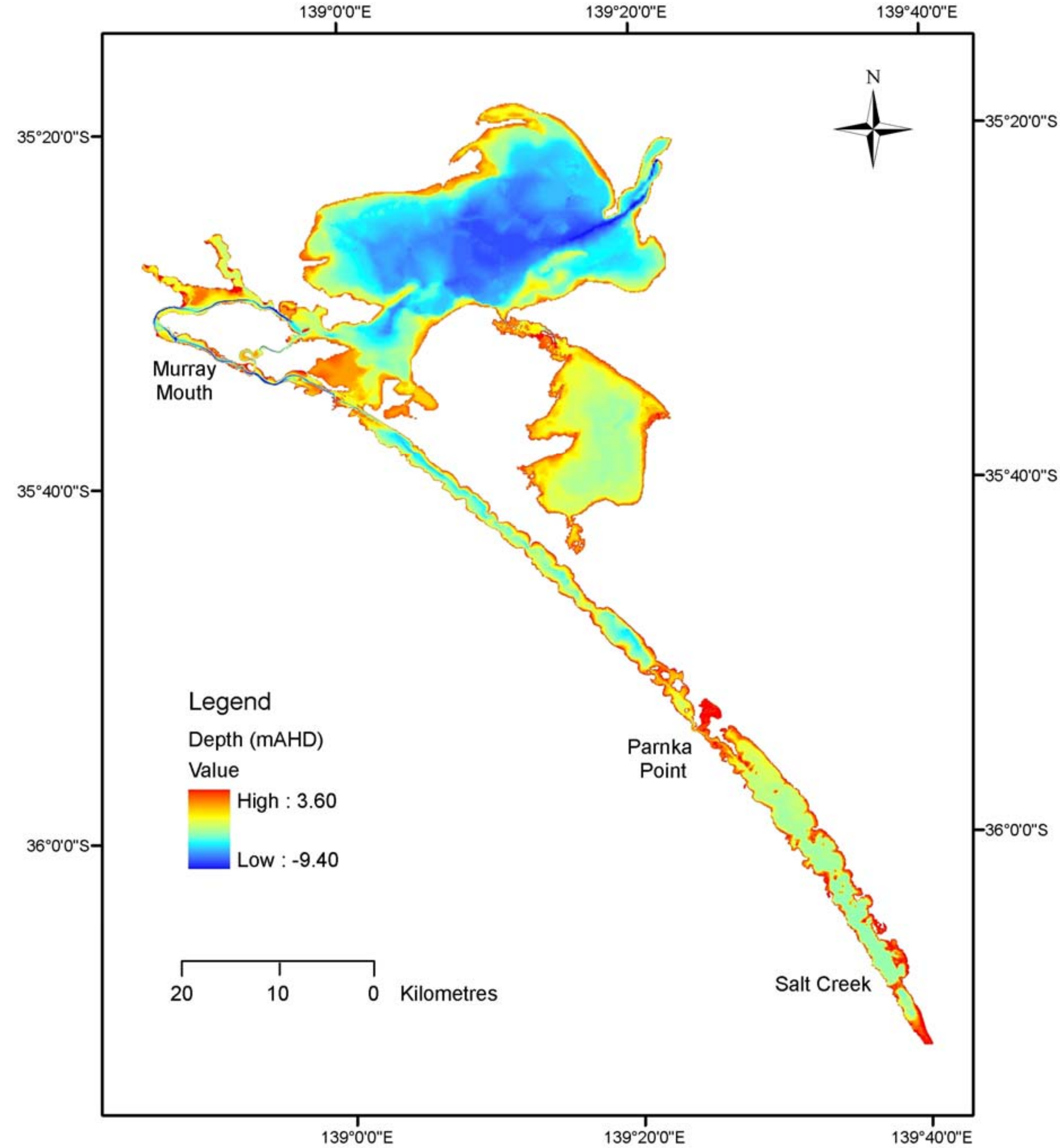

Figure 3.9. Final bathymetry for the Coorong, Lower Lakes and Murray Mouth.

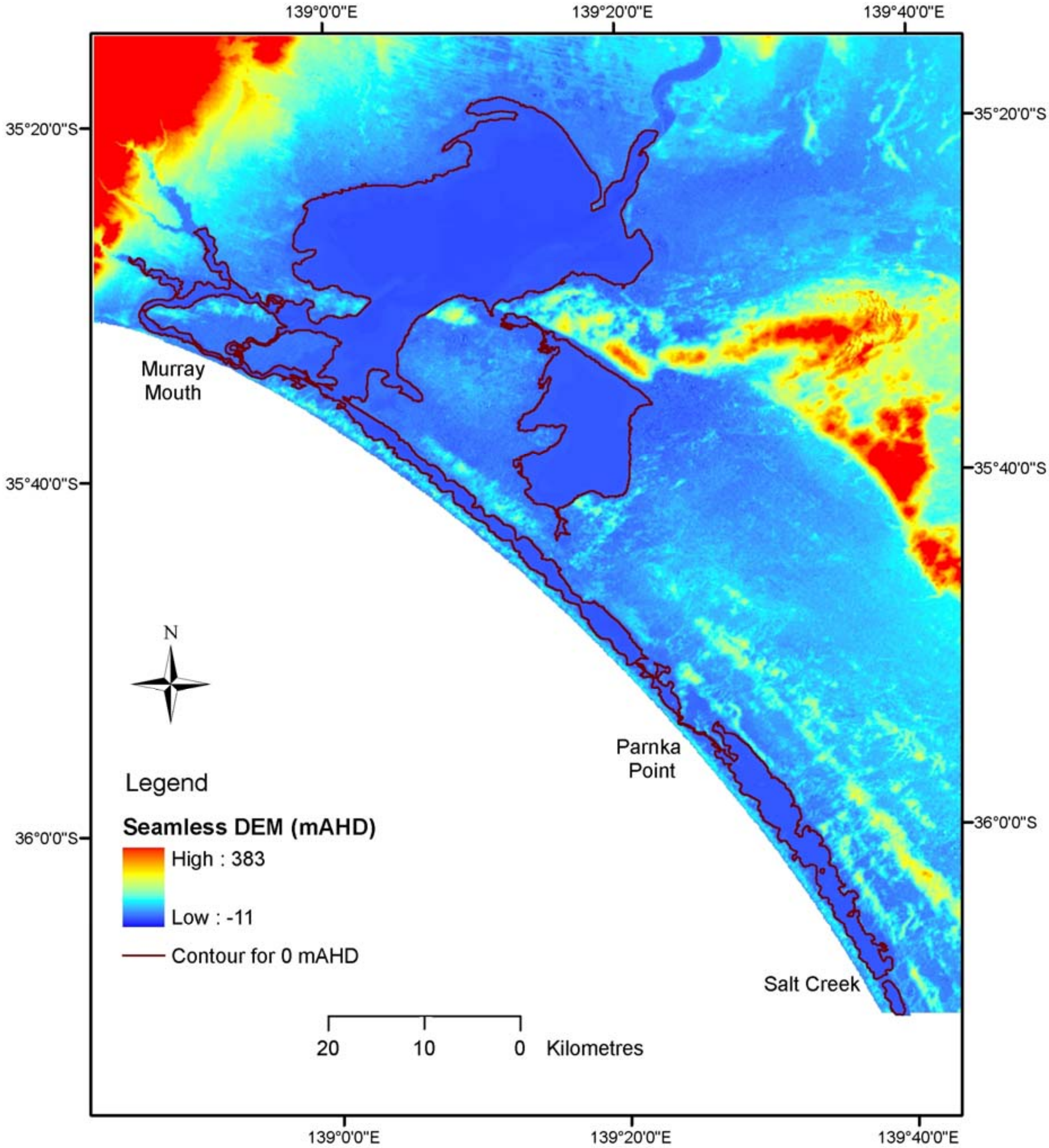

Figure 3.10. Seamless DEM for the Coorong, Lower Lakes and Murray Mouth (CLLAMM) region.

3.5. Discussion

The bathymetry modelling for the Murray Mouth and the South Lagoon using satellite imagery produced a reasonable prediction of depths for both of these areas where bathymetry was previously unknown. However, the depth for the southern quarter of the South Lagoon was underestimated, which could be directly attributed to poor reflectance because of less clear or turbid water. The water in the Murray Mouth region tends to be clearer due to the tidal incursion of sea water and the water clarity progressively diminishes towards the South Lagoon. The Salt Creek area at the far end of the South Lagoon has virtually no tidal influence and the water is very turbid. Water clarity was particularly important in the South Lagoon where visibility was very low (<0.64m secchi depth at Parnka Point compared to 2 m in the North Lagoon and Murray Mouth, Ye (2008), unpublished data). The influence of water clarity on reflectance is obvious in the higher accuracy of the depth predictions in the Murray Mouth region compared to the South Lagoon.

The bathymetry models for the Murray Mouth and the South Lagoon were not perfect and could be improved in a number of ways. Access to more comprehensive ground survey data for these regions would enable improvement in the errors and uncertainty in these models. Various techniques of handing errors and uncertainty are described in many papers (Hengl *et al*. 2004; Wechsler 2003; Fisher 1998). One commonly cited means of improving prediction would be to include a variable accounting for water turbidity, which may enhance the predictive power of the model. However, the turbidity data would need to align with the dates of satellite overpass, and so while some turbidity data is presently available for the Coorong, it would be difficult to use in this case.

The integration of the DEMs derived from different sources with different resolutions and accuracy is a challenging task (Buckley 2004; Mitchell *et al*. 2002). Bathymetry and topographic DEMs from three different sources with varying horizontal and vertical resolution and accuracy were used for deriving a seamless DEM for the Coorong and the surrounding areas. The interpolated bathymetric data for the Lakes and the North Lagoon of the Coorong collected using an echo-sounder had different spatial resolutions in different areas and the vertical accuracy was believed to be +/- 10 cm. By comparison, the modelled bathymetry for the Murray Mouth and the South Lagoon had a resolution of 25 m^2 and with mean absolute errors of 0.39 m and 0.33 m, respectively. Finally, the topographic DEM was derived through radar altimetry from NASA's SRTM (Shuttle Radar Topography Mission) project with approximately 83 m^2 resolution and one metre vertical accuracy. Nevertheless, a seamless DEM for the region has been successfully derived through integrating these datasets. However, the main issue remains the vertical resolution of the bathymetry compared to the topographic DEM. Although a seamless DEM was derived by integrating these two datasets, the elevation at the water-land interface may not be accurately interpolated because of the large difference in the vertical resolution between the datasets. Additional ground survey data on the land surface adjacent to the shoreline to 1 cm vertical resolution would enhance the accuracy of the model, and it is hoped that this will be achieved through future LIDAR altimetry efforts. LIDAR technology has improved greatly in recent years, and modern experimental systems are able to map bathymetry to at least 40 m depth with a vertical accuracy of 0.15 m (Lohani, 2009). This technology could be the best option for acquiring a high resolution bathymetry for the South Lagoon, particularly in areas where an eco-sounder cannot be used, although it is fairly expensive and not currently widely available.

The final seamless DEM was produced as a raster model with 25 m by 25 m resolution, which enables users to employ the dataset in various applications requiring elevation/bathymetry data. However, the vertical accuracy of the dataset differs from those of the parent datasets and varies spatially according to the source and the density of the bathymetric dataset.

3.6. Summary

The reflectance values from the LANDSAT5 and SPOT5 bands were used to generate a bathymetry for the Murray Mouth and the South Lagoon in order to address the existing data gap and to generate a seamless bathymetry for the Coorong and the region. The Generalized Additive Model predicted reasonable bathymetry for the Murray Mouth and the South Lagoon. However, the depth for the southern quarter of the South Lagoon was underestimated, which could be directly attributed to poor reflectance because of less clear or turbid water. The accuracy of the predicted bathymetry could be improved by applying a correction based on ground survey data and also using water turbidity as a predictor, especially in the model for the South Lagoon. Finally, a seamless DEM for the Coorong and the surrounding areas was derived by merging bathymetry and topographic DEMs from three different sources with varying horizontal and vertical resolution and accuracy. The final seamless DEM was produced as a raster model with 25 m by 25 m resolution and would be very useful for various studies requiring elevation data.

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4. Sediment mapping of the Coorong: Implications for habitat distributions

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4.1. Executive Summary

The Coorong, Murray Mouth and Lower Lakes region is renowned for its unique biological diversity, providing habitat for more than 200 species of birds and fish. The area is viewed as highly significant for its social, economic and ecological values at local, national and international levels. The current low water level in the Lower Lakes has been threatening the delivery of fresh water into the system, which is necessary to maintain a salinity gradient and water levels conducive to ecological health. The Coorong, Lower Lakes and Murray Mouth Ecology Research Cluster (CLLAMMecology) aimed to develop a better understanding of the impact of the flow regime on the functioning of the system for ecological sustainability of the region.

One of the objectives of the Dynamic Habitat Project within the CLLAMMecology Research Cluster was to produce sediment maps to enhance our understanding of benthic habitat distribution in the Coorong. The boundaries of sediment distribution and biological communities are, however, subjective and sediment maps should be seen as a first step in defining the distribution of habitats. In this work, we mapped a series of sediment characteristics influencing benthic habitat distribution along the Coorong, including sediment textural characteristics, as well as organic carbon and nitrogen, and mineral composition.

Maps of the distribution of mean grain size, sorting, organic carbon and nitrogen were developed for the estuary and North Lagoon using generalized additive models. Sediment transport in the Coorong was assumed to be linked to tidal incursions at the Murray Mouth, and also the quality and quantity of water flow through the barrages. As a consequence, maps were produced taking into account distance from the Murray Mouth, the underwater topography, distance to shore, and also salinity, amongst other variables. As no detailed bathymetry data is available for the South Lagoon, a simpler approach was used to map all parameters, including inorganic carbon and gypsum, for the whole Coorong. In this case, inverse distance weighting (IDW) was used, a mathematical method for surface fitting using the weighted averages of nearby points.

Our results suggest three main depositional areas along the Coorong, where sediments are fine and organically-enriched: (1) the middle channel of the lagoons, (2) the constriction between the North and South Lagoons known as Parnka Point, and (3) the western (seaward) shores of the North Lagoon, particularly south of Long Point. The sediment maps give the spatial distribution of sediment attributes and are useful tools in helping to identify habitats for benthic fauna and foraging grounds for migratory birds. This information will help managers to make informed decisions about the allocation of limited resources for gaining the maximum benefit from the system.

4.2. Introduction

The Coorong, Murray Mouth and Lower Lakes region offers a unique array of habitats from freshwater, estuarine and marine to hypersaline, and provides an interconnected ecosystem supporting more than 200 species of birds and fish, including 20 species of migratory waders (CLLAMM 2007; EconSearch 2004; Edyvane 1999; Carpenter 1995). The area is viewed as highly significant for its social, economic and ecological values at local, national and international levels (Department for Environment and Heritage 2007). The international significance of the region is demonstrated through its listing as a Ramsar site, while its national significance has been recognized by its designation as one of the six icon sites under The Living Murray initiative (Seaman 2003). The 2008 low water level in the Lower Lakes, attributed to the drought in the Murray River tributaries and the level of extractions in the Murray Darling Basin, has interrupted the delivery of fresh water to the system, which is necessary to maintain a salinity gradient and water levels conducive to ecological health. At present, the water level in the Coorong is at an historic low, and salinity has risen to extremely hypersaline in the southern part of the lagoon, beyond the physiological limits of many species, which now seek refuge in the northern part of the lagoon (CLLAMM 2008). The Coorong, Lower Lakes and Murray Mouth Ecology Research Cluster (CLLAMMecology) aimed to develop a better understanding of the impact of the water flow regime on the functioning of the system, to provide management options for ecological sustainability of the region.

At the ecosystem level, physical, chemical and biological processes and the interactions between them govern system function and sustainability (Mann 1991). Physicochemical conditions are crucial determinants of the range of habitats available for flora and fauna. In the Coorong, the presence of mudflats on the eastern (landward) and western (seaward) shores and frequent inundation of these areas provides good habitat for invertebrates, and hence offers substantial foraging grounds for a large population of migratory birds (Edyvane 1999). Habitat characterization in subtidal areas is less clearly defined, but key drivers are water level, salinity, temperature and sediment characteristics (CLLAMM 2007 2008; Jones 1950).These physico-chemical variables drive the recruitment of larvae of sessile fauna and the proliferation of aquatic vegetation (e.g. *Ruppia* spp.) (Heijs *et al.* 2000; Snelgrove and Butman 1994), thus having a significant effect on the availability of food resources for the wider system.

The protection of critical aquatic habitats requires a detailed definition of their spatial distribution. One of the objectives of the Dynamic Habitat Project within the CLLAMMecology Research Cluster was to produce sediment maps to enhance our understanding of benthic habitat distribution in the Coorong. The mapping of benthic habitats has been traditionally based on geophysical and sediment data, due to the difficulties in acquiring biological data at the scale of the landscape (Kenny *et al.* 2003; Roff *et al.* 2003). The boundaries of sediment distribution and biological communities are, however, subjective, and sediment maps should be seen as a first step in defining the distribution of habitats (McBreen *et al.* 2008). In this work, we mapped a series of sediment characteristics influencing benthic habitat distribution along the Coorong, including sediment textural characteristics, as well as organic carbon and nitrogen content, and mineral composition. Particle size distributions were used as indicators of prevailing hydrodynamic conditions through the delineation of depositional and erosional areas (Storlazzi and Field 2000). The organic carbon and nitrogen content of sediments was investigated as a proxy for organic matter accumulation, thus reflecting the availability and origin of food resources for benthic detritivores (Ruttenberg and Goñi 1997). The effects of salinity on sediment composition were assessed through the measurement of gypsum and carbonate (inorganic carbon), which reflect changes in the saturation state of the water column driven by evaporation and water circulation (Lazar *et al.* 1983).

Maps of sediment distribution in the Coorong were produced by using surface interpolation techniques (Méar *et al.* 2006; Leecaster 2003). The method used is dependent upon the amount of data on sediments, its variability and trends, and also the availability of other datasets that would potentially correlate with the variable of interest. Maps of the distribution of mean grain size, sorting, organic carbon and nitrogen were developed for the estuary and North Lagoon using generalized additive models (GAM) (Wood 2003; Hastie and Tibshirani 1990). Sediment transport in the Coorong was assumed to be linked to tidal incursions at the Murray Mouth, and also the quality and quantity of water flow through the barrages (Webster 2005). As a consequence, maps were produced taking into account distance from the Murray Mouth, the underwater topography, distance to the eastern and the western shores, and also salinity, amongst other variables. As no detailed bathymetric data are available for the South Lagoon, a simpler approach was used to map all parameters, including inorganic carbon and gypsum, for the whole Coorong. In this case, inverse distance weighting (IDW) was used, a mathematical method for surface fitting using weighted averages of nearby points (Environmental Systems Research Institute 2001).

These sediment maps give the spatial distribution of sediment attributes and are useful tools for predicting the availability of habitat for benthic fauna and foraging grounds for migratory birds. This information contributes to a better understanding of the distribution of the areas of high ecological value for these species that will provide managers with the ability to make informed decisions about the allocation of limited resources for gaining the maximum benefit from the system.

4.3. Methods

4.3.1 Study area

The Coorong is a large lagoon system on the southeast coast of South Australia, and is geographically located between the Lower Lakes (Lake Alexandrina and Lake Albert) and the Southern Ocean (Figure 4.1). Barrages were built at five locations, Goolwa Channel, Mundoo Channel, Boundary Creek, Ewe Island and Tauwitchere to prevent sea water entering into the Lakes. The lagoon begins at the Murray Mouth and stretches southeast for over 100 kilometres, parallel to the ocean (CLLAMM 2007). The Younghusband Peninsula, a series of 1-3 kilometre wide sand dunes, separates the lagoon from the ocean.

4.3.2 Sampling

Twelve sites were sampled along the length of the Coorong in October and November 2006, and March 2007, with three cross-lagoon transects separated by 500 m per site (Figure 4.1). These transects were also surveyed using underwater video (see Chapter 2), and the sites have been the subject of intensive investigation by other groups in CLLAMMecology (Noell *et al.* 2009; Rogers and Paton 2009a; Rogers and Paton 2009b; Rolston and Dittmann 2009). Typically, five sets of sediment cores were collected at approximately even intervals along each transect using 71 mm (internal diameter) PVC tubes capped with rubber bungs. The overlying water in the tube was carefully discarded to minimise surface disturbance and the top layer sliced. Samples for carbon, nitrogen and gypsum analysis (n = 178) comprised the top 0-1 cm of the cores and were transferred into pre-combusted glass jars. Samples for particle size analysis were obtained from additional cores (n = 178) and comprised the top 0-4 cm of the cores. These samples were transferred into aluminium trays. All samples were transported on ice and stored frozen at -20ºC.

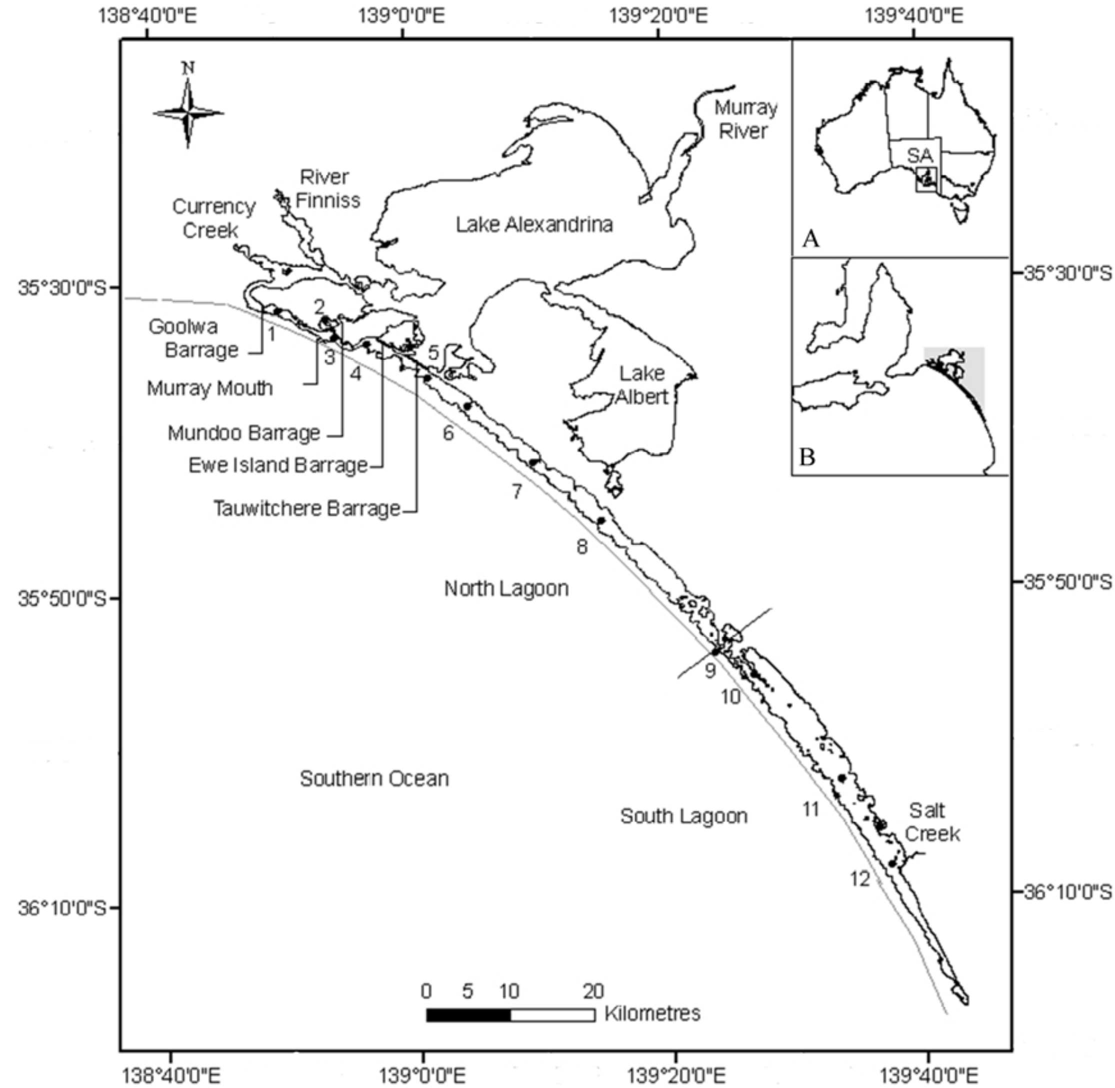

Figure 4.1. Locations of the reference sites in the Coorong Lagoon: 1 = Goolwa; 2 = Mundoo; 3 = Barker Knoll; 4 = Ewe Island; 5 = Pelican Point; 6 = Mark Point; 7 = Long Point; 8 = Noonameena (in the North Lagoon); 9 = Parnka Point; 10 = Villa dei Yumpa; 11 = Jack Point and 12 = Salt Creek (in the South Lagoon). The Australian map (A) shows the state boundaries and the study area in South Australia (SA) while the inset map (B) highlights the study area shown in the main map.

Particle size

Samples were oven-dried at 105°C for at least 16 h. Samples were dispersed with a 50 g L^{-1} sodium hexametaphosphate solution in an ultrasound bath for 15 min then left to soak overnight, and sonicated again for 15 min (Bouyoucos, 1962; Buchanan, 1984). Dispersed samples were wet sieved to exclude particles >1 mm just before analysis. Particles >1 mm typically comprised less than 3% of the total and were discarded (Fernandes, unpublished results). Particle size analyses were performed using a Malvern Mastersizer 2000 laser diffraction analyser, which has a practical measuring range from 0.02 to 2000 μm. Particle size distributions were analysed with the software package GRADISTAT, with the Folk and Ward graphical method used to calculate grain size parameters (Blott and Pye 2001). This method is relatively insensitive to samples with a large particle range in the tails of the distribution and provides a robust tool to compare compositionally variable samples. Parameters used to describe grain size distributions included the mean grain size, the spread of sizes around the mean (sorting), the symmetry or preferential spread of the distribution to one side of the mean (skewness), and the degree of concentration of the grains relative to the average (kurtosis).

Carbon and nitrogen

Samples were freeze-dried, sieved to remove large shell fragments >500 μm, and homogenized with a mortar and pestle. These sieved samples were analysed for carbon and nitrogen in a LECO TruSpec elemental analyser. Sub-samples for organic carbon analysis were pre-treated with 1 N hydrochloric acid to remove carbonates, rinsed with MilliQ water to remove hygroscopic salts and oven-dried at 50ºC for at least 16 h using a method modified from Fernandes and Krull (2008). Organic carbon was calculated from concentrations measured in pre-treated and untreated aliquots; inorganic carbon was calculated as the difference between total carbon and organic carbon.

Gypsum

Samples were freeze-dried, sieved to remove large shell fragments >500 μm, and homogenized with a mortar and pestle. Gypsum ($CaSO_4.2H_2O$) was determined using the thermogravimetric method of Artieda et al. (2006), which has a quantification limit of 2%. Approximately 10 g was sequentially dried at 70ºC and 90ºC, and gypsum determined as the loss in weight between these temperatures, assuming a water loss of 14.95% for pure gypsum. Gypsum values <2% were considered as 1% for the sake of spatial and statistical analysis.

Statistical analysis of measured data

Particle size parameters, as well as carbon, nitrogen and gypsum content of sediments, were analysed with the software package STATISTICA (StatSoft, Tulsa, OK). Principal-component analysis (PCA) was used as an exploratory technique to identify broad sediment types according to particle size parameters. PCA was based on standardized data in the correlation matrix, with principal components retained when eigenvalues were >1. Sediments types were assigned according to the loading of individual samples on the first two principal components. Analysis of variance (one-way ANOVA) was used to determine the significance of observed differences ($\alpha = 0.05$) in carbon, nitrogen and gypsum content and C:N molar ratios between broad sediment types (fine, intermediate and coarse), and location along the Coorong (estuary, North and South Lagoons), both factors treated as fixed. Variables were log-transformed when there was a need to improve normality as indicated by normal probability plots. Tukey post-hoc tests were performed when significant differences were detected. Linear regressions were used to assess whether and how a given variable was related to other variables.

4.3.3 Modelling and mapping

Sediment modelling for the North Lagoon

Generalized additive modelling (GAM) was chosen to find the relationship between the sediment characteristics measured and a range of potential predictor variables (described below) for the northern part of the Coorong. A detailed description of the model and the model selection procedures are given in Chapter 3. The GAM including all variables for predicting sediment attributes is expressed as follows:

$$g(SA) = \beta + s(\text{Northing}) + s(\text{Easting}) + s(\text{Depth}) + s(\text{Slope}) + s(\text{Aspect}) + s(\text{distance to the eastern shore}) + s(\text{distance to the western shore}) + s(\text{distance to the nearest shore}) + s(\text{distance from the Murray Mouth}) + s(\text{salinity}) \quad (4.1)$$

where g is the identity link function, SA is the sediment attribute of interest, β is the fitted intercept and s is a spline smoother for each predictor variable.

The predictor variables were first analysed for inter-correlations. Table 4.1 presents the correlation matrix for all ten variables. The geographical coordinates (Easting and Northing), were highly negatively correlated (r = -0.98). Due to the NW-SE orientation of the Lagoon, the distance to the Murray Mouth had a high positive (r = 0.97) and negative (r = -98) correlation with the Easting and the Northing, respectively. Depth had a very negligible correlation (r = <-0.08) with its two derivative variables (slope, aspect) and with the other variables. The salinity gradient along the Lagoon, i.e. low salinity (35 g/L) at the northern end (Goolwa Channel) and high salinity (~100 g/L) at the southern end (Salt Creek), resulted in a high positive correlation (r = 0.97) with the Easting and the distance from the Murray Mouth, and high negative correlation (r = -0.98) with the Northing. The rest of the variables did not show strong correlation with other variables, except for a negative correlation (r = -0.54) between the distance to the eastern and the western shores. As we are using the GAM for predictive modelling within the range of the predictor variables used to develop it, collinearity in the predictor variables is not a problem, although it would be if we were undertaking hypothesis testing (Quinn & Keough 2002)

Table 4.1. Correlation matrix for the predictor variables used in the GAM for modelling sediment attributes in the Coorong.

Variable	1	2	3	4	5	6	7	8	9	10
1	1.00									
2	-0.98	1.00								
3	0.09	-0.10	1.00							
4	-0.39	0.37	-0.08	1.00						
5	0.19	-0.20	-0.03	-0.15	1.00					
6	0.97	-0.98	0.07	-0.37	0.20	1.00				
7	0.23	-0.27	0.26	-0.15	0.08	0.23	1.00			
8	0.07	0.01	0.06	0.05	-0.16	0.04	-0.54	1.00		
9	0.24	-0.20	-0.30	-0.37	0.07	0.21	0.05	0.11	1.00	
10	0.97	-0.98	0.14	-0.37	0.17	0.97	0.33	0.07	0.23	1.00

Where 1 = Easting, 2 = Northing, 3 = Depth, 4 = Slope, 5 = Aspect, 6 = Distance from the Murray Mouth, 7 = Distance to the eastern shore, 8 = Distance to the western shore, 9 = Distance to the nearest shore and 10 = Salinity.

For modelling sediment attributes all ten predictor variables were used as long as sufficient degrees of freedom were available. In the case of nitrogen, the input dataset only had 67 sample points as some samples did not contain enough material for analysis (either nitrogen was below the detection limit or the sample was limited in size), and thus there were insufficient degrees of freedom available to fit all 10 variables. As Easting, Northing, Distance from Murray Mouth and Salinity were all highly correlated (Table 4.1), only Salinity was retained (as the variable explaining the highest % deviance in total nitrogen of this group). This left a 7 variable global model, which was explored further.

GAM was implemented using the MGCV package in R-stat software (Wood and Augustin 2002; Wood 2001). The final model was determined using forwards stepwise selection, as proposed by Blanchet et al. (2008). This approach uses a global statistic as a stopping criterion in order to find a model with the minimum number of predictor variables that can explain almost the same variance as the global model with all predictor variables. The global adjusted R^2 was used as the stopping criterion for modelling sediment characteristics. For each variable, the generalized cross validation (GCV) score was used to determine the optimum degrees of freedom (smoothness of the fit) to use. Variables were then added to the model on the basis of their F-statistic (after accounting for existing variables in the model), until either no additional variables contributed significantly to the model fit, or the global stopping criterion was reached. Analysis of variance (ANOVA) was also performed to test for significant differences between the final model and the global model.

Insufficient data were available to retain a subset for model validation purposes. Hence all sample data were used for model development, and a predicted value was then determined for each sample point. The goodness of fit of the final model, as well as its precursors and the global model, was assessed by comparing the predicted and the measured values for each sample point. A common measure of prediction error, the root mean square error (Equation 4.2) was used to compare the prediction power of the different models (Verfaillie *et al.* 2006; Antonopoulos *et al.* 2001) and the model with the least error was applied to the data for the North Lagoon for generating sediment attribute maps:

$$\text{Root Mean Square Error} = \sqrt{\sum_{i=1}^{N} \left(P_i - M_i\right)^2} \qquad (4.2)$$

where N is the number of measured data, P is the predicted value for sample i and M is the corresponding measured value.

Datasets for the generalized additive model

(a) Topographic variables

The underwater topography of the lagoon was considered to be a major factor influencing sediment distribution in the Coorong. The lagoon is about 2-3 km wide and is characterized by a deep channel in the middle and shallower areas towards the eastern (landward) shore, whereas the western (seaward) shore is mostly steeply sloping. An interpolated bathymetry (in vector format-point data) for the lakes and the North Lagoon was obtained from the South Australian Water Corporation (SA Water). The underlying data for this bathymetry were collected using an echo-sounder and global positioning system (GPS) installed in a small boat in May 2004. The depth data were referenced to the Australian Height Datum (AHD) and the accuracy of the original dataset was assumed to be ± 10 cm (Miles 2006).

Slope and aspect also describe underwater topography and might have influenced the distribution of sediment along the lagoon. Slope measures the steepness or gradient of a surface in degrees between 0 (horizontal) and 90 (vertical), while aspect is the compass direction of hill faces and is also measured in degrees between 0 (north) and 360 (north). These layers were derived from the digital elevation model developed from the bathymetry data (see Chapter 3) using the Spatial Analyst tool in ArcGIS (v 9.2) (Environmental Systems Research Institute 2008). The aspect layer in degrees was lineralised by applying Equation 3 which also removed negative values, as ArcGIS represents flat areas as having a slope of –1 rather than 0 (Menzel *et al.* 2006):

$$\text{Aspect} = (1-\cos(\text{aspect in degree})) + (1-\sin(\text{aspect in degree})) \qquad (4.3)$$

(b) Geographical variables

Sediment distribution in estuaries is influenced by currents and the particle size of the sediment itself. Coarse sediments require stronger currents for transportation and settle more quickly than fine sediments (McLusky, 1981). Hence, fine sediments are likely to be transported further from their source. In the Coorong, the major sources of sediment include the Southern Ocean (via water flow through the Murray Mouth), the Lower Lakes and River Murray (via water flow over the barrages) and the adjacent shores via windblown transport and surface runoff. The western shore adjoins active sand dunes on the Younghusband Peninsula, which are likely to be a minor source of aeolian transported sediments. Thus, the distance to the Murray Mouth, the eastern (landward) and western (coastal) shores, and the distance to the nearest shore, were used in the model. These layers were derived by estimating the distance to the nearest respective boundary (landward or coastal shore) from each point in the bathymetry dataset in ArcGIS 9.3 (Environmental Systems Research Institute 2008).

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Geographic location has also been considered an important predictor variable for explaining spatial variability in sediments (Dray *et al.* 2006). To take geographic location into account, the spatial coordinates (easting and northing) were used as explanatory variables in the model.

(c) Salinity

Salinity is one of the main ecological drivers of the Coorong and exerts a strong influence on physical and biological processes (CLLAMM 2007). Hence, salinity (g/L) was also included as a predictor variable in the model. Sampled data measured at 10 locations along the Coorong in June 2007 were used to derive a GIS-layer for salinity using the IDW method (Burrough and McDonell 1998) in ArcGIS 9.3.

Sediment mapping for the North Lagoon

A dataset with all predictor variables was created for the entire North Lagoon. The distance from the Murray Mouth, eastern shore, western shore and the nearest shore were calculated for each point in the bathymetry data set, which consisted of geographic co-ordinates (Easting and Northing) and depth. The raster datasets of aspect, slope and salinity were converted into point format and joined to the bathymetry.

The best model for each sediment attribute was applied to the entire dataset for the North Lagoon and a predicted value for each data point obtained. The predicted values were imported into GIS and joined with the respective geographical coordinates. Finally spatial maps for each sediment attribute were derived by interpolating the predicted data using the IDW method. All these operations were performed in ArcGIS 9.3.

Sediment mapping for the Coorong as a whole

To produce sediment maps for the entire Coorong including both the North and the South Lagoons, the IDW method available in the geostastical analyst extension of ArcGIS 9.3 was used (Environmental Systems Research Institute 2008). The sample size (Table 4.2) was not adequate to capture variability within the sites or across the entire lagoon through the use of any of the standard geostatistical methods. Although kriging is a commonly-used geostatistical method and has demonstrated a good prediction capacity for sediment (Méar *et al.* 2006; Leecaster 2003) and soil properties (Liu *et al.* 2006; Gotway *et al.* 1996), this method resulted in a radical smoothing of the data and also could not depict the spatial variability of mean grain size within individual sites or across the lagoon. However, the IDW method, an exact interpolation, broadly captured the variability in the mean grain size at the regional scale and had better goodness of fit than another exact interpolation method, the radial basis function (thin-plate spline method) (Burrough and McDonell 1998).

Hence, IDW was chosen to generate maps for all sediment parameters for the Coorong.

Table 4.2. Sample size for sediment attributes in the North Lagoon and the entire Coorong.

Sediment Attributes	Number of samples	
	Coorong as a whole[1]	North Lagoon only
Grain size and sorting	166	117
Organic and inorganic Carbon	144	112
Nitrogen	113	67
Gypsum	154	110

[1] The total number analysed varied as a function of the amount of sediment available once the samples were dried, and detection limits for the different tests.

IDW is a deterministic method and calculates the weighted average for each known point in the neighbourhood as the inverse of the distance from the point to be predicted (Longley *et al.* 2002). The number of neighbours, neighbourhood shape, orientation and the form of the weighting function were tested to choose the best parameters for interpolation. A model with a minimum of 5 and a maximum of 10 neighbours in a four-sectored neighbourhood oriented at 45^0 with an optimized power value minimised the root mean square error. The model attempted to use the specified number of data points (minimum 5 and maximum 10 neighbours) from every sector. If five neighbours (the minimum) were not available within each sector, the nearest points outside the sector were also used. The 45^0 orientation of the neighbourhood captured a general trend in the data because of the NW-SE orientation of the lagoon. The power value for distance determined the rate of weight decay for the points in the neighbourhood. Higher power values rapidly reduced the weights of points farther away from the prediction location and vice versa. The optimum power value used in the model was chosen to give the prediction with minimum root mean square error and was automatically determined by the software (Environmental Systems Research Institute 2008).

4.3.4 Goodness of fit of GAM and IDW

A comparison of the goodness of fit of GAM and IDW was performed by evaluating the root mean square errors derived from the difference between predicted and measured values. Equation 2 was used for calculating the root mean square errors for all sediment attributes for the GAM predictions while the values were directly obtained from implementing the IDW model in the ArcGIS.

4.4. Results

4.4.1 Measured sediment attributes

Particle size distribution

Sediments showed a wide range of particle size distributions, which were broadly distributed into three main groups according to the grain size parameters of individual samples (Figures 4.2 and 4.3):

(1) The finest sediments had high sorting and low kurtosis values (n = 36; Figures 4.3a,c) resulting from a mixture of particles of different (albeit small)

size classes. The sediments in this group consisted of muds and muddy sands showing a unimodal or bimodal distribution, with either a fine mode dominated by silts (~18µm) or a coarse mode dominated by fine sands (~187µm) or both (Figure 4.2b). Forty-seven percent of these samples were from deep sediments ≥1 m accumulating in the middle channel of the lagoons, and 36% from intermediate depths of 0.5-1 m. The remaining few samples in this group, or 17% of the total, came from shallow depths along the western (seaward) shores mostly between Noonanema and Parnka Point. These fine sediments were well represented throughout Parnka Point, where 60% of samples fell into this group.

(2) Sediments with intermediate mean grain size and sorting values (n = 53; Figure 4.3a) were predominant between Goolwa and Barker Knoll, historically the estuarine part of the Coorong. Sixty-four percent of all samples falling into this group came from this part of the Coorong (Figure 4.2a). These samples had low skewness and high kurtosis values (Figure 4.3b,c), indicative of a more homogenous group of particles when compared to the fine sediments described above. The sediments in this group were generally sands and muddy sands with a unimodal distribution centred on fine sands (~209µm) (Figure 4.2b).

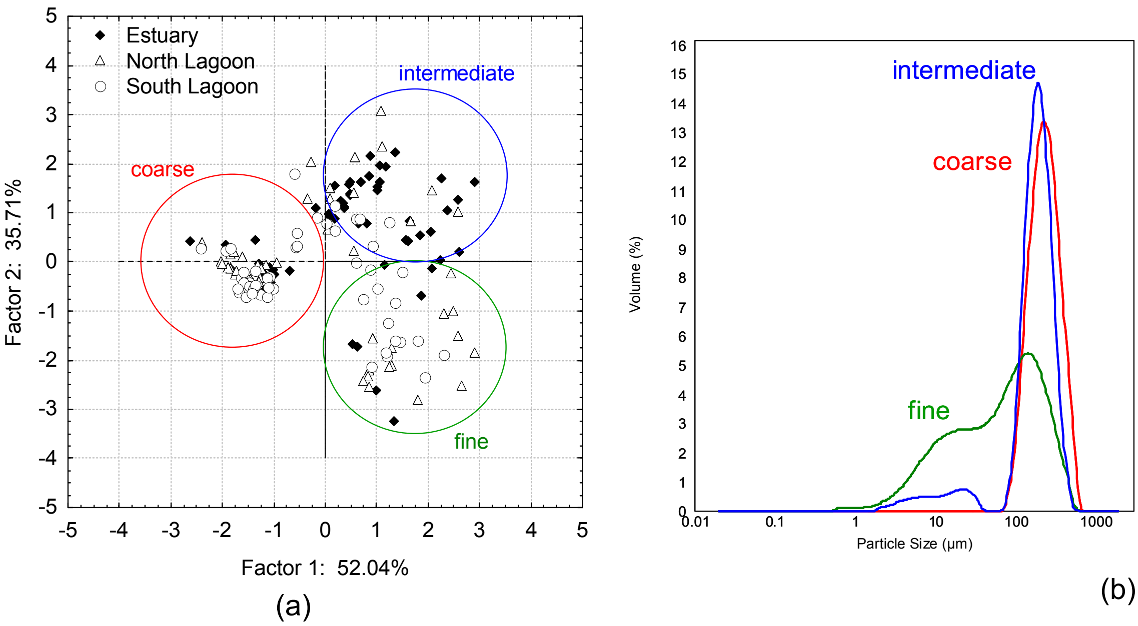


Figure 4.2. Principal Component Analysis (PCA) showing sediments according to mean grain size, sorting, skewness and kurtosis (a), and the typical particle size distribution of each group identified in the PCA (b).

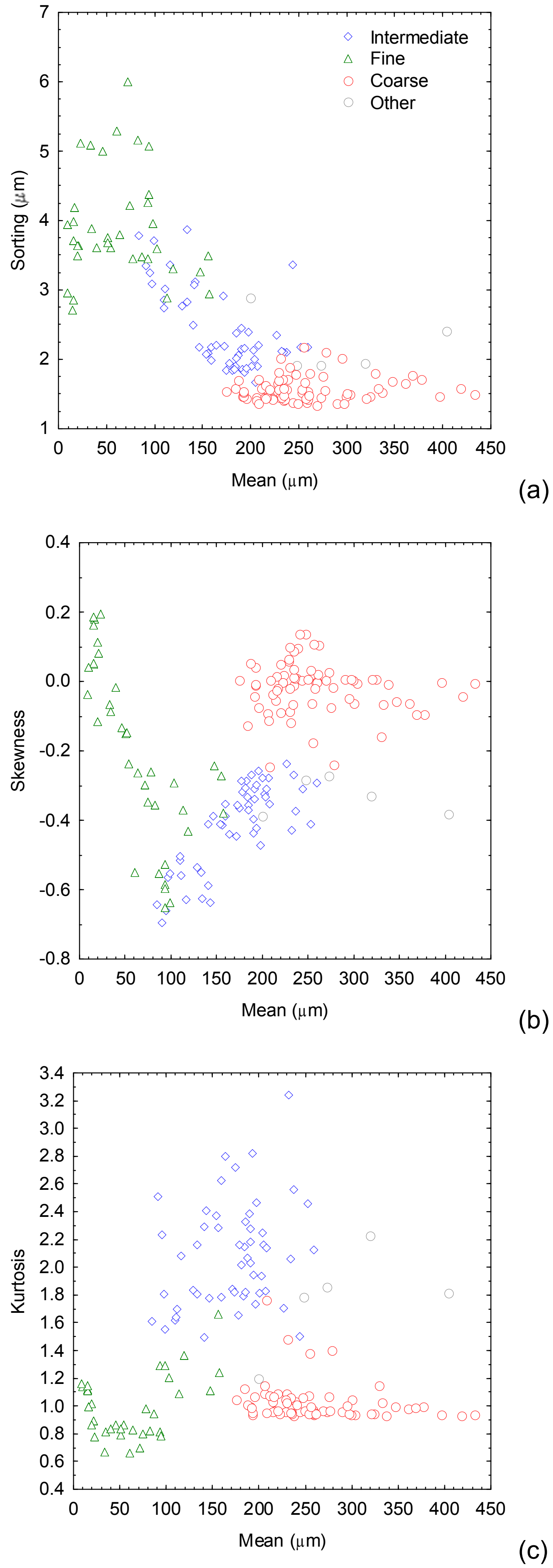
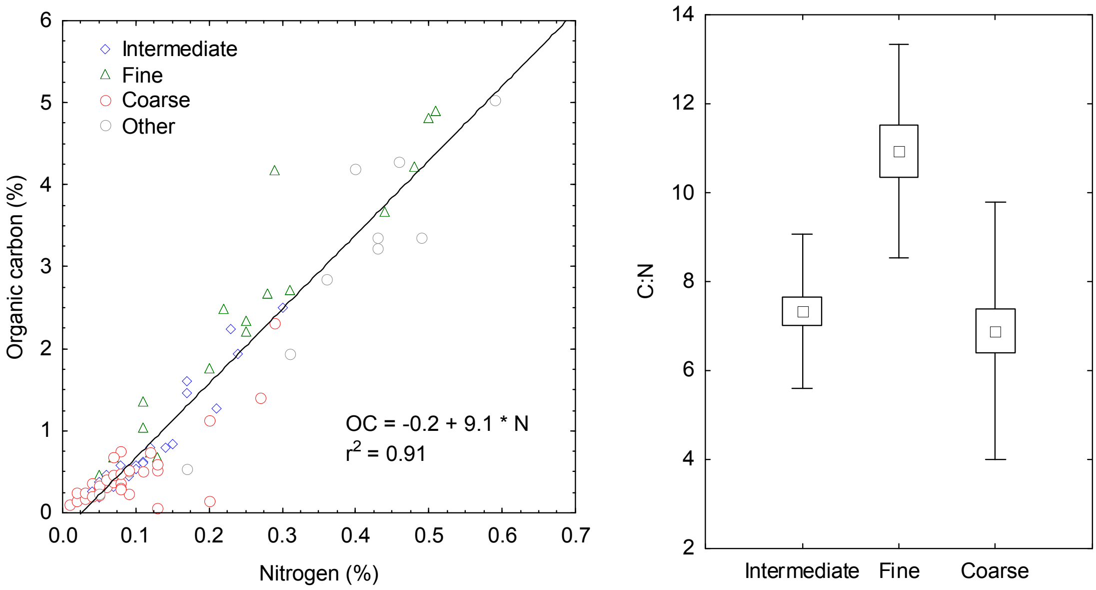


Figure 4.3. Mean vs sorting (a), skewness (b) and kurtosis (c) values according to the sediment groups identified in Figure 4.2. Samples labelled as ‘other’ were not clearly separated by the principal components in Figure 4.2.

(3) The coarsest sediments had low sorting, high skewness and intermediate kurtosis values (n = 72; Figure 4.3) as a consequence of a negligible contribution from fine size classes (Figure 4.2b). Sediments in this group were classified as sands with a unimodal distribution centred on medium sands (~253μm). The particle size distribution characteristic of this group was the most common throughout the Coorong lagoons. These sediments were particularly predominant along the eastern (landward) shores of the North Lagoon, typically found at shallow depths <0.5 m (35%) and intermediate depths of 0.5-1 m (26%). This sediment type was also widespread throughout the South Lagoon.

Organic carbon and total nitrogen

The distribution of organic carbon and total nitrogen content of sediments broadly followed particle size characteristics, with the highest values found in the fine sediments and lowest in the coarse sediments described in the previous section (Figure 4.4a). The results of ANOVA indicate a significant difference between these sediment types for both organic carbon ($F_{2,133}$=63.252, P<0.001) and total nitrogen ($F_{2,99}$=49.504, P<0.001). The slope of the linear regression between these variables suggests C:N molar ratios between 10 (when the intercept is set to zero) and 11 (Figure 4a), suggesting an important planktonic or bacterial component to sedimentary organic matter (Ruttenberg and Goni, 1997). Fine sediments had significantly higher C:N ratios than the other sediment types (Figure 4b; ANOVA $F_{2,78}$=17.293, P<0.001). There were 162 samples analysed for organic carbon. Of these, 11 samples showed inconsistently high organic carbon results when compared to total carbon, leading to the calculation of negative inorganic carbon values; these samples were excluded from the dataset.



(a) (b)

Figure 4.4. Organic carbon vs nitrogen content of sediments according to the particle size groups identified in Figures 4.2 and 4.3 (a), and C:N molar ratios for the same groups (b). Values in (b) are the mean, boxes represent standard error and bars standard deviation. Samples labelled as 'other' were either not analysed for particle size, or were not clearly separated by the principal components in Figure 4.2.

Inorganic carbon and gypsum

The results of ANOVA indicate a significance difference in inorganic carbon values ($F_{2,148}$= 83.132, P=<0.001) and gypsum ($F_{2,154}$=31.609, P<0.001) between the estuary, North and South Lagoons. Inorganic carbon values were lowest in the North Lagoon and peaked in the South Lagoon, with intermediate values in the estuary (Figure 4.5a). In the estuary, the highest inorganic carbon values were associated with coarse sediments. Gypsum values also increased along the salinity gradient, with the highest (and most variable) values recorded in the South Lagoon (Figure 5b). Gypsum was significantly enriched in fine sediments (ANOVA $F_{2,139}$=14.969, P<0.001).

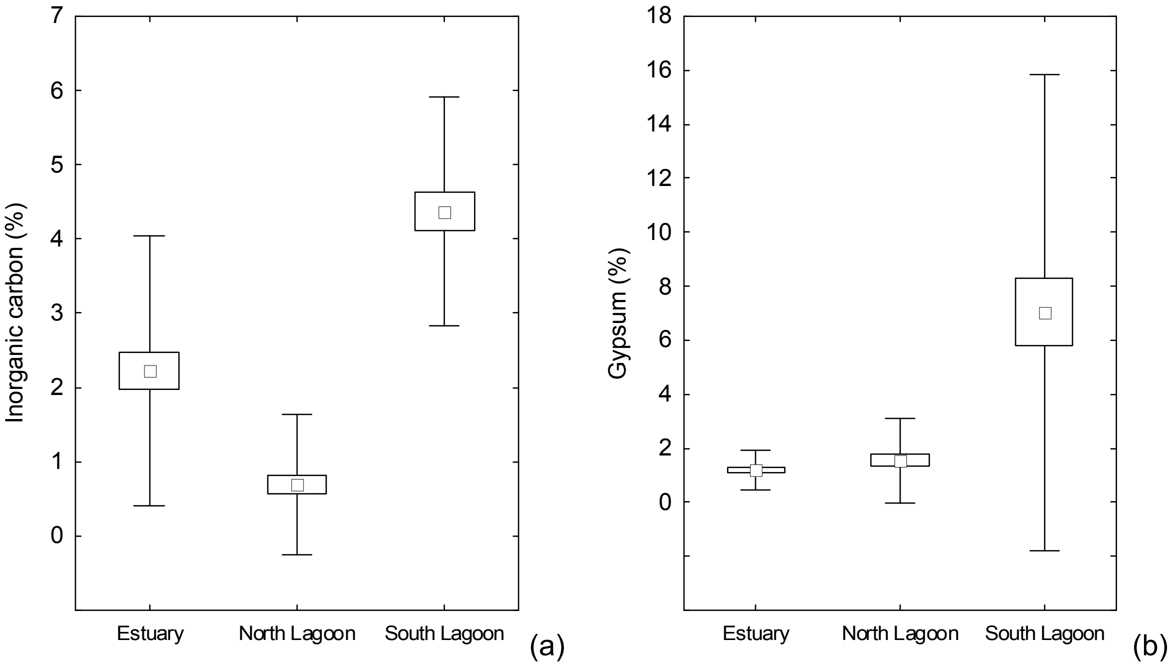


Figure 4.5. The content of inorganic carbon (a) and gypsum (b) in sediments of the estuary (n=55), North Lagoon (n=59) and South Lagoon (n=49). Values are reported as the mean, boxes represent standard error and bars standard deviation.

4.4.2 GAM for North Lagoon

Mean grain size

The model with six-variables met the stopping criterion and stood as the final model for mean grain size. Table 4.3 summarizes all the models tested, their variance statistics, and prediction errors. The global model with all 10 predictor variables had an adjusted R^2 of 0.462 and a GCV score of 5874.8. The Northing and distance to the eastern shore explained almost equal variability of 15% each. Depth was the third most important variable and contributed 8.1% variability while the fourth variable, distance to the western shore, explained slightly above 9%. The fifth and sixth variables, slope and aspect contributed 6.4% and 3.4%, respectively. Forward selection identified the “best” model as having six predictor variables (distance to the eastern shore, depth, slope, northing, distance to the western shore and aspect).

This model had a lower cross validation score (GCV) and higher adjusted R^2 of 0.474 than the global model. The analysis of variance did not show a significant difference between the six-variable model and the global model. The prediction error measured by the root mean square value improved with the addition of each new variable into the model. The final model had the best prediction of mean grain size, as indicated by the lowest root mean square error, even lower than the global model. The six-variable model was considered to be the best model for predicting mean grain size distribution in the North Lagoon.

Table 4.3. Forward selection models for mean grain size: summary of model parameters, variance statistics and prediction error.

Model Name	Variable added[1]	GCV[3] score	Adjusted R-Square	Variance explained (%)	Root Mean Square Error
Model 1	east_dist	8004.7	0.116	15.0	85.32
Model 2	depth	7273.5	0.199	23.1	81.19
Model 3	northing	6391.2	0.329	38.6	72.54
Model 4	west_dist	5989.7	0.401	47.9	66.82
Model 5	slope	5760.6	0.451	54.3	62.55
Model 6	aspect	5781.1	0.474	57.7	60.18
Model 7[2]	All	5874.8	0.462	57.0	62.71

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is east_dist, model 2 is east_dist + depth, etc). east_dist = Distance to the eastern shore, west_dist = Distance to the western shore, [2]Global model with all 10 predictor variables; [3]GCV = Generalized Cross-Validation.

The relationship between mean grain size and the explanatory variables in the six-variable model is illustrated in Figure 4.6. Sediment becomes finer to about 500 m distance to the eastern and western shores (Figure 6a and 6d) and with depth (Figure 4.6b). The Northing had a complex influence on sediment grain size (Figure 4.6c). As slope increased to approximately 3.5 degrees, sediments became finer, whereas further increases in the slope resulted in sediments becoming coarser (Figure 4.6e). Aspect had no clear effect on grain size (Figure 4.6f).

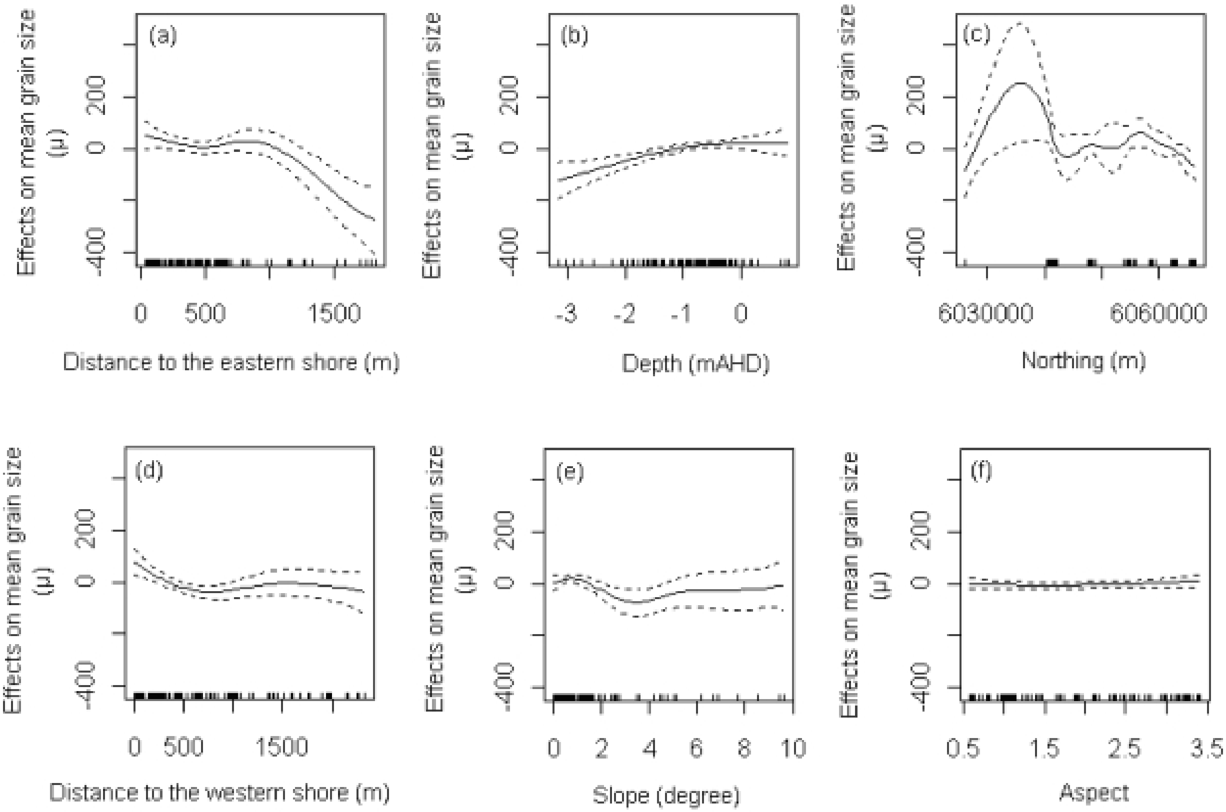


Figure 4.6. Response curves for predictor variables and mean grain size for the final six-variable model for the North Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Sorting

A global model with all 10 predictor variables was implemented for sorting, a measure of the spread of sizes around mean grain size. A five-variable model (depth, distance to the eastern shore, easting, northing and slope) slightly exceeded the adjusted R^2 of 0.353 for the global model (Table 4.4). Depth alone explained about 30% of the variability, followed by distance to the eastern shore, which accounted for nearly 6% of the variability. Northing explained about 5%, Easting ~ 3% and slope <2% of the variabilityin mean grain size. This model also had the lowest GCV score of all the models, and was considered the best model by the forward selection method.

Analysis of variance indicated no significant difference between the final model and the global model. Compared to its precursor models, the final model with five predictor variables had the closest root mean square error of 0.773 to the global model with error of 0.759. The best predictive power was found for the model with five-predictor variables. Thus, this model was selected for predicting the distribution of sorting values in the North Lagoon.

Table 4.4. Forward selection models for sorting: summary of model parameters, variance statistics and prediction error.

Model Name	Variable added[1]	GCV score[3]	Adjusted R-Square	Variance explained %	Root Mean Square Error
Model 1	depth	0.902	0.243	29.9	0.872
Model 2	east_dist	0.859	0.292	35.6	0.836
Model 3	easting	0.836	0.318	38.5	0.816
Model 4	northing	0.830	0.346	43.2	0.785
Model 5	slope	0.824	0.359	44.9	0.773
Model 6[2]	All	0.870	0.353	46.9	0.759

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is depth, model 2 is depth + east_dist, etc). east_dist = Distance to the eastern shore; [2]Global model with all 10 predictor variables; [3]GCV = Generalized Cross-Validation.

The relationship between sorting and the explanatory variables in the final five-variable model (Model 5) is illustrated in Figure 4.7. Sediments were increasingly poorly sorted (high values) with depth (Figure 4.7a), distance to the eastern shore (Figure 4.7b) and slope (Figure 4.7e). The sorting value also increased with both Easting (moving from the west to east) and Northing (moving from the south to the north), but the confidence intervals were large (Figures 4.7c,d).

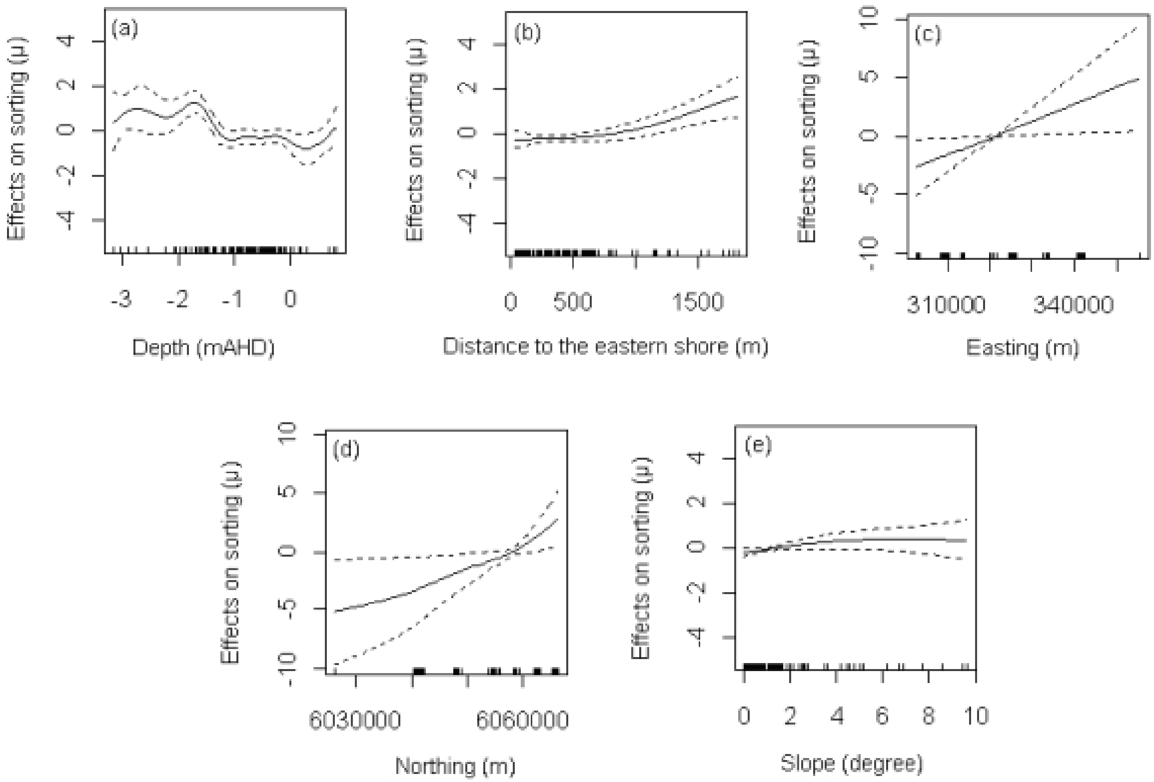


Figure 4.7. Relationship between the explanatory variables and sorting for the final five-variable model of the North Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Organic carbon

A global model was run with all 10 predictor variables against sediment organic carbon content. A summary of the model parameters, variance statistics and prediction error is presented in Table 4.5. A three-variable model including depth, slope and northing exceeded the global adjusted R^2 of 0.529, making it the best model found by the forward selection method. The first variable, depth, explained much of the variability (44.7%) while the second and third variables, northing and slope contributed 9.6% and 7.5% respectively. The rest of the variables explained only 2.4% of the variability in total. This model also had a better GCV score than the global model. The analysis of deviance did not show a significant difference between these two models. The three-variable model identified by forward selection also had the best goodness of fit due to the prediction error being very close to the model with all predictor variables (Model 4). Thus, this model was selected for predicting organic carbon distribution in the North Lagoon.

Table 4.5. Forward selection models for organic carbon: summary of model parameters, variance statistics and prediction error.

Model Name	Variable added[1]	GCV score[3]	Adjusted R-Square	Variance explained %	Root Mean Square Error
Model 1	depth	0.548	0.401	44.7	0.68
Model 2	northing	0.5063	0.477	54.3	0.62
Model 3	slope	0.483	0.533	61.8	0.56
Model 4[2]	All	0.517	0.532	64.2	0.55

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is depth, model 2 is depth + slope, etc). [2]Global model with all 10 predictor variables; [3]GCV = Generalized Cross-Validation.

The relationship between organic carbon and each of the predictor variables in the final three-variable model is shown in Figure 4.8. Depth and slope show a cubic and largely quadratic (except for large values where data are sparse) relationship with organic carbon, respectively (Figures 4.8a,b). The highest organic carbon was predicted at depths of about -2.9 m and the lowest at +0.17m (Figure 4.8a). The northing shows a complex effect on organic carbon distribution in the North Lagoon (Figure 4.8b).

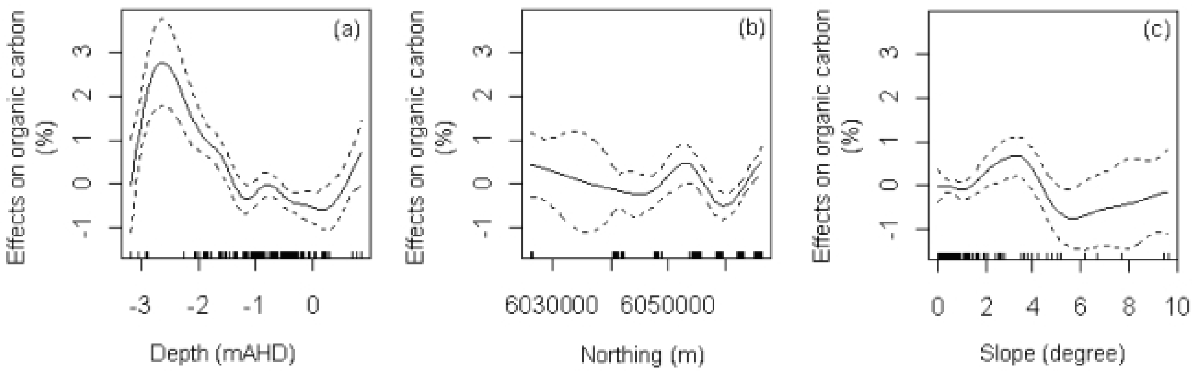


Figure 4.8. Relationship between the explanatory variables and organic carbon for the model with three variables in the North Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Total nitrogen

A global model with 7 variables was run against total nitrogen content. Table 4.6 presents a summary of the models tested with the forward selection method. Forward selection identified the “best” model as having five-variables (depth, slope, distance to the nearest shore, distance to the western shore, and distance to the eastern shore). The first variable, depth, alone explained 44.7% of the variance and the subsequent three variables each added slightly more than 5%. The fifth variable (distance to the eastern shore) explained a very low proportion of the variance (< 2 %). This model had the lowest GCV score and a higher adjusted R^2 than the global model. However, the difference between these two models was not statistically significant.

Table 4.6. Forward selection models for nitrogen: summary of model parameters, variance statistics and prediction error.

Model Name	**Variable added**[1]	**GCV score**[3]	**Adjusted R-Square**	**Variance explained %**	**Root Mean Square Error**
Model 1	depth	0.019	0.388	44.7	0.1584
Model 2	slope	0.0198	0.417	49.9	0.1576
Model 3	near_dist	0.0204	0.441	55.2	0.1569
Model 4	west_dist	0.02009	0.484	61.1	0.1623
Model 5	east_dist	0.01965	0.502	63.0	0.1623
Model 6[2]	All	0.0219	0.497	64.5	0.1607

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is depth, model 2 is depth + slope, etc). near_dist = Distance to the nearest shore, west_shore = Distance to the western shore and east_dist = Distance to the eastern shore; [2]Global model with all 7 predictor variables; [3]GCV = Generalized Cross-Validation.

Although the forward selection method found a five-variable model to be the best model, the prediction error was slightly higher than the three-variable model with depth, slope and distance to the nearest shore (Model 3). The single variable model (Model 1) with depth as the only predictor variable also had lower prediction error than the global model. Based on the lowest prediction error, the three-variable model was selected for predicting nitrogen distribution in the North Lagoon.

The highest nitrogen content occurred at about -2.50 m, and lowest at -1.0 m (Figure 4.9a). Nitrogen content was highest when the slope was zero and lowest when it was ~ 2^o (Figure 4.9b). High nitrogen content was also found at distances > 500 m from the nearest shore.

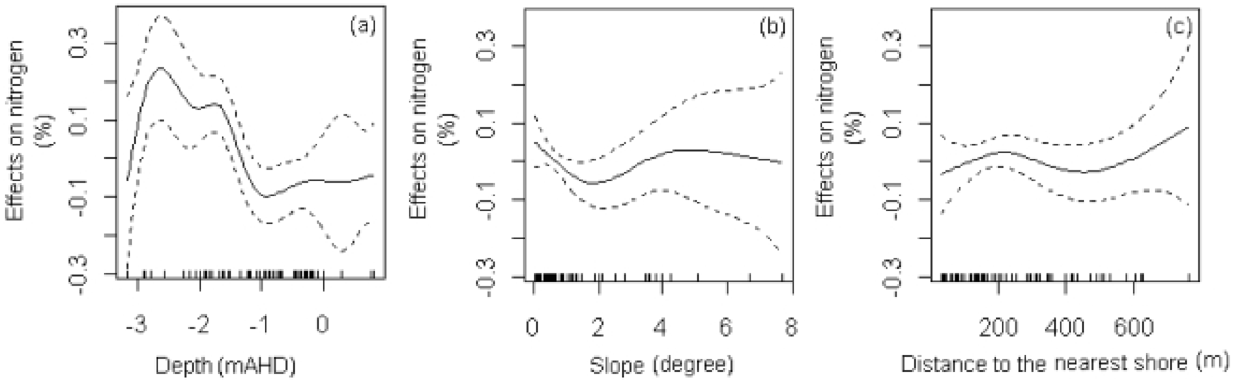


Figure 4.9. Relationship between three explanatory variables and nitrogen content in the North Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Inorganic carbon

The global model with all 10 predictors had an adjusted R^2 of 0.634. Forward selection identified the “best” model as having four variables (northing, salinity, distance to the nearest shore and distance to the western shore – see Table 4.7). The northing and salinity explained 45 % and 13.9 % of the variability, respectively, whereas the additional variables in Models 3 and 4 explained 7.1% and 4.3% of the variability. This four-variable model had both a GCV score and adjusted R^2 close to that of the global model (Table 4.7). The analysis of deviance did not show a significant difference between these two models.

Table 4.7. Forward selection models for inorganic carbon: summary of model parameters, variance statistics and prediction error.

Model Name	Variable added[1]	GCV score[3]	Adjusted R-Square	Variance explained %	Root Mean Square Error
Model 1	northing	1.63	0.412	45	1.19
Model 2	salinity	1.41	0.528	58.9	1.03
Model 3	near_dist	1.35	0.579	66.0	0.93
Model 4	west_dist	1.21	0.627	70.3	0.87
Model 7[2]	All	1.19	0.634	70.8	0.86

[1]The variable name in this column indicates the new variable added to the previous model (e.g. model 1 is northing, model 2 is northing + salinity, etc). near_dist = Distance to the nearest shore and west_shore = Distance to the western shore; [2]Global model with all 10 predictor variables; [3]GCV = Generalized Cross-Validation.

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Although Northing and salinity explained much of variability in the sample data, the model with only these two variables had a prediction error higher than the four-variable model, which had the lowest prediction error, close to the global model. Hence, the four-variable model was chosen for predicting the distribution of inorganic carbon in the North Lagoon.

Inorganic carbon content had a very complex relationship with both Northing and salinity (Figures 4.10a,b), but decreased with distance to the nearest shore (Figure 4.10c). The inorganic carbon content gradually increased up to about 250 m from the western shore and then decreased (Figure 4.10d)

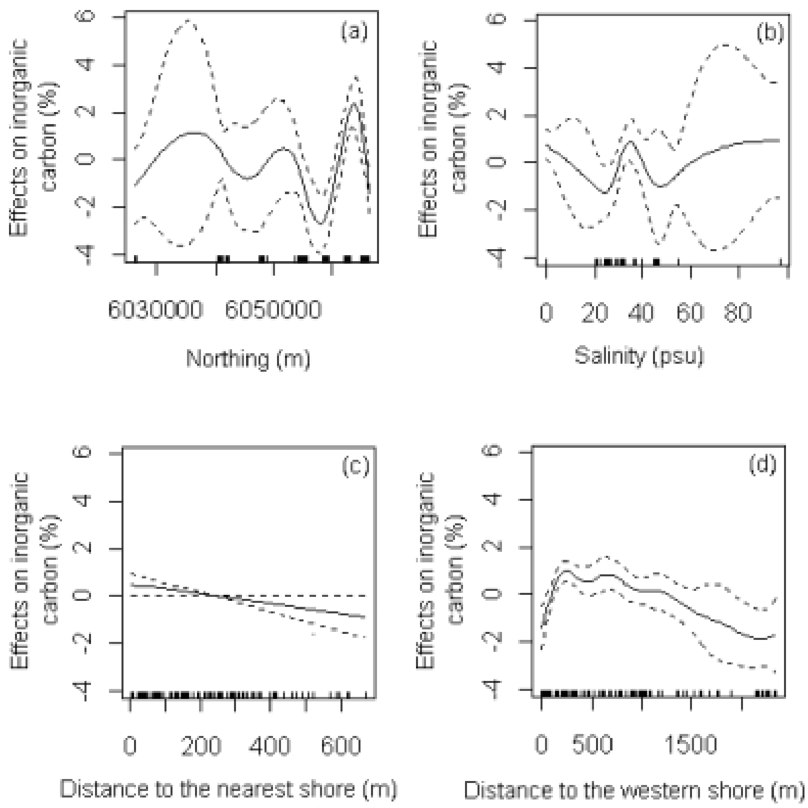

Figure 4.10. Relationship between predictor variables and inorganic carbon content in the North Lagoon. The solid line is the smooth function of the explanatory variable, while the dashed lines indicate the 95% confidence region.

Gypsum

For gypsum distribution, the global model had an adjusted R^2 of 0.195 and explained only about 33 % of the deviance. As there is a very low correlation between the predictors and gypsum distribution in the North Lagoon, a distribution map for gypsum has not been generated. These results mainly reflect the low gypsum content in the North Lagoon, mostly below the quantification limit of 2% for the analytical method.

4.4.3 Spatial maps for the North Lagoon and the Coorong

Particle size distribution

Sediment maps derived from GAM depicted general trends for mean grain size and sorting distribution in the North Lagoon (Figures 4.11a,b). Fine sediments (< 100 μm; see Figure 4.3) occupied the deep channel (below -2.0 mAHD) along the North Lagoon and some areas on the western shore. Intermediate sediments (100 - 200 μm; see Figure 4.3) were mostly found in the areas adjacent to the deep channel and predominated between Mark Point and Noonameena. Areas around the Murray Mouth and adjacent to the eastern (landward) shores were mostly coarse sand (> 200 μm; see Figure 4.3) except for the north of the Murray Mouth.

Poor sorting values (> 3 μm) were mostly associated with fine and intermediate sediments, while areas with coarse sand had better sorting (< 2 μm). Sediments on the eastern (landward) shore were coarse and well sorted, whereas sediments adjacent to the western (seaward) shore were fine to intermediate and poorly sorted.

Maps for mean grain size and sorting distribution for the entire Coorong generated by the IDW method are presented in Figure 4.12. The distribution of both sediment attributes is overly generalized and variability in the sample data is not reflected in these maps. Intermediate sediments dominate overall, while coarse sediments are found at the Murray Mouth region, areas between Pelican Point and Long Point and to the south of Villa dei Yumpa (Figure 4.12a). In these maps, sediments have mostly intermediate sorting (2-3 μm). The coarse sediments in the Murray Mouth, in the small area to the north of Noonameena (on the eastern shore) and south of Villa dei Yumpa, all have good sorting (< 2 μm). However, coarse sediments between Pelican Point and Long Point have intermediate sorting values (2-3 μm) and a patch to the north of Noonameena (on the western shore) and about 13 km to the north of Parnka Point had poor sorting values (> 3 μm) (Figure 4.12b).

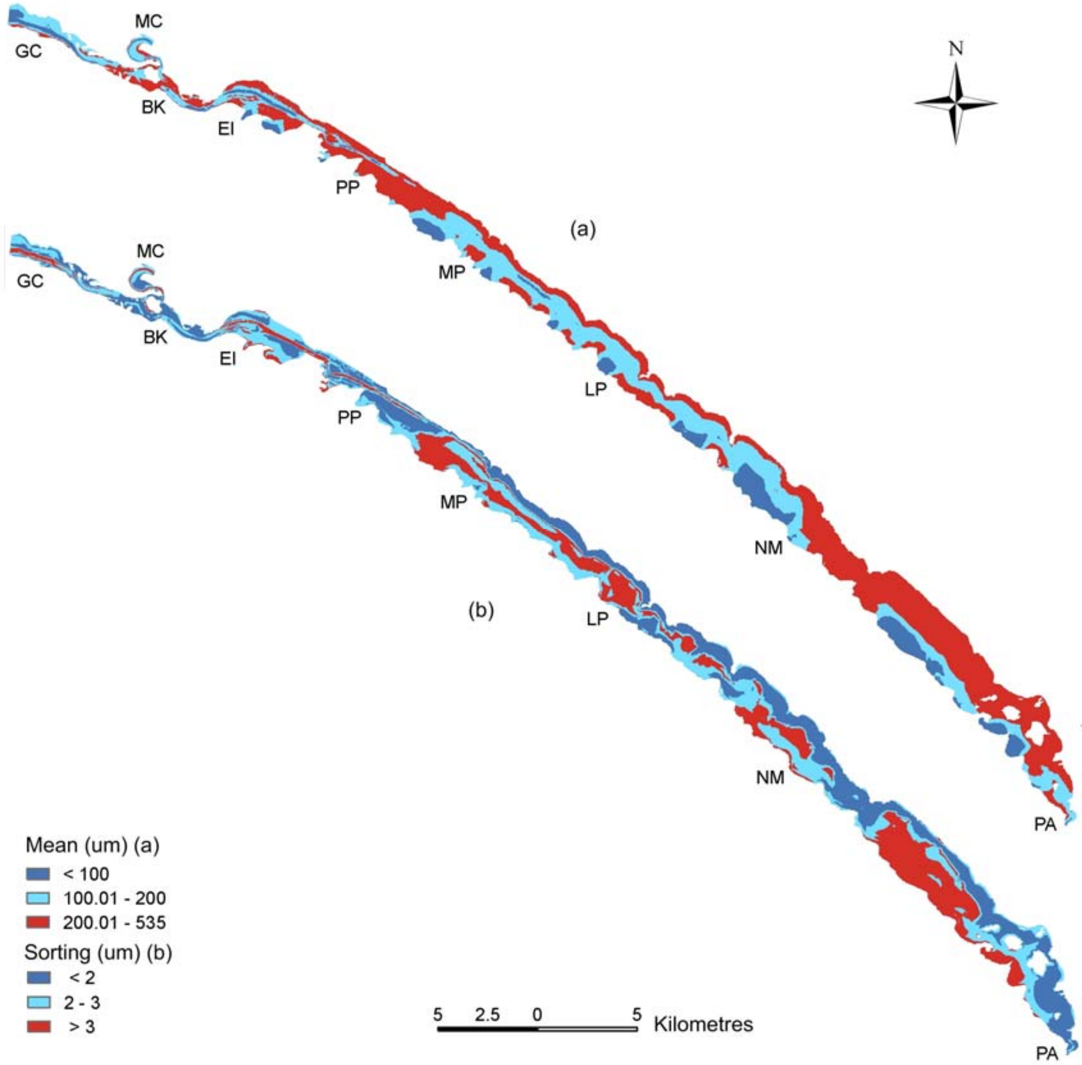

Figure 4.11. Mean (μm) (a) and Sorting (μm) (b) distribution in the North Lagoon derived from the generalized additive model. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena and PA = Parnka Point. The sediment classes for the mean and sorting were approximately defined based on the sediment groupings in Figure 4.2)

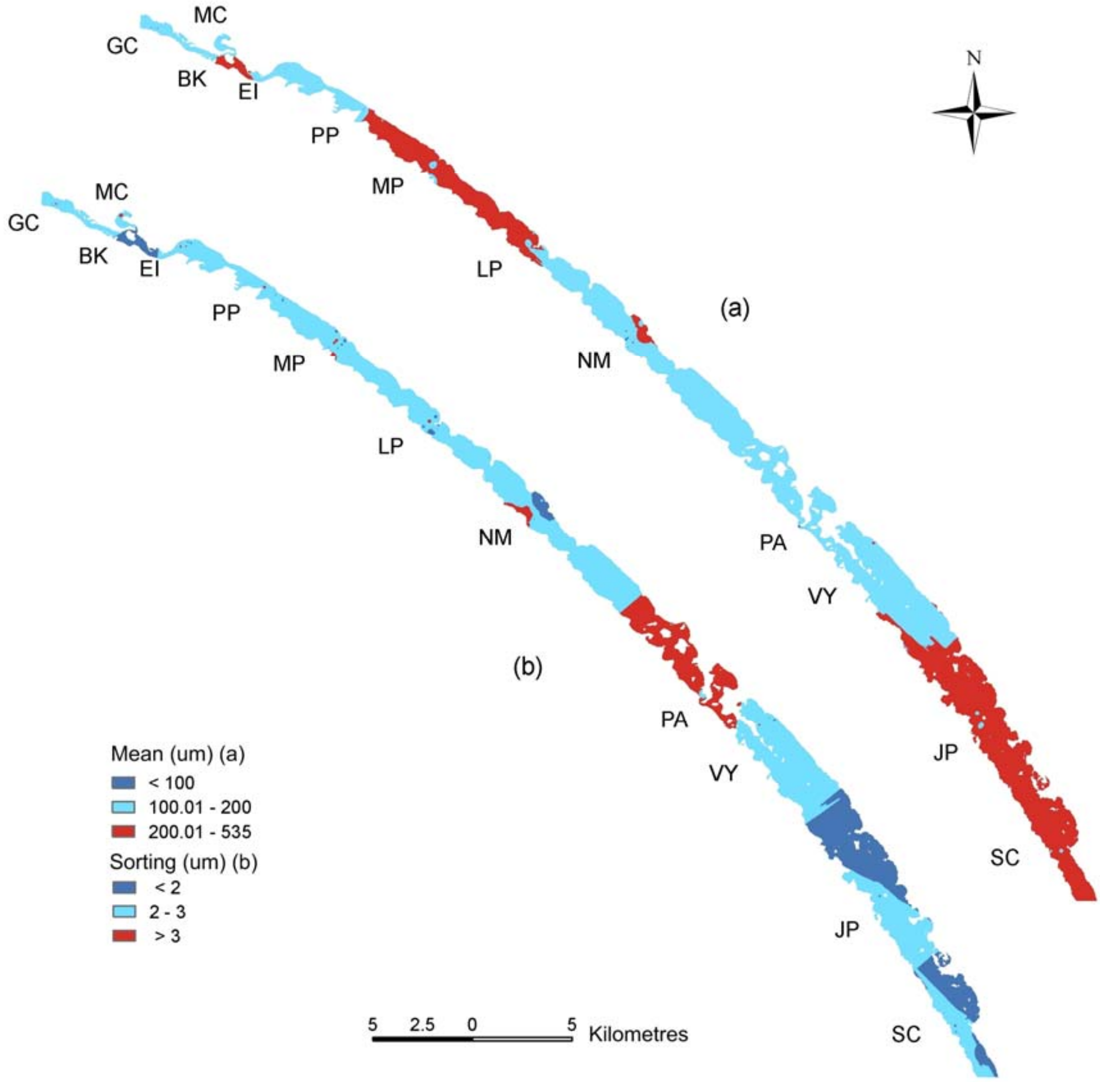

Figure 4.12. Mean (µm) (a) and Sorting (µm) (b) distribution in the entire Coorong derived by the inverse distance weighting method. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa; JP = Jack Point and SC = Salt Creek. The sediment classes for the mean and sorting were approximately defined based on the sediment groupings in Figure 4.2)

Organic carbon and total nitrogen

The distribution of organic carbon and total nitrogen content of sediments are broadly consistent with the sediment size distribution in the North Lagoon (Figure 4.13). High values of organic carbon (> 2 %) and total nitrogen (> 0.3 %) were generally associated with fine and intermediate sediments and low values with the coarse sediments. The deep channel to the north of Ewe Island had mostly fine and intermediate sediments, high organic carbon and total nitrogen contents. Coarse sandy areas around the Murray Mouth had low organic carbon (< 1 %) but medium total nitrogen content (0.11 - 0.3 %).

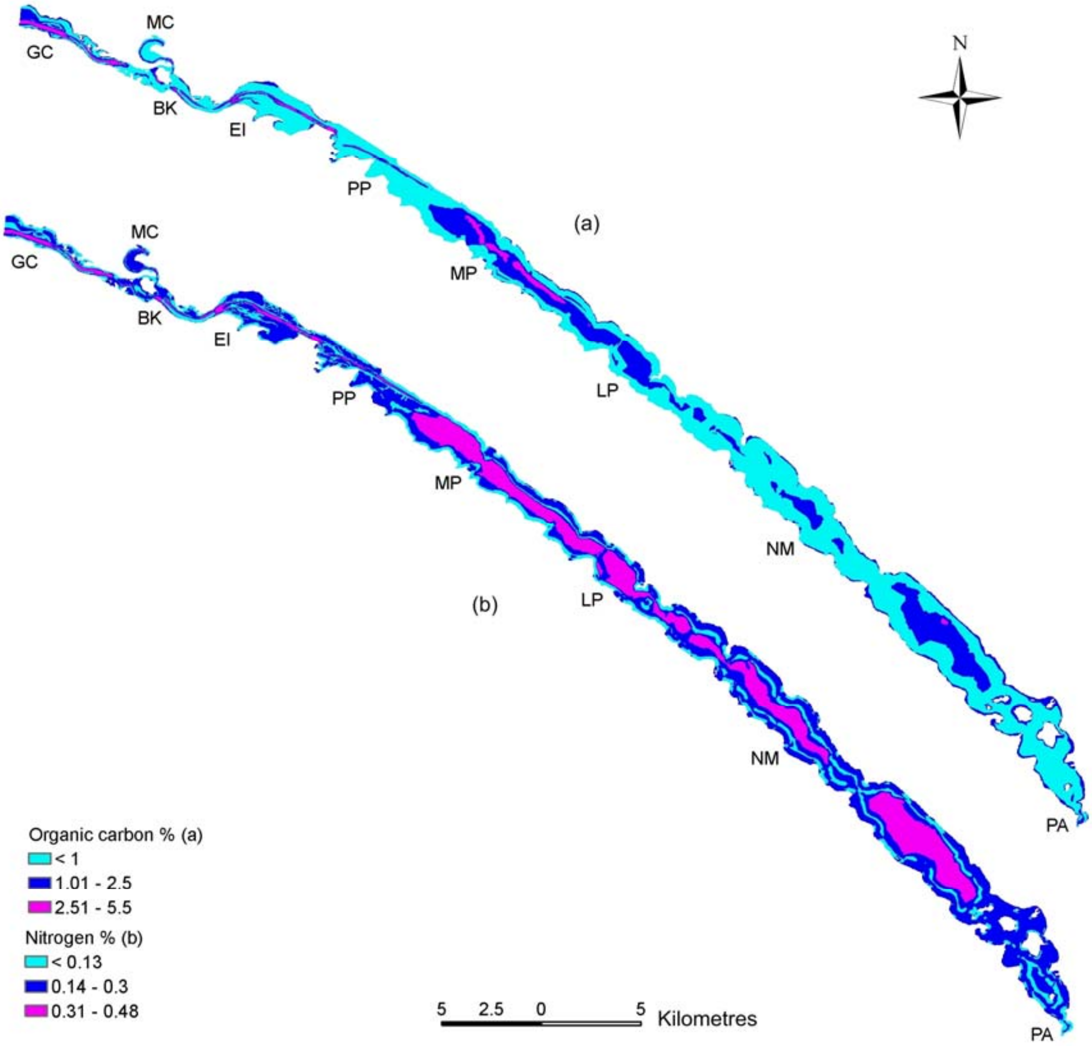

Figure 4.13. Organic carbon % (a) and total nitrogen % (b) distribution in the North Lagoon derived by the generalized additive model. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena and PA = Parnka Point. The classes for the organic carbon and nitrogen were approximately defined based on the sediment groupings in Figure 4.4).

The map generated by IDW for the whole Coorong predicts low organic carbon content (<0.1 %) for both the North and South Lagoons, regardless of particle size distribution. However, small patches of medium organic carbon content are evident at some reference sites (Figure 4.14a). The map generated for total nitrogen content predicts medium values (0.11 - 0.3 %) for the entire Coorong except for the areas about 10 km to the north and 6 km to the south of Parnka Point (Figure 4.14b)

As in the particle size maps (Figure 4.12), the local influence of the sample data is not clearly visible in organic carbon and total nitrogen maps (Figure 4.14), however, it is seen in high resolution maps of the reference sites.

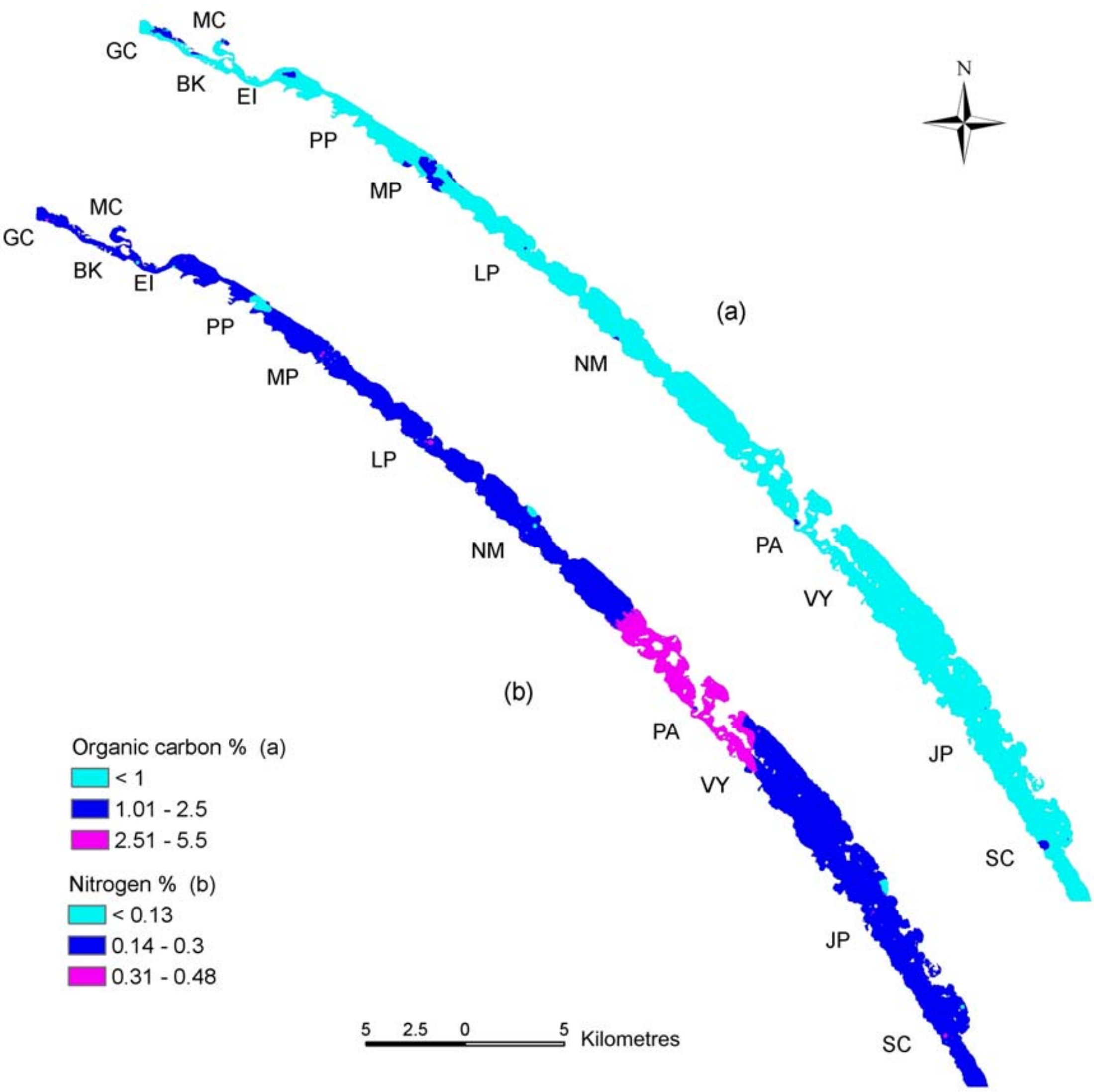

Figure 4.14. Organic carbon (a) and total nitrogen content (b) distribution in the Coorong derived by the inverse distance weighting method. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa; JP = Jack Point and SC = Salt Creek. The classes for the organic carbon and nitrogen were approximately defined based on the sediment groupings in Figure 4.4).

Inorganic carbon and gypsum

High inorganic carbon content (> 3 %) was observed in the Murray Mouth region and between Noonameena and Parnka Point, predominantly along the western shore. Sediments with low inorganic carbon content (< 1%) were more likely to appear between Ewe Island and Mark Point, whereas patches of low inorganic carbon also existed at Goolwa Channel, Mundoo Channel, Ewe Island and to the north of Noonameena. The area between Mark Point and Noonameena and to the north of Parnka Point along the eastern shore showed medium inorganic carbon content (1 - 3 %) (Figure 4.15).

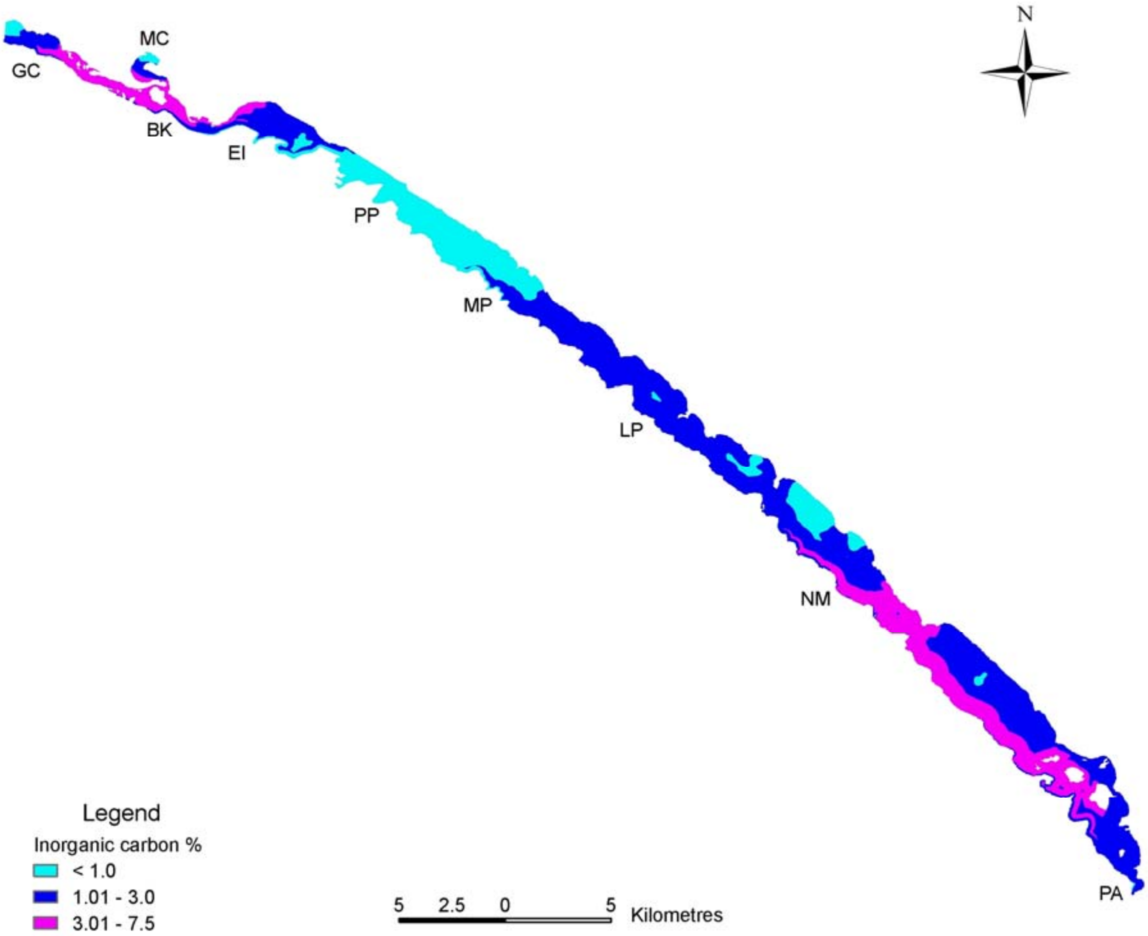

Figure 4.15. Inorganic carbon % distribution in the North Lagoon derived by the generalized additive model. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena and PA = Parnka Point. The classes for the inorganic carbon were approximately defined based on the sediment groupings in Figure 4.5).

In the maps of the whole Coorong, the South Lagoon is predicted to have high inorganic carbon content while the North Lagoon shows medium inorganic carbon between Parnka Point and Noonameena, around Ewe Island, Goolwa Channel and Mundoo Channel. Sediments between Noonameena and Pelican Point and a patch at Goolwa Channel had low inorganic carbon content (Figure 4.16a).

The prediction map for gypsum content in the whole Coorong is shown in Figure 4.16b. About half of the Coorong had high gypsum content (> 3 %) to the south of Noonameena and the other half had medium (2.01 - 3 %) or low (< 2%) gypsum content (Figure 4.16b).

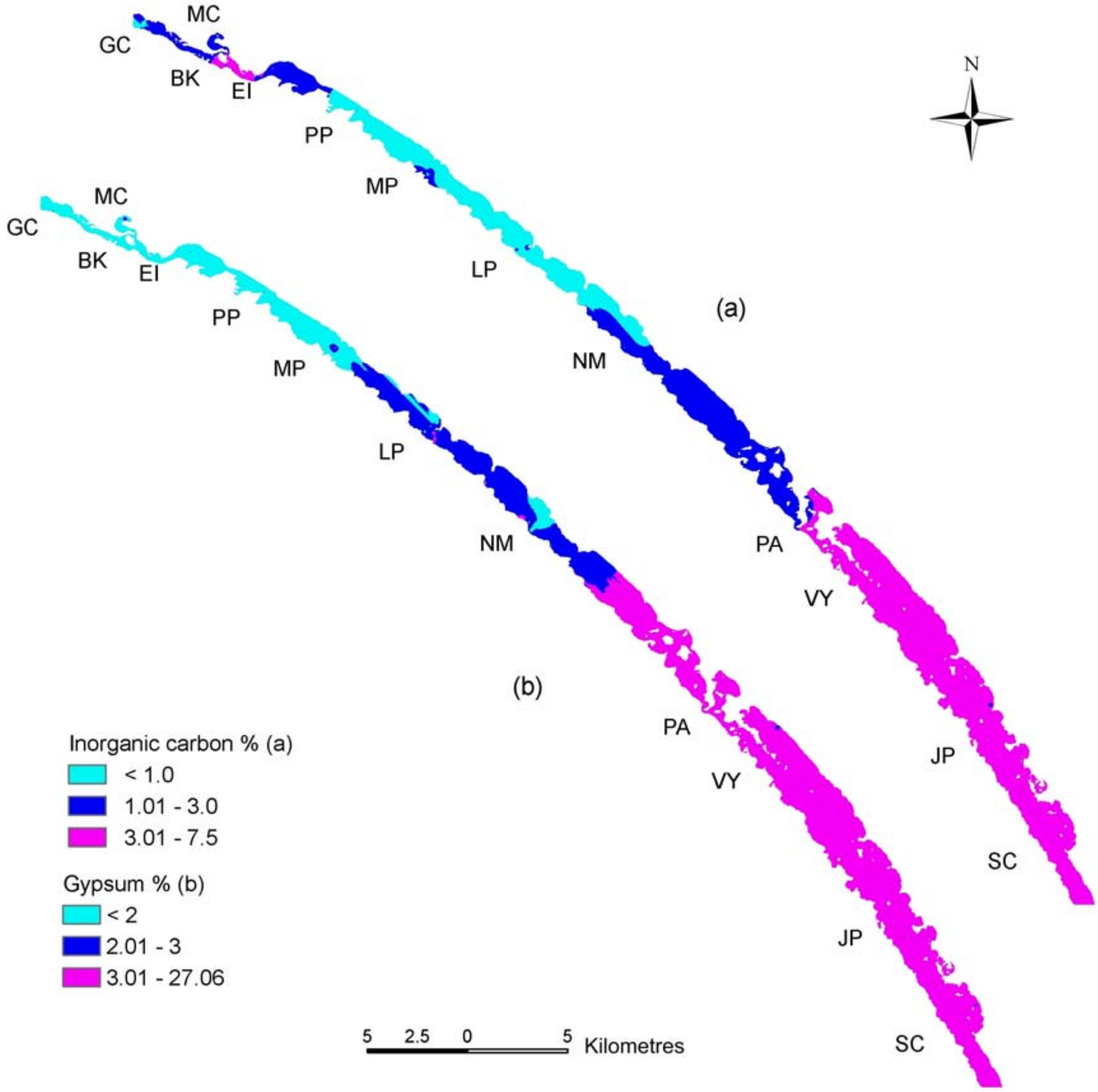

Figure 4.16. Inorganic carbon % (a) and Gypsum % (b) distribution in the Coorong derived by the inverse distance weighting method. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa; JP = Jack Point and SC = Salt Creek. The classes for the inorganic carbon and gypsum were approximately defined based on the sediment groupings in Figure 4.5).

4.4.4 Goodness of fit of GAM and IDW models

The goodness of fit of the GAM and IDW models was assessed by comparing the root mean square errors derived from the differences between predicted and measured values. Based on this parameter, GAM performed better than IDW for predicting mean grain size, sorting, organic carbon, nitrogen and inorganic carbon in the North Lagoon (Table 4.8).

Table 4.8. Comparison of root mean square values for the GAM and IDW models.

Parameters	Root Mean Square Error by GAM	Root Mean Square Error by IDW
Mean grain size	62.6	85.93
Sorting	0.76	1.1
Organic carbon	0.56	0.96
Total nitrogen	0.158	0.197
Inorganic carbon	0.77	0.99

4.5. Discussion

Our results suggest three main depositional areas along the Coorong, where sediments are fine and organically-enriched: (1) the middle channel of the lagoons; (2) the constriction between the North and South lagoons known as Parnka Point; and (3) the western (seaward) shores of the North Lagoon, particularly south of Long Point. The sediments accumulating in these areas have higher C:N ratios, suggesting that these fine sediments are partially derived from terrestrial runoff or riverine inputs (Ruttenberg and Goñi 1997). Deposition is likely driven by reduced wave action and minimal sediment resuspension as a consequence of depth (middle channel), low flows (Parnka Point), or protection from prevailing winds by the dune system (western shores) (Webster 2005). While at deeper sites this accumulation of organic matter might lead to patchy anaerobic conditions detrimental to the survival of fauna (e.g. invertebrates) (Fernandes and Tanner 2009), shallower depositional areas might constitute important feeding grounds for higher trophic levels (e.g. fish and birds) (Geddes and Francis 2008; Rossi 2003; Bachelet *et al.* 1996). The high salinities recorded at sites south of Long Point, however, are likely to shift secondary production towards microbes, negating the ecological potential of these fine-grained sediments (Rizzo *et al.* 1996). Further north, many of the depositional areas would also have limited value as feeding grounds for wading birds because depth would push them out of the foraging depth range for these animals.

The composition and size of sediments in the estuarine part of the Coorong suggests some accumulation of fines, albeit at much lower rates when compared to the depositional areas described above. Strong flooding tidal currents potentially act to transport coarse coastal sands into the mouth and estuary, and reduce the deposition of fines (Webster 2005; 2006). The areas with the strongest erosional character along the Coorong lagoons, where deposition is less likely to occur, are typically found at shallower depths on landward shores. These sites are more exposed to the prevailing south-southwesterly winds (Bone 1990), resulting in the winnowing out of fine organic-rich sediment fractions by wind-driven wave action.

The impact of the salinity gradient on sediment composition is clearly reflected in the spatial distribution of inorganic carbon and gypsum. While coarse calcareous sands from coastal waters are likely the cause for slightly higher inorganic carbon values in the estuary when compared to the North Lagoon (Li *et al.* 1996), the extremely high inorganic carbon values in the South Lagoon are indications of the precipitation of carbonate at high salinities (Ford 2007). This hypothesis is corroborated by the precipitation of gypsum in the same area, a product typical of evaporitic basins (Caumette *et al.* 1994). The precipitation of inorganic minerals in the salinity gradient is potentially large enough to explain some of the discrepancies found in the analysis of organic carbon. A significant fraction of the precipitated inorganic minerals are likely lost during the acid washing step of sample treatment, leading to unreasonably high organic carbon results and negative inorganic carbon values.

Between the two methods used to map sediment attributes in the Coorong, GAM demonstrated better goodness of fit based on the root mean square error when compared to IDW. However, the aim of this study was to produce sediment maps from the sample data, hence the best method would be the one which produces better spatial prediction of sediment attributes. As a consequence, the sediment maps derived from both methods were further evaluated to scrutinize the spatial prediction ability of these two methods (Leecaster 2003; Isasks and Srivastava 1989). GAM depicted a clear pattern for particle size (mean and sorting), organic and inorganic carbon, and total nitrogen distribution in line with the selected variables in the final models. Depth (bathymetry) was one of the highly significant variables for predicting all sediment attributes except for inorganic carbon. This finding is consistent with the deposition of fine and organic-rich sediments along the deep channel, leaving coarse organic-depleted sediments to accumulate on flat shores. In contrast, inorganic carbon content was mostly a function of position along the salinity gradient.

IDW maps were highly generalized and did not show a specific trend or pattern at the local level despite huge variations in the sample data across the Lagoon. These maps also suffered from the inherent problem of IDW “bull’s eye” features in the maps (De Smith *et al.* 2006), which could be attributed to the sparse distribution of samples. These features were highly visible in the maps when sample data had extremely high or low values compared to other samples in the neighbourhood. When other geostatistical methods including kriging, co-kriging and radial basis functions were tested for the sample data, none were able to capture the variability in the system. Adequate sampling density is required to produce a sensible map with a high level of confidence using these methods. Leecaster (2003) suggested a sampling density of 1.4 per square km for Santa Monica Bay to obtain a high confidence level for the kriging method. As the Coorong offers a diverse geomorphology as well as underwater topography both across and along the Lagoon, the samples collected at the 12 sites were limited in number for using the geostatistical methods including IDW. However, resource constraints meant that sampling had to be targeted at the 12 reference sites, and did not allow a sampling program designed to map the sediments of the whole Coorong. Due to the complexity and variability in the system, a dedicated spatial sampling design based on the prior analysis of spatial correlation among the variables is necessary to obtain accurate sediment maps for the Coorong (Caeiro *et al.* 2003).

Although GAM has been widely used for studying non-linear species-environment relationships parameters (Jensen *et al.* 2005; López-Moreno and Nogués-Bravo 2005; Denis *et al.* 2002), so far as we are aware, this method has not previously been used to characterise the spatial distribution of sediment properties in a complex environment. Application of GAM to the North Lagoon generated spatial maps for all five sediment attributes, capturing the regional as well as local variability in the sample data based on the non-linear relationship between the sediment attribute and the predictor variables selected in the models. Forward selection with a stopping criterion (Blanchet *et al.* 2008) was a straight-forward method to select a model with the least number of predictor variables with almost the same predictive ability as the global model.

4.6. Summary and Conclusions

GAM was able to explore the significant relationships between the predictor variables and the sediment characteristics in the North Lagoon with a small number of sample data, and generated sediment maps depicting local variability both across and along the Lagoon. The variability explained by the selected models ranged between 45 and 70%, which could be expected to rise greatly with more samples and a sampling design targeted at mapping the entire Lagoon, rather than relying on samples that were collected to map smaller subsections of the Lagoon, as is done here. The sediment maps derived from GAM were spatially consistent with the physical distribution of various sediment attributes in the North Lagoon. However, the maps for the entire Coorong were generated by using the inverse distance weighting method and were greatly generalized without capturing specific patterns of sediment deposition in the Lagoon.

Along the Coorong Lagoons, the deposition of fine organic-rich sediments occurs in deeper waters of the middle channel, at Parnka Point, and along western (seaward) shores, particularly between Noonameena and Parnka Point. The potential ecological value of these shallow depositional areas as feeding grounds for higher trophic levels is negated by the extremely high salinities recorded south of Long Point. The steep salinity gradient between the estuary and the South Lagoon also changes the composition of sediments, as indicated by intense precipitation of carbonates and gypsum. The chemical changes in the water column driving mineral precipitation are likely to have a strong influence on shifting the balance between autotrophs and microbes at the base of the food chain.

4.7. References

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5. Mudflat Geomorphology and Availability at Varying Water Levels in the Coorong

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5.1. Executive Summary

The status of the Coorong wetlands as migratory bird habitat has been due primarily to the opportunities they provide for large numbers of birds to feed in a highly productive estuarine and lagoonal environment. A significant proportion of this foraging occurs on the large tracts of mudflat found throughout the Coorong. The productivity of the mudflats varies along the length of the Coorong, dependent primarily on water quality (particularly salinity), nutrient inputs, sedimentary structure, and the duration, frequency and extent of inundation. Resident macroinvertebrate populations and aquatic vegetation such *Ruppia* species are both an indicator of productivity in the mudflats and a food source for fish and birds.

This report presents high resolution topographic/bathymetric models for the 12 CLLAMMecology reference sites in the Coorong, as derived from survey data, along with their geomorphological characteristics. Results confirm the importance of the South Lagoon in terms of mudflat habitat, as it contains some 61% of available mudflat, as measured in the reference sites. Mudflats throughout the Coorong are generally likely to be geomorphically stable with mean mudflat slopes averaging 0.72%. Mudflat shapes are indicative of an accreting sedimentary environment. All mudflats should be highly productive if the necessary physical, chemical and biological conditions existed.

Across all 12 reference sites the 0 m to 0.5 mAHD elevation range is most significant as it contains approximately 43% of all available mudflat area. The second most important elevation class is -0.5 m to 0 mAHD, containing approximately 40% of total available mudflat area. Hypsometric analysis shows that for the South Lagoon the mudflat areas at elevations between 0m and 0.5 mAHD yield the greatest availability of habitat and suggest that manipulations of water level should be kept within this range. Ideally, the most important elevation range is 0.2 m to 0.4 mAHD, as manipulations in this range accomplish wetting and drying of the maximum area of mudflat, most of which is found in the South Lagoon. If mean water levels can be maintained at close to optimal levels, then natural high-frequency, wind-driven oscillations in water levels will inundate large areas of mudflat.

5.2. Introduction

The Coorong, part of the Ramsar-listed wetland of international significance located at the terminus of the Murray-Darling River System, has been affected by much-reduced water levels in recent years. This is due to a combination of factors, including reduced inputs from the Murray-Darling Baisn through the barrages at Lake Alexandrina, reduced flows from the Upper South East Drainage (USED) scheme and reduced connectivity between the South and North Lagoon due to sedimentary deposition in the channel at Parnka Point (Figure 5.1).

The status of the Coorong wetlands as migratory bird habitat has been due largely to the opportunities they provide for large numbers of birds to feed in a highly-productive estuarine and lagoonal environment. A significant proportion of this foraging occurs on the large tracts of mudflat found throughout the Coorong. These mudflat areas are inundated periodically depending on water levels, which change at a range of frequency cycles on an hourly, daily, seasonal, annual or decadal basis depending on fluctuations in driving factors. The major drivers of water level are regular tidal action (particularly in those areas closer to the Murray Mouth), extreme tidal events such as king tides (which can push marine water far into the system), freshwater inputs, evaporation (particularly in the summer months) and wind.

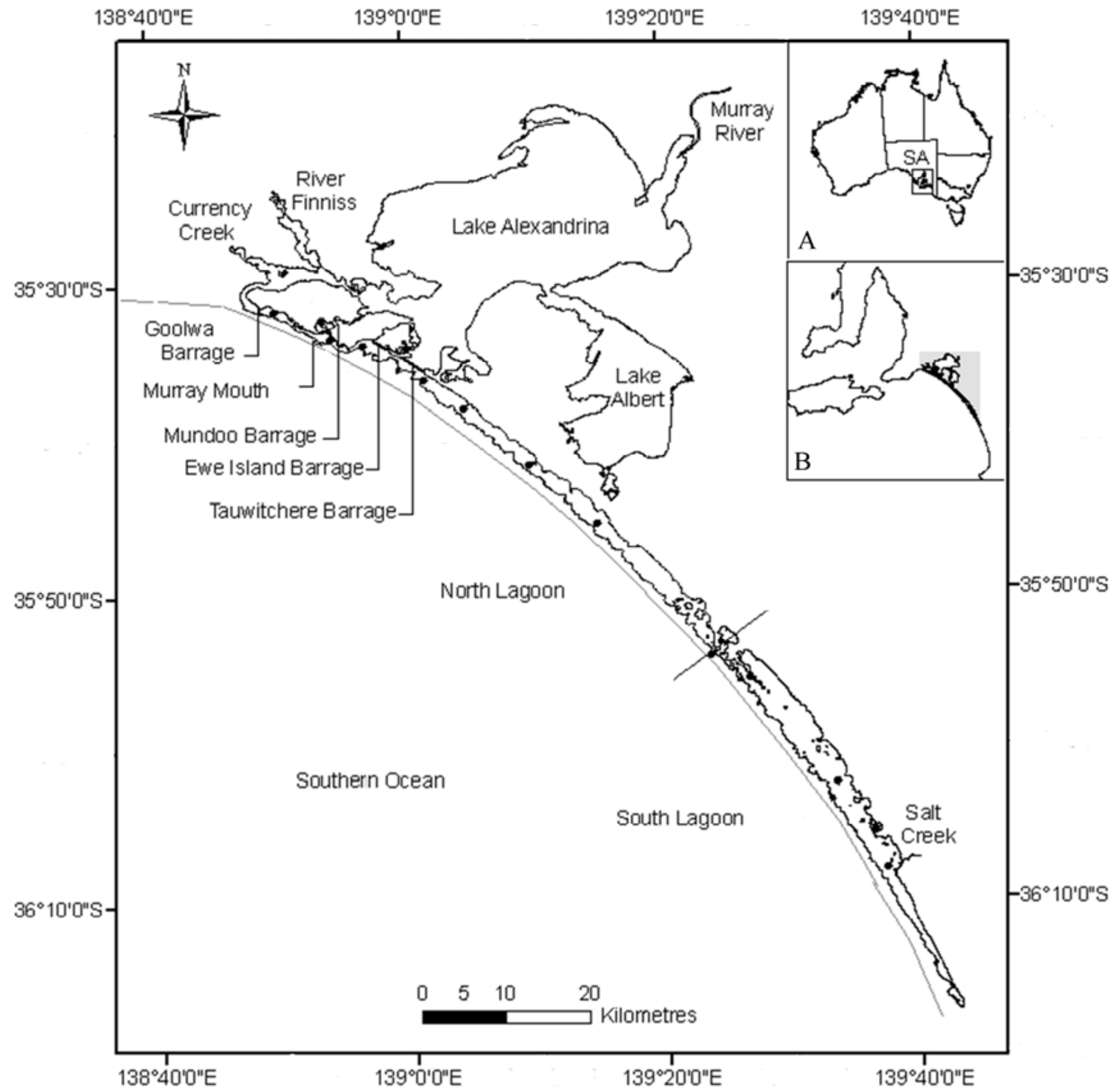

Figure 5.1. Locations of the reference sites in the Coorong (1-12).

Mudflats can be of high ecological value because they support high levels of productivity in both flora and fauna. They can be valuable as bird foraging areas and as nursery and feeding areas for fish (Dyer *et al.* 2000). Many species of waders, in particular, are dependent on coastal intertidal areas where they can feed on macrobenthic invertebrates on exposed mudflats (Piersma *et al.* 1993). In the Coorong, the productivity of the mudflats varies along its length, dependent primarily on water quality (particularly salinity), nutrient inputs, sedimentary structure, and the duration, frequency and extent of inundation. Resident macroinvertebrate populations and aquatic vegetation such *Ruppia* species are both an indicator of productivity in the mudflats and a source of prey for fish and birds. Rolston and Dittmann (2009) present the results of an analysis of macroinvertebrate populations throughout the Coorong.

As freshwater inputs to the Coorong system have reduced in recent years, this has had a marked effect on the potential productivity of the mudflat areas. As water levels have dropped, water quality has plummeted and salinity levels have risen. Mudflat areas which were once subject to the more regular wetting and drying cycles necessary to maintain their biological productivity (Boyes and Allen 2007) are exposed for longer periods such that they dry-out permanently, or if they are inundated, particularly in the South Lagoon, salinity levels are so high that productivity levels would be similar to those found in salt lakes. Rolston and Dittmann (2009) found that infaunal numbers declined rapidly when mudflats in the Coorong were exposed as water levels drop.

In tidal mudflats, the mid-tidal region (halfway between the high and low water marks) is usually the most important for infaunal communities in terms of species richness, abundance and biomass, and productivity normally differs with respect to tidal elevation and shore slope (Boyes and Allen 2007). In the Coorong, tidal mudflats are found near the Murray Mouth, and other mudflat areas also experience substantial changes in inundation on an hourly or daily basis due to wind-driven wave action and wind-forced changes in water levels. Variations in water level and mudflat morphology affect mudflat inundation and are critical to both the structural stability of mudflats in the system and their productive potential.

In terms of the morphology of mudflats in the Coorong, topographical analysis allows for prediction of habitat availability at varying water levels, and also provides an indication of the stability of mudflat sediments, which in turn affects their productivity. The cross-shore profiles of mudflats are dominated by tidal, wind and wave processes and the contributions of these processes to total sediment transport (Kirby 2000). Erosional flats are dominated by wind-generated waves, which are characterized by a concave-upwards profile. Tidally-dominated flats have a convex upwards profile and are believed to accrete over time (Pritchard *et al.* 2001). The productivity of mudflats can also have either a positive or negative influence on their morphological stability. Biostabilisation may occur due to the presence and density of microphytobenthos, algal mats, some species of worms and mussel mats, while conversely biodestabilisation is the result of bioturbation caused by burrowing bivalves, polychaetes and crustaceans (Uncles *et al.* 2003).

Restoring and maintaining mudflat productivity in the Coorong is a significant conservation goal which will restore the now-flagging status of the Coorong as a Wetland of International Significance, through providing viable foraging habitat for birdlife. The Dynamic Habitat Program, under the CLLAMMecology Research Cluster, seeks to quantify mudflat availability in the Coorong at varying water levels along a range of reference sites located throughout the system. This has been carried out through development of topographic models that can be analysed in a GIS environment to predict spatial extent and availability of mudflats, when linked to the varying water levels output from the existing hydrodynamic model for the Coorong (Webster 2007). The fine-scale topographic models of the reference sites form the basis of the dynamic habitat modelling presented in chapter 6 and can be run for various flow scenarios to predict potential bird habitat. The outputs of this modelling will also be useful for incorporation into other models of bird foraging behaviour developed by the Key Species Program within CLLAMMecology. In addition, they will allow managers to make decisions on the operation of the various management levers which affect water levels in the Coorong to achieve maximum ecological benefit. In particular, where management agencies are operating in an environment of restricted freshwater availability, there is a need to ensure that any allocations are being put to maximum productive use to enhance the biological viability of the system.

Compared with most other habitats mudflats have not been well researched and little is known about the processes occurring in them (Kirby 2000; Dyer *et al.* 2000). This study provides information on their physical potential as habitat and complements work done in other parts of the CLLAMMecology Research Cluster to characterize the biological attributes of mudflat areas throughout the Coorong. Compared to sandy shores, mudflats have a greater complexity due to the behaviour of the cohesive sediment and the roles of biological as well as physical processes (Kirby 2000). Characteristics of mudflat sediments throughout the Coorong are presented in chapter 4.

5.3. Methods

Twelve reference sites were utilised in this study, located along the length of the Coorong: eight in the North Lagoon and four in the South Lagoon (Figure 5.1). For the eight North Lagoon sites, detailed bathymetry was available from the South Australian Water Corporation (SA Water), which was used as the basis of the modelling carried out for this study. At the other sites located in the South Lagoon, detailed surveying of mudflat morphology was carried out throughout 2007 and 2008 using a SOKIA SET5 30RK Surveying Instrument, complemented by Differential Global Positioning System (DGPS) survey and at deeper water depths by kayak-mounted sonar. At all sites, mudflat topography was interpolated from supplied and field-collected data using radial basis functions in the Geostatistical Analyst extension of ArcGIS (ver.9.3) (Environmental Systems Research Institute 2008). The source datasets and processing and modelling methods used are described in the following sections.

5.3.1 Source Datasets

North Lagoon Reference Sites

The South Australia Water Corporation (SA Water) collected depth data for the Lower Lakes (Lakes Alexandrina and Albert) and the North Lagoon of the Coorong in order to derive bathymetry for the region. The data were provided as point data at varying resolutions in AutoCAD DXF format and the data collection procedures and accuracy of the bathymetric dataset are described in chapter 3. The bathymetric data for the North Lagoon had a point spacing of 25 m in the area between the Murray Mouth and Mark Point and 50 m south to Parnka Point. The Goolwa Channel had a point spacing of 10 m. The vertical accuracy of the original depth data collected by the echo-sounder is ± 10 cm (Miles 2006). However, the accuracy of the boat position, the effects of motion on the depth and position readings, and the effects of tidal variation on the interpolated bathymetry are not known. The Ewe Island reference site in the North Lagoon had only partial bathymetric data available due to its proximity to the Murray Mouth, where no bathymetry was available. The bathymetry for this site was modelled from LANDSAT5 spectral reflectance using the methods described in chapter 3, and the finer resolution DEM for the site was interpolated from the modelled data.

South Lagoon Reference Sites

There was no suitable bathymetric data available for the South Lagoon, arising from difficulties in accessing the Lagoon to carry out a bathymetric survey similar to the North Lagoon. The shallow water depths of the South Lagoon, combined with numerous outcropping limestone reef structures, make boat navigation difficult. Consequently, the four reference sites: Parnka Point, Villa dei Yumpa, Jack Point and Salt Creek, were manually surveyed using a combination of techniques. These included a SOKIA SET5 30RK Surveying Instrument with an accuracy of ± 0.002 m, a watercraft-mounted Garmin 400 Sonar with an accuracy ± 0.05 m and a Trimble Pathfinder Pro XRS DGPS with a recorded horizontal site accuracy of ± 0.35m. For those areas between the high-water shoreline, with the upper boundary usually delineated by the presence of fringing vegetation, and shallow-water depths up to 0.5 m, a standard survey using tripod and prism arrangement was carried out recording XYZ positional readings, which were later processed using ProLink 1.15 (Point Software Inc. 2001). Trimble Pathfinder 4.00 (Trimble Navigation Ltd. 2007) software was used to convert the survey data into ArcGIS (ver.9.3) (Environmental Systems Research institute, 2008) shapefile point datasets. XY reference positioning of survey station location and backsite locations was accomplished using Differential GPS to an accuracy of ± 0.35m. Corrections to AHD were made using the closest available reference data north of Parka Point.

Survey data from the Surveying Instrument were complimented by waterline data collected during 2007 and 2008 at different times of the year, and hence varying water levels, using the Trimble Pathfinder Pro XRS DGPS, which allowed the measurements of mudflat slope and shape to be extrapolated over the 1km-wide analysis area used for each site. For water depths greater than 0.5 m, a Garmin 400 Sonar mounted on a kayak, and calibrated using a depth measuring pole, was used to collect depth measurements on transects across the full width of the Lagoon. Depths were recorded as waypoint attributes in a GPS with a corrected horizontal accuracy of <2m. At shallow depths of less than 0.5 m across the Lagoon and on the far western shore, depths were measured manually using a measuring pole with an accuracy of ± 0.005m. All water-based depth measurements were carried out early in the morning on still days to avoid any influence of wind forced tilt of the water surface and wave effects. GPS waypoint files were converted to XYZ positions in metres and imported into ArcGIS (ver.9.3) (Environmental Systems Research institute, 2008) as point shapefiles. This data was then corrected to AHD using tie-in points with the ground survey data. The combined survey data yielded between 650-900 XYZ points at each South Lagoon reference site, which was then interpolated to produce DEMs for each site.

5.3.2 Interpolation Methods

For each reference site the topographic/bathymetric models (DEMs) were generated using radial basis functions in the Geostatitistical Analyst extension in ArcGIS (ver.9.3) (Environmental Systems Research Institute 2008). In all models thin-plate splines were used, utilising a minimum of 10 neighbours and a maximum of 15 in a standard search area. Four search sectors oriented at 45 degrees were used as this captured the direction of major trends in the input data, due to the general NW-SE orientation of the Lagoon. Thin-plate splines have been widely used in surface modelling (Glenn *et al.* 2006) because they produce an excellent fit to the input data being interpolated and can model scattered data points effectively without the need for experimental data points (Boyd *et al.* 1999). While a number of other methods are regularly used for surface interpolation from scattered point data, such as IDW, B-splines and geostatistical methods such as kriging, they will in most cases produce similar results dependent on the spatial distribution of the original data (Isaaks and Srivastava 1989; Gooverts 1997). In this analysis, the thin plate spline models produced the best fit and lowest Root Mean Square (RMS) error in the resultant surfaces. All models used an inverse multiquadratic kernel function for the interpolation (Environmental Systems Research Institute 2008). The resultant models were at 1 m horizontal resolution and 0.001 m vertical resolution, to allow for accurate estimation of changes in habitat availability at different water levels. The 1 m horizontal resolution allows for mudflat areas to be calculated to the nearest metre, although all results here are presented in hectares for ease of interpretation.

5.3.3 Hypsometric Analyses

Hypsometric characterisation of shoreline shape has been widely used in geomorphological analysis of coasts (Kirby 2000). The hypsometric curve is calculated as the cumulative area of shoreline available at ascending elevations. It provides an indication of the nature of the surface and whether it is subject to sedimentary accretion or erosion (Carter 1988). For the current study, the shape of the hypsometric curve at each reference site also provides an indication of the rate of change in habitat availability as water level in the Coorong increases or decreases.

In this analysis, hypsometry was calculated through a GIS routine implemented in ArcGIS (ver.9.3) (Environmental Systems Research institute 2008) adapted from scripts available in GT Spatial Tools and using the methods developed for tidal mudflat modelling by Xander Bakker, *Grontmij Nederland bv* (Bakker pers. comm.). Essentially the process involved extracting all DEM cells above a certain height (in this case above -0.5 AHD, because this was approximately 0.5m below the minimum observed water level in the South Lagoon), and converting respective AHD increments to polygons. Polygonal areas can then be calculated for each grid cell height and cumulative areas calculated. Plotted results then yield the hypsometric curve for each site.

5.3.4 Volumetric Analyses

Calculations on the volumes of water required to manipulate water levels in the South Lagoon were carried out using the 3D Analyst extension of ArcGIS (ver.9.3) (Environmental Systems Research institute 2008). The bathymetric model used in this process was generated from satellite and transect data and is described in detail in chapter 3. All estimates are based on volumetric calculations relative to an input reference plane, and as such assume an artificial horizontal water level. In reality, any linearly flowing system over a large area will contain a natural gradient in the water surface and this is evident in the water level output from the hydrodynamic model (Webster 2007) for the Coorong. However, the surface gradient is highly variable depending on flow conditions and time of the year. Water surface gradients in the Coorong are also regularly affected by wind set-up conditions.

5.3.5 Determination of Wind Effects on Water Level

Wind is well known as a major driver of high frequency oscillations in water levels and circulation over large water bodies (Shilo *et al.* 2007; Schwab and Beletsky 2003) and is considered a major ecological driver for the Coorong system (Lamontagne *et al*. 2004). These effects have been quantified in the Lower Lakes (Noye 1973) and in the North Lagoon of the Coorong (Noye and Walsh 1976) but not in the South Lagoon where the majority of mudflats are present. Webster (2007) stated that wind driven effects on water level in the Coorong are in the order of ± 5 cm. In the current study, wind effects on water level were measured in the South Lagoon at Villa dei Yumpa where large mudflat areas are present. This area forms the northernmost end of the main expanse of water which makes up the South Lagoon. Measurements were taken over a series of individual time periods capturing changes in water levels between zero wind speed and high wind speed events, events which occur regularly in the Coorong. In particular, the sampling sought to capture the effects of the most common higher intensity southerly winds (Noye and Walsh 1976) which blow parallel to the main axis of the South Lagoon.

An integrated water level, wind speed and wind direction data logger was not available for the current study and therefore simple measurement methods were applied. This involved the use of three graduated poles from which water levels could be read, spaced at 100m intervals and varying depths in the Lagoon. Locations were recorded using DGPS and depth correlated to AHD using the fine-scale bathymetric model for Villa Dei Yumpa (appendix 5.2). Wind speed was measured using a digital anenometer and wind direction was measured using handheld GPS. Measurements were taken using three replicates at 30 minute intervals at each location. While this provides only a partial insight into the effects of wind on water levels in the South Lagoon, it does indicate the likely maximum changes possible and illustrates the importance of these effects for wetting and drying of the mudflats over short timescales.

5.3.6 Methodological Limitations

The North Lagoon bathymetry is an interpolated product, and because it was based on echo-sounder measurements made in a boat which did not venture into depths of less than 1 m, it is not ideal for the purposes of mudflat modelling. The bathymetry of those areas between 1m depth and the shoreline is estimated linearly from the waterline. However, the integrity of the final DEMs for the North Lagoon reference sites was checked through a number of validation surveys using the Surveying Instrument. As the South Lagoon sites were surveyed using the same instrument, the models generated for these four reference sites provide a highly accurate representation of mudflat shape.

The physical location and morphology of the mudflats of the Coorong is heavily influenced by the underlying and exposed eroded Pleistocene limestone bedrock and abandoned cliff structures (Bourman *et al.* 2000) which can be found throughout the Lagoons. As such, some areas of the mudflats are not purely sedimentary structures and therefore their geomorphic controls are not as strongly influenced by erosional and depositional processes and sedimentary structure. The mudflat models developed as part of the current study do not record the location of outcropping limestone or tubeworm atolls within the model extents, which would obviously have different properties and different habitat potential to sediments. However, these areas are very limited in size within the analysis areas and are likely to have only a small influence on mudflat area calculations.

5.3.7 Linking to the Hydrodynamic Model

A one-dimensional hydrodynamic model for the Coorong was developed by CSIRO Land and Water (Webster 2007). This model is able to predict changes in water level and salinity along an approximately 160 km linear transects running from the south of the South Lagoon of the Coorong to just south of the Murray Mouth in the North Lagoon (Figure 5.1). It is based on water level measurements at various locations along the Coorong and tidal and barrage flow data, and wind data from the period before the current disconnection between the Lower Lakes and the Coorong. Output consists of modelled water levels at 1 km intervals at 1 hour time steps and the model can be run for a range of possible flow scenarios.

A dynamic habitat model linking output from the hydrodynamic model to the fine-scale topographic/bathymetric models at each reference site was written in ArcGIS (ver.9.3) (Environmental Systems Research institute 2008) ModelBuilder (chapter 6). This allows modelled scenarios from the hydrodynamic model to be linked to the mudflat models presented here and predict habitat availability for past, current or predicted time periods. A full description of the dynamic habitat model and its outputs is presented in chapter 6, and it is a tool that can be used by managers to understand how mudflat habitat availability has changed over time, and predict how it will change in the future for any given flow scenario.

5.4. Results

5.4.1 Surface Modelling

High resolution cell-based topographic models of shorelines, mudflats and bathymetry were generated for each of the 12 reference sites using thin plate spline models. Each of these covers a 1 km wide section of the Coorong and is positioned perpendicular to the general linear axis of the Coorong, which generally follows the ocean shoreline. Each model has a cell resolution of 1 m. The goodness of fit of the spline surfaces was assessed through cross validation between the resultant surfaces and the points from which they were generated. The validation plots showing the relationship between the predicted and measured surface at each site are shown in Appendix 5.1a and the cross validation results are presented in Appendix 5.1b.

The quality of the resultant surfaces varies according to the nature of the input data, particularly its spatial distribution, and the surface fitting characteristics of the thin plate spline models. Larger numbers of input points were used in the North Lagoon reference sites due to the availability of the interpolated bathymetric dataset for the area, and at varying resolutions. The large numbers of points and their regular spatial distribution also results in considerably reduced mean and RMS errors for the North Lagoon, and therefore better surface fit, relative to the South Lagoon sites.

The twelve fine-scale topographic models depicting mudflats, shorelines and bathymetry at each reference site are presented in Appendix 5.2 and an example is shown in Figure 5.2. Each captures a very different morphology depending on the location of islands within the site, shoreline shape and the physical processes acting at each site. In geomorphic terms, the areas represented by the reference sites can be subjected to various groupings dependent on where they occur in the system. The most obvious differences occur between North and South Lagoon sites, with the two Lagoons acting to some extent as separate systems although connected through a narrow channel at Parnka Point. The North Lagoon is dominated by marine inputs through the Murray Mouth and freshwater flows over the barrages. The South Lagoon is affected by surface flows from the USED and groundwater flows, as well as flow from the North Lagoon, and evaporation has a much greater influence on water levels. The Mundoo Channel reference site is somewhat anomalous in the system, occurring on a connecting channel from Lake Alexandrina, which is shaped by channel flow and marine tidal variation.

In the North Lagoon, the reference sites from Pelican Point north are all dominated by deeply- incised channels to depths of between -2.7 and -3.6 mAHD. The three other North Lagoon sites, Mark Point, Long Point and Noonameena, do not contain incised channels and have shallower maximum depths. This is most likely due to increased sedimentation around the northern reaches of the North Lagoon, influenced primarily by marine sediments from the areas around Murray Mouth.

In the South Lagoon, the bathymetry at Parnka Point, Villa dei Yumpa and Jack Point is dominated by current-incised channels through which most south-north water flow occurs in the system. Sedimentation is most likely greatest at the northern end of the South Lagoon. Salt Creek is at the southern end of the system and is, on average, the deepest part of the Lagoon, containing the largest water volume, but it is unlikely to be subjected to significant flow effects. The dominant process at depth is more likely wind induced gyres acting in a confined limestone-bounded basin. Areas that function as salt lakes when disconnected from the Coorong at lower water levels, such as those around Parnka Point, would also be subject to aeolian deflation when dry, in which strong winds scour sediments from the exposed basins (Cooke *et al.* 1993).

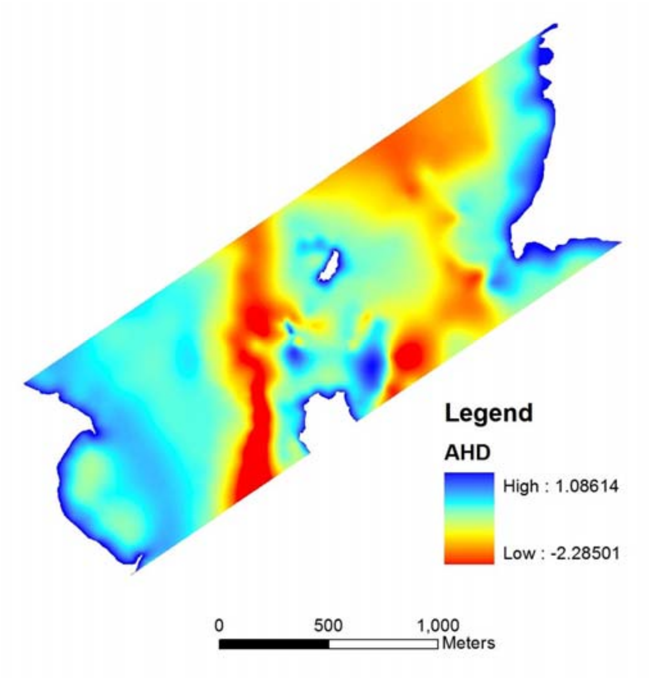

Figure 5.2. High Resolution Surface Model for Jack Point Reference Site – an example

5.4.2 Mudflat Parameters

General mudflat area parameters for each reference site at 0.5 m vertical intervals within the range -0.5 m to 1.5 mAHD are provided in Table 5.2 below. Height intervals of 0.5 m have been utilised for descriptive purposes only. The South Lagoon dominates total mudflat availability in the Coorong, containing approximately 61% of total area, compared to approximately 39% in the North Lagoon, as measured in the reference sites. Across all 12 reference sites, the 0 m to 0.5 mAHD elevation range is most significant as it contains approximately 43% of all available mudflat area. The second-most important elevation class is -0.5 m to 0 mAHD, containing approximately 40% of total available mudflat area. Only approximately 17% of mudflat is available at elevations above 0.5 mAHD for the Coorong as a whole. Villa dei Yumpa, Parnka Point and Jack Point are the most significant sites across the Coorong in terms of mudflat area containing 22%, 18% and 15% of the total respectively.

The general trend in the North Lagoon for the elevation classes in the -0.5 m to 0.5 mAHD range, is for increasing mudflat area from the south to the north up until Pelican Point and then decreasing mudflat area in the remaining northern sites. The limited and sometimes non-existent mudflat area available at elevations above 0.5 mAHD in the North Lagoon is due to the more stable mean water levels closer to the Murray Mouth (less subject to seasonal and annual variation) and lower mean water levels compared to the South Lagoon, resulting in less sedimentary deposition above 0.5 mAHD. The elevation class containing the majority of mudflat area for the North Lagoon in terms of mudflat area is the -0.5 m to 0 m elevation range, which is generally the area below the high water mark in tidally-influenced sites.

The general trend for the South Lagoon is for increased mudflat availability moving from south to north. The most important elevation class in terms of habitat availability is likely to be the 0 m to 0.5 mAHD, as this is the water level range most commonly experienced in recent years for the Coorong. Chapter 6 presents historical water level data predicted from the hydodynamic model which is somewhat higher under normal flow conditions. The 0 m to 0.5 mAHD range shows a trend of increasing mudflat availability from south to north. It is also an important elevation range for total mudflat area as it contains 49% of total mudflat across the four reference sites of the South Lagoon. The relatively large surface areas in the range -0.5 m to 0.5 mAHD for Villa dei Yumpa reflect the influence of islands and a peninsula dissecting the Lagoon (see Appendix 5.2) and the consequent large mudflat area that has developed in low current conditions. The large areas of mudflat at higher elevations at Parnka Point are primarily due to the presence of large salt pan areas to the east which become connected to the Lagoon at higher water levels. South-north water flow, strong winds from the south (Noye and Walsh, 1976), particularly during winter, and the constriction between the North and South Lagoons at Parnka Point, would also be responsible for increased sedimentation in the northern areas of the South Lagoon.

Of the total mudflat area available at the reference sites between -0.5 m and 1.5 mAHD in the South Lagoon, Salt Creek contains 11%, Jack Point 23%, Villa dei Yumpa 36% and Parnka Point 28%. For the North Lagoon reference sites, the mudflat area is fairly consistent across most sites, with Pelican Point containing the largest mudflat area. This is due to the presence of a significant mid-channel sand island at Pelican Point which is normally exposed only at low tide or when water levels are low.

Table 5.2. General Mudflat Area Parameters at each Reference site (S-N).

Reference Site	Mudflat Area (ha)					% Total Mudflat
	-0.5 to 0 mAHD	0.0 to 0.5 mAHD	0.5 to 1.0 mAHD	1.0 to 1.5 mAHD	Total -0.5 to 0.5 mAHD	
Salt Creek	20.01	27.47	25.97	9.44	82.89	6.86
Jack Point	71.05	94.53	15.44	0.41	181.43	15.01
Villa de Yumpa	148.97	100.43	11.42	1.27	262.09	21.68
Parnka Point	13.76	136.73	34.28	22.23	207.01	17.13
Noonameena	32.47	17.70	20.11	0.12	70.40	5.82
Long Point	18.87	23.19	14.51	0.00	56.57	4.68
Mark Point	23.98	17.51	10.26	0.00	51.75	4.28
Pelican Point	39.57	46.38	12.15	0.00	98.09	8.12
Ewe Island	12.55	8.61	8.82	0.18	30.17	2.50
Barker Knoll	31.08	21.06	17.48	1.61	71.23	5.89
Mundoo Channel	56.54	12.97	0.00	0.00	69.51	5.75
Goolwa Channel	12.89	6.66	7.55	0.52	27.60	2.28
Total	481.75	513.23	177.98	35.79	1208.75	100
% Total Mudflat	**39.86**	**42.46**	**14.72**	**2.96**	**100**	

Mudflat slopes at each reference site in the same four elevation classes are provided in Figure 5.3. The 0.5 mAHD elevation increments used are for descriptive purposes only. The slope of mudflats provides an indication of their stability, with low slope mudflats more stable and more biologically active (Dyer *et al.*, 2000) as larger areas are subject to wetting and drying action as water levels increase and decrease due to tides, wind and wave action. Steeper slopes in mudflats are indicative of erosional surfaces and are likely to be less stable and less biologically active (Dyer *et al.*, 2000). Across the 12 reference sites the highest mean mudflat slopes are present at Goolwa in the 0 m to 0.5 mAHD range (1.64%) and Villa dei Yumpa at the 1.0 m to 1.5 mAHD range (1.43%). Mean mudflat slopes are generally quite low throughout the Coorong and average 0.72% across all reference sites. Generally, the North Lagoon reference sites had slightly lower mean mudflat slopes (0.67%) compared to the South Lagoon (0.82%).

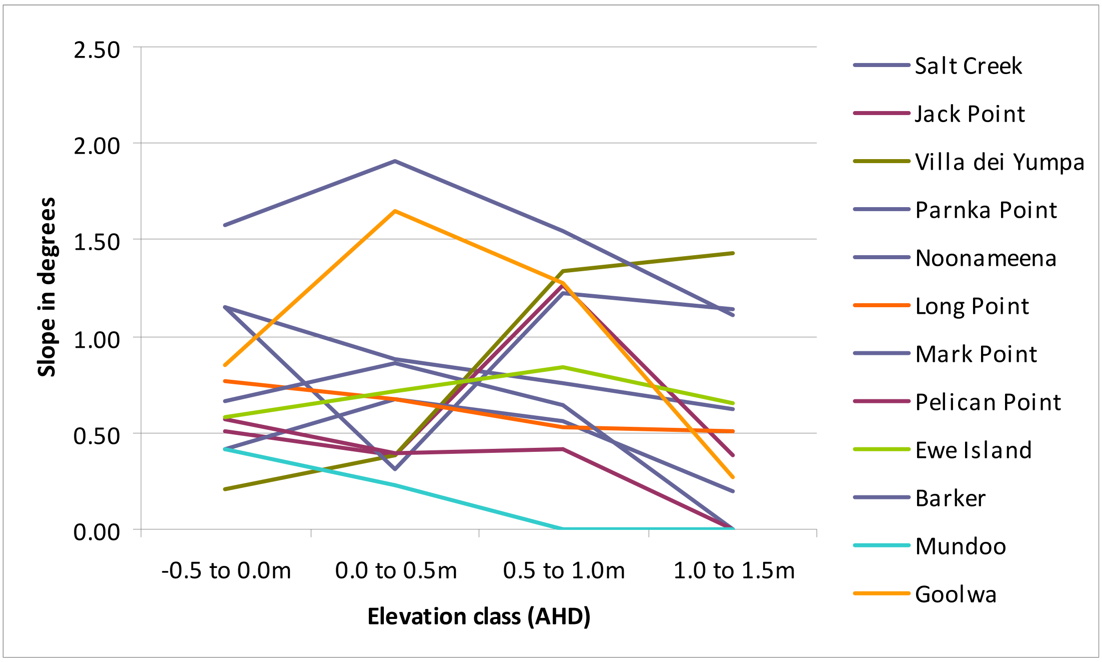

Figure 5.3. Mudflat Slopes at each Reference Site.

At the four reference sites in the South Lagoon mean mudflat slopes are very low at less than 0.82%, indicative of stable mudflats in a relatively low energy environment. Across all four sites the lowest slopes are found generally in the 0 m to 0.5 mAHD range. Highest slopes are found at elevations above 0.5 mAHD, except for Salt Creek where the highest slopes occur at depths below -0.5 mAHD. The highest maximum slopes are found at Parnka Point, which is indicative of the geomorphically-constrained deeply-incised channel running through this section connecting the North and South Lagoons of the Coorong.

5.4.3 Hypsometric Curves for Mudflats

The hypsometric curves for the mudflats at each reference site provide an indication of the stability of the mudflats in terms of accretion or erosion and also provide an indication of where the greatest benefits will be achieved in maximizing habitat availability by increasing water level. The shape of the hysometric curves may, however, be influenced by the quality of the input data, which is an important consideration for the North Lagoon reference sites, in particular at higher elevations, due to the interpolation process used (Milles 2006). The hypsometric curve for Jack Point is shown in Figure 5.4 and the hypsometric curves for all reference sites are shown in Appendix 5.4. Hypsometry of the North Lagoon mudflats is markedly more linear than that of the South Lagoon. Only Mundoo Channel in the North Lagoon exhibits a typical marine shoreline hypsometry, with steep slopes at lower elevations followed by lower slopes at higher elevations (Carter 1988). Pelican Point, in particular, exhibits rapid gains in cumulative mudflat area between 0.25 m and 0.3 mAHD, which is probably the exposure threshold of the large mid-channel sand island.

The hypsometric curves at all four reference sites in the South Lagoon show a rapid increase in cumulative mudflat area above 0 mAHD. In general terms, this increase is greatest in the 0 m and 0.5 mAHD range. Parnka Point and Jack Point display somewhat typical hypsometric curves for shorelines, with a characteristic sinusoidal shape (Carter 1988), with areas of concavity in the curve at elevations below 0 mAHD and areas of convexity above 0 mAHD. Salt Creek shows modest, near-linear increases in mudflat availability above -0.5 mAHD, while Villa dei Yumpa shows a rapid linear increase between -0.5 m and 0.5 mAHD and minimal gains above 0.5 mAHD. Relatively small accumulations in mudflat area occur in the -0.5 to 0 mAHD range at all sites. With Villa dei Yumpa being the most important site in the Coorong in terms of total available mudflat area, the hyposmetric curve shows that 1 m of variation in water level between -0.5 m and 0.5 mAHD achieves a large and significant 250 ha gain in cumulative mudflat area.

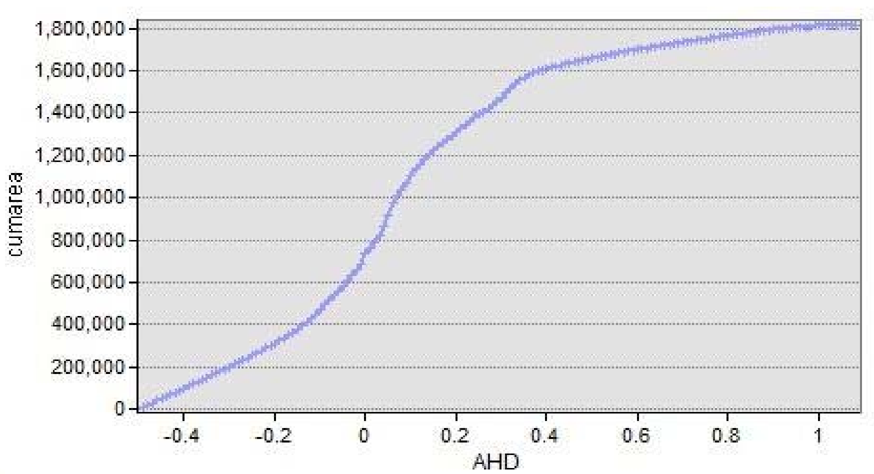

Figure 5.4. Hypsometric curve for Jack Point Reference Site – an example.

5.4.4 Wind Effects on Water Level in the South Lagoon

The results of the measurements of wind speed in relation to water level carried out at Villa dei Yumpa in the South Lagoon provide some indication of the likely influence of wind in wetting and drying mudflats over short timescales, and these are presented in Figure 5.5. While only a portion of the data collected was directly comparable due to variations in wind direction, they do show that changes in water level can be in the order of 0.8m between 0 and 16.4 m/s. This is considerably greater than the 0.1m suggested in Webster (2007).

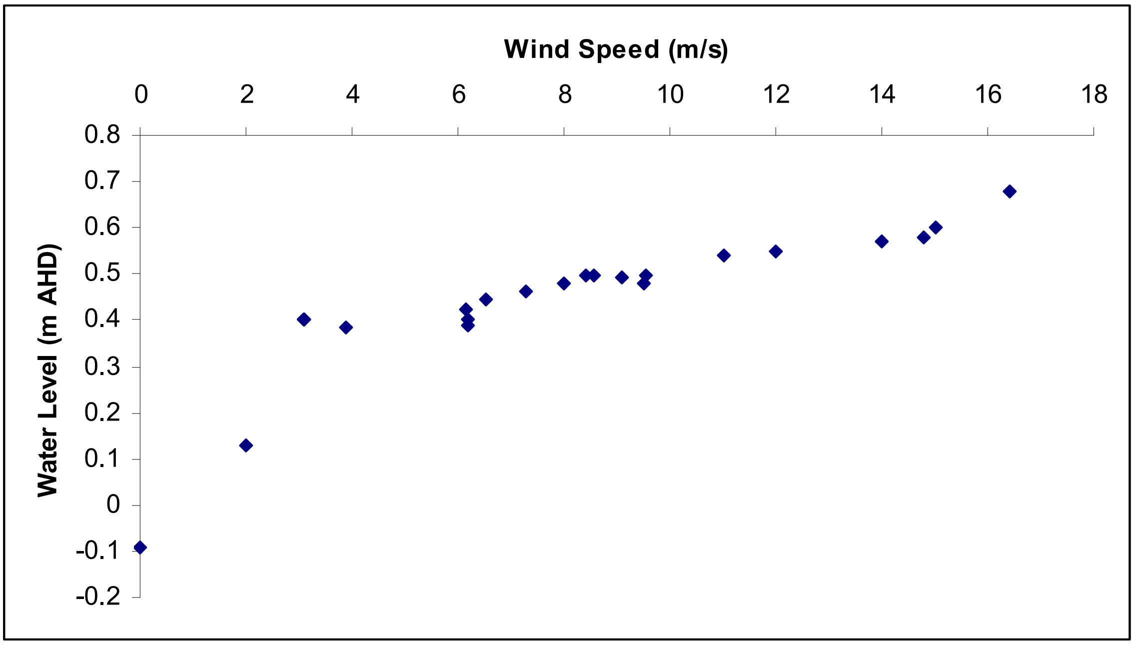

Figure 5.5. Wind effects on water level at Villa dei Yumpa (wind direction 328-342 deg.).

5.5. Discussion

The hydrodynamic model for the Coorong (Webster 2007) shows that for typical flow scenarios there is usually some gradient present in the water surface along the length of the Lagoon, dependent on flows to and from the system. These gradients would need to be taken into account for determination of changes in habitat availability at different water levels. However, some generalisations can be made about the area of mudflats in relation to AHD. Only some 17% of total available mudflat exists at elevations above 0.5 mAHD. A rise in water level of 0.5 m above 0 mAHD results in a decrease of nearly 43% in mudflat availability. In terms of mudflat area alone, water level manipulations within this elevation range will return the greatest habitat benefit, but this does not take into account the effects of poorer water quality on habitat at lower water levels. Higher salinities, in particular, have a marked impact on productivity (Rolston and Dittmann 2009).

Results show clearly that the South Lagoon is considerably more important than the North Lagoon in terms of mudflat availability, as it contains the majority (61%) of all available mudflat at the reference sites. This occurs even though only four reference sites in the South Lagoon were included in the analysis compared to eight in the North Lagoon. Thus, if these sites are typical of the Coorong, then it is likely that the South Lagoon contains substantially more than two thirds of the available mudflat in the Coorong, although a full fine-scale bathymetry for the full Coorong would be required to confirm this. The management implications are that water level manipulations in the South Lagoon are far more important in terms of increasing available mudflat habitat. Although they are currently less productive biologically due to lower water levels and high salinity levels (Rolston and Dittmann 2009), increased water availability in the South Lagoon could provide considerable ecological benefits, provided water quality improved sufficiently for macroinvertebrates and macrophytes to colonise the mudflats that would become available.

The mudflats of the Coorong are exposed to a unique range of physical and biological processes depending on where they occur in the system. While the current study quantifies the availability of mudflats at various water levels and can be linked to the system-wide hydrological model, it does not account for the varying levels of productivity at the various reference sites. So, while habitat may be available at a given water level, it may not necessarily be biologically productive or suitable as high-quality foraging habitat. This would depend on a complex range of interactions at each reference site.

The exact positioning of the location of the 1km-wide analysis polygon used for each reference site will influence available habitat at any one site due to variations in the shoreline and the area of mudflat captured within the polygon at each reference site. However, results do provide an indication of the mudflat morphology at various points along the Coorong and also permit comparison between the different systems of the North and South Lagoons.

The lagoon-scale bathymetric modelling described in chapter 3 makes it possible to calculate the quantity of water required to achieve significant ecological benefits in the South Lagoon. However, this would need to be delivered in such a way as to flush existing low quality water from the system. Previous discussions on making environmental flows available to the Coorong focus on delivery over the Barrages (MDBC 2003; 2004), but as this delivers water to the South Lagoon through a constricted channel at Parnka Point, little flushing can occur. The volume of the South Lagoon at 0 mAHD is estimated at 98 GL from the bathymetric model of chapter 3. To achieve a 0.5 m rise in water level above 0 mAHD in the South Lagoon it would be necessary to provide an estimated 44 GL to the system, assuming that all input water was retained in the South Lagoon and did not flow into the North Lagoon. However, this would only dilute the existing hypersaline water, dependent on the salinity of input flows, and thus substantially greater flows would be required to both increase water levels and flush out existing low-quality water. Transferral of hypersaline water through the North Lagoon would also be likely to have significant ecological impacts.

Low summertime water levels in the South Lagoon in recent years, down to approximately 0 mAHD, result in much larger areas of mudflat being exposed compared to typical water levels above 0.5 mAHD. However, this occurs in combination with hypersaline conditions and drying of exposed sediments and consequently viable, biologically-active mudflats are reduced in availability. Even with good water quality, available mudflat habitat does not necessarily equate to high-quality mudflat. Rather, quality will also depend on how high above water the mudflat is or what depth of water covers it, and how long it has been exposed. The best quality mudflats, in terms of habitat for macroinvertebrates and thus foraging grounds for birds, are likely to be those that are covered by a shallow layer of water, and/or that have only recently become exposed (Dyer 1998). Mudflats that have been well above water level for extended periods (weeks to months), are likely to have few macroinvertebrates (Rolston and Dittmann 2009), and will thus also be very poor foraging grounds for birds. Similarly, while mudflats > 10-20 cm deep may have a high abundance of macroinvertebrates (depending on species) and also provide suitable habitat for *Ruppia* and various fish species, they will not be available to wading birds (Rogers and Paton 2009).

Dyer *et al.* (2000) found that most significant differences in flora and fauna in the upper zones of mudflats were due to variations in sediment grain size and that the main driving variables are tidal range, exposure to waves and mudflat slope. Mudflat slopes across the four reference sites in the South Lagoon show an increase at elevations above 0.5 mAHD (Appendix 3), indicating that they are likely to be less productive (Dyer 1998) than mudflat areas below 0.5 mAHD. However, low overall slopes of less than 0.72% across all reference sites indicate that all mudflat areas are likely to be highly stable and relatively productive (Dyer *et al.* 2000), if the other appropriate physical, chemical and biological conditions are present. Geomorphically-stable mudflats with limited sedimentary processes occurring are characteristic of sheltered estuarine or lagoonal sites (Boyes and Allen 2007). Small geomorphic elements within the surface shape of mudflats are also likely to affect biological productivity (Anibal *et al.* 2006). In particular, alternating meso-topographic concave and convex features may contain varying macroinvertebrate populations despite no differences in physico-chemical characteristics of the sediments (Anibal *et al.* 2006). Such meso-topographic features are present in mudflats throughout the Coorong, but are not captured in the resolution of the topographic/bathymetric models presented here.

The generally-linear hypsometry of the North Lagoon contrasts with that of the South Lagoon. Results indicate that between -0.5 m and 1.0 mAHD mainly linear gains in cumulative mudflat area occur. This suggests that there is no critical elevation threshold at which water levels should be maintained in the North Lagoon, in terms of maximising mudflat availability. In the current conditions during disconnection from the Lower Lakes, marine inputs maintain mean water levels at little higher than 0 mAHD.

The hypsometry of the South Lagoon reference sites, which contain the majority of total mudflat area, suggests that the greatest changes in cumulative mudflat area occur in the range 0.2 m to 0.4 mAHD. This is important because it suggests that artificially varying the water level within this range will achieve the maximum possible benefits in terms of wetting and drying the maximum area of mudflat. Based on the South Lagoon volumetric model presented in chapter 3, the manipulations in this range would involve injecting some 18 GL of water into the system, ignoring any water loss into the North Lagoon.

An important aspect of the physical characteristics of mudflats which determine their geomorphic form and behaviour is the grain size distribution. Grain size plays an important role in mudflat dynamics (Uncles *et al.* 2003), both in the way in the mudflats will respond to erosional and depositional processes and in terms of biological productivity. Grain size also affects drainage and water temperature which act as drivers of mudflat dynamics (Le Hir *et al.* 2000) and influences the distribution of fauna and flora (Boyes and Allen 2007; Dyer *et al.* 2000,). The morphological characteristics of the Coorong mudflats should therefore be considered in the context of their grain size characteristics. Grain size structure and spatial distribution determined from sampling conducted as part of the Dynamic Habitat project is presented in chapter 4.

The evolution of the mudflat often involves a winnowing process by which coarser grained material, which is mainly the skeletal remains of intertidal macrofauna, is driven upshore by waves and often lies above the typical high water mark (Kirby, 2000). This is consistent with conditions observed in the Coorong (chapter 3). The winnowed mud fraction is reworked into deposition areas, resulting in an accumulation of finer sediments at depth (chapter 3). Deposition on flats leads to thin, discontinuous, normally-consolidated veneers, which provide host sediments for a restricted invertebrate population (Kirby 2000). This is compounded in the Coorong by high levels of salinity, particularly in the South Lagoon, which have reduced the quantity and diversity of macroinvertebrates in these habitats (Rolston and Dittmann 2009). Highly saline environments therefore provide only limited foraging for waders, with *Artemia* spp. (brine shrimp) usually being the only food source available (Masero *et al.* 1999).

Wind-driven changes in water levels in the Coorong can have a significant effect on the area of mudflat inundated over short time periods (Rogers and Paton 2009). Water level variations due to wind are commonly observed in large water bodies (Thompson 1983). Measurements made during extreme wind events at Villa dei Yumpa in the South Lagoon, showed a change in water level of approximately 0.8m in less than 24 hours between windspeeds of 0 and 16.4 m/s, with a wind direction between 228 and 342 degrees (Southerly winds) which achieve a near maximum wind set up along the South Lagoon. Such changes can occur in a matter of hours, as afternoon winds develop and increase in intensity, or as frontal systems move through. Wind is therefore likely to be the primary high frequency factor affecting inundation of mudflats, and in turn mudflat availability and possibly productivity. In addition, in the North Lagoon and estuarine area, there is a tidal movement that propagates through the Murray Mouth. Daily tidal signals are obvious as far south as Mark Point, although the tidal cycle is reduced to ~ 10 cm compared to ~ 80 cm at Barker Knoll, and only the spring/neap tidal cycle penetrates to Long Point. In combination, tidal activity and wind forcing can change inshore water levels at Mark Point by up to 60 cm over periods of days to weeks (Webster 2007).

5.6. Summary, Conclusions & Management Implications

Mudflats form critical habitat for many species in the Coorong, in particular wading birds. Maximising the productivity of mudflats, through maintaining water levels and water quality is essential for ensuring the Ramsar status of the Coorong by providing coastal foraging habitat required by migratory birds. Healthy mudflats support large and diverse macroinvertebrate populations, are important as fish breeding areas and form substrate for submerged aquatic vegetation such as *Ruppia* species. Restoring the productivity of the Coorong mudflats is an important conservation goal for the region.

The characterisation of mudflat morphology undertaken in this study allows for detailed estimates of mudflat habitat availability at different water levels. This study confirms the importance of the South Lagoon in terms of mudflat habitat, as it contains some 61% of available mudflat as measured in the reference sites. The results show conclusively that for the South Lagoon the mudflat areas at elevations between 0 m and 0.5 mAHD yield the greatest availability of habitat and suggest that manipulations of water level should be kept within this range. Ideally, the most important elevation range is 0.2 m to 0.4 mAHD, because manipulations in this range accomplish wetting and drying of the maximum area of mudflat, most of which is found in the South Lagoon, as measured in the reference sites. If water levels can be maintained at close to optimal levels, then natural, high-frequency wind-driven oscillations in water levels will inundate large areas of mudflat. Mudflats throughout the Coorong are generally likely to be geomorphically stable with mean mudflat slopes averaging 0.72%. Mudflat morphology is thus indicative of an accreting sedimentary environment (Pritchard *et al.* 2002) and all mudflats should be highly productive if the necessary physical, chemical and biological conditions existed. Currently, however, mudflats throughout the Coorong are in poor condition in terms of biological productivity, apart from some areas near the Murray Mouth (Rolston and Dittmann 2009) and this is indicative of the degraded state of the system (Phillips and Muller 2006).

By linking the GIS models presented here to the hydrodynamic model of Webster (2007), as detailed in section 6.3.2, it is possible to predict how mudflat availability will change along the length of the Coorong under any given flow scenario. This is modelled for a number of scenarios in chapter 6. This will allow managers to compare different potential scenarios for their influence on mudflat availability, and take this important habitat into account when making decisions on the quantity, timing and duration of flows to be released into the system. Water levels have direct implications for biological functioning and may also affect productivity at higher trophic levels (Boyes and Allen 2007). While water levels above 0.5 mAHD provide a diminishing return in terms of increases in mudflat habitat availability, the flushing effects of freshwater inputs into the system at these water levels would most likely be far more beneficial in terms of increased ecological viability, mainly due to the effects on water quality and greater productivity at lower salinities.

5.7. References

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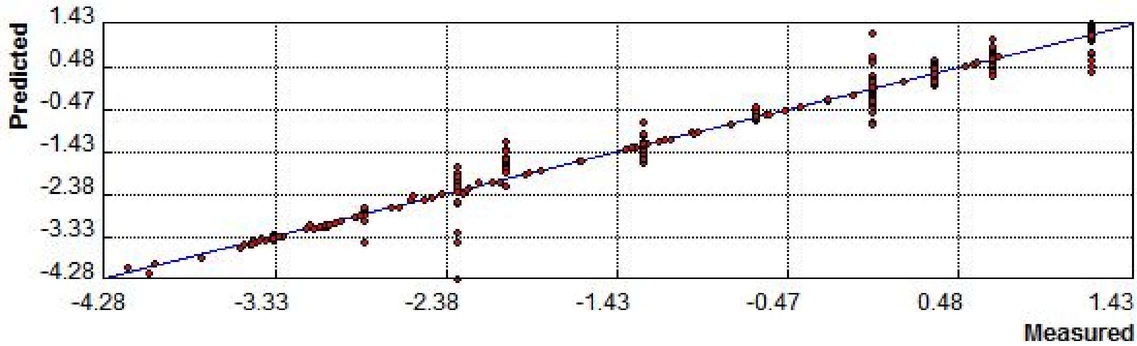
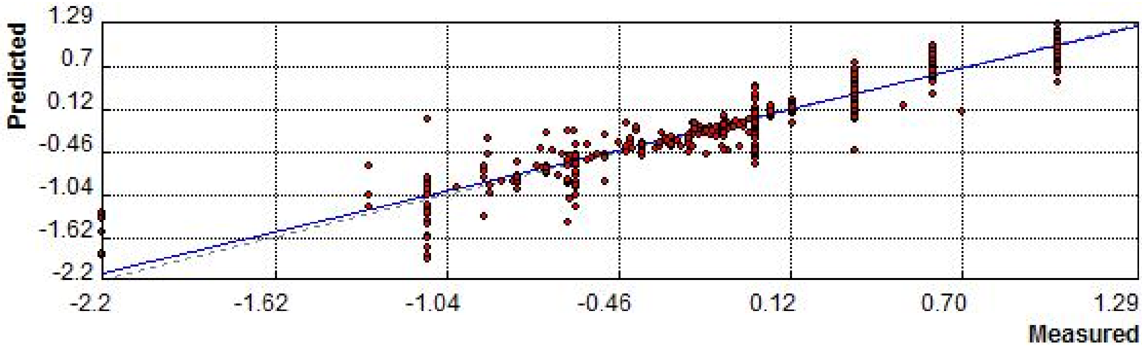
5.8. Appendices

Appendix 5.1a: Surface Validation Results showing fit between predcited surface and measured surface for each reference site.

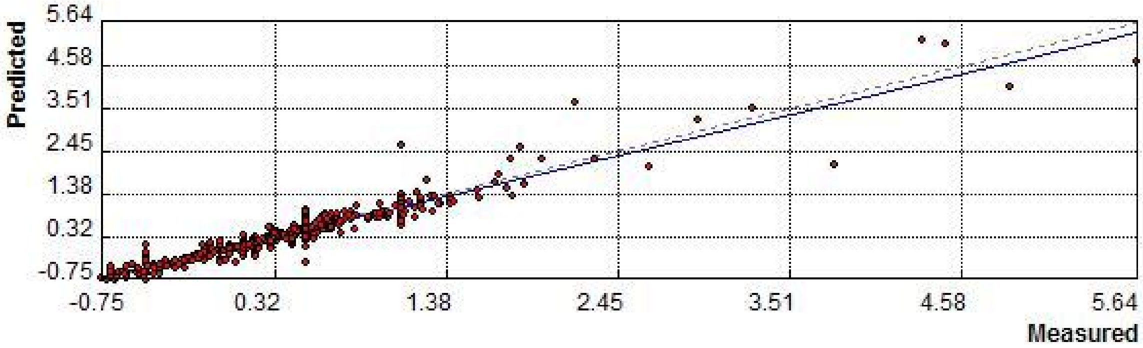
Salt Creek



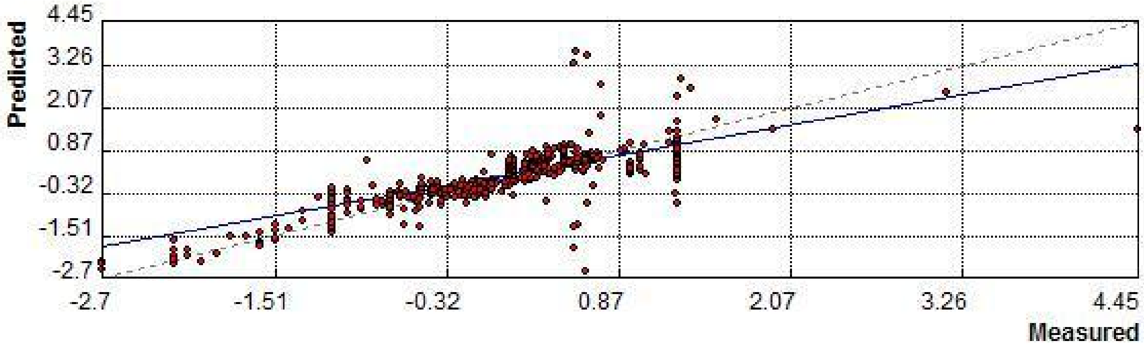
Jack Point



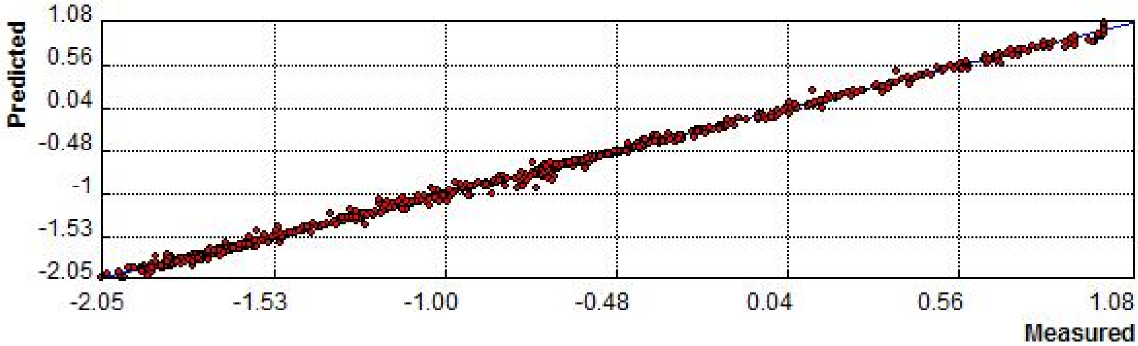
Villa dei Yumpa



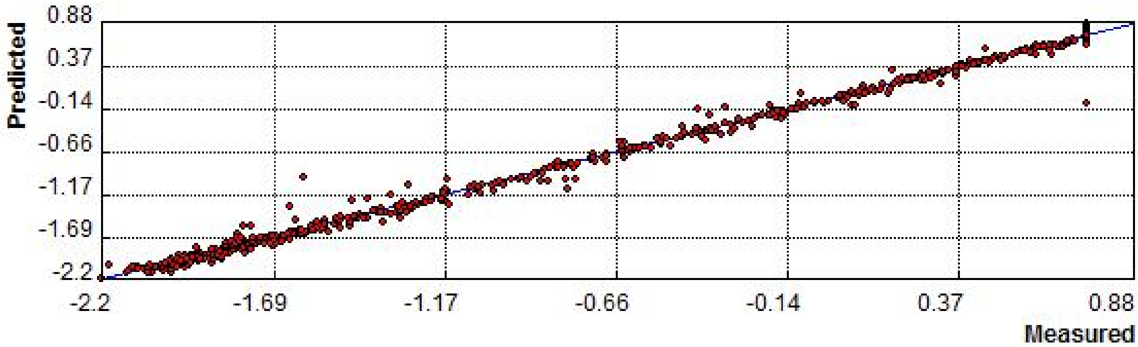
Parnka Point



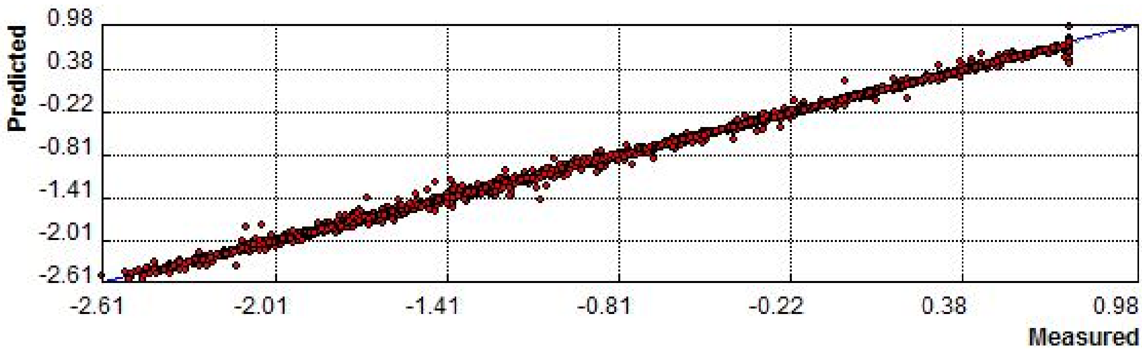
Noonameena



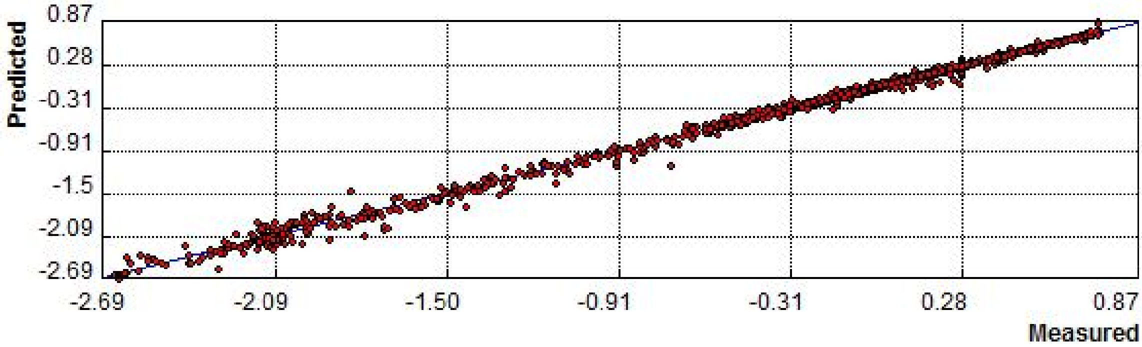
Long Point



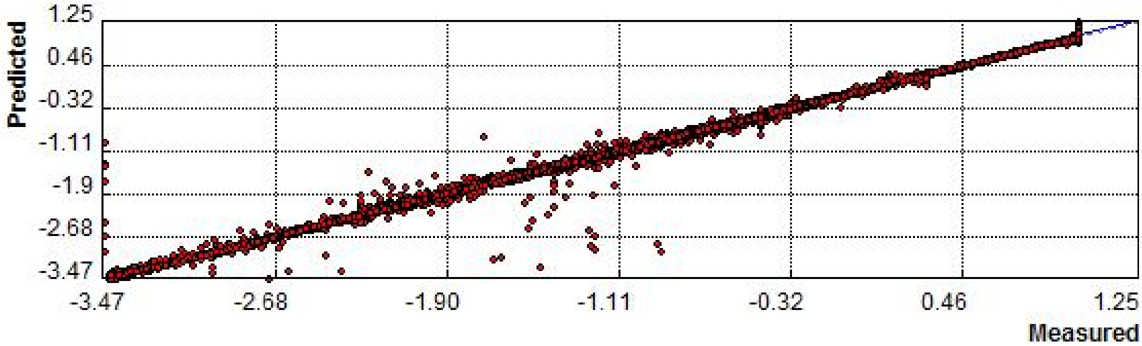
Mark Point



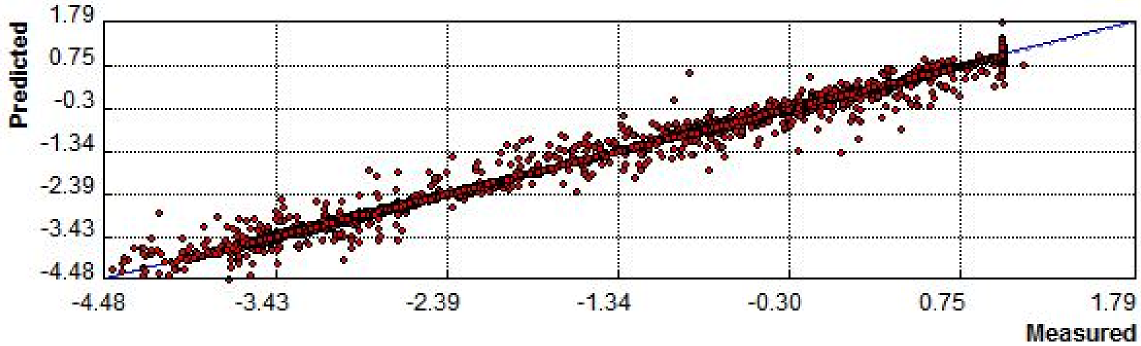
Pelican Point



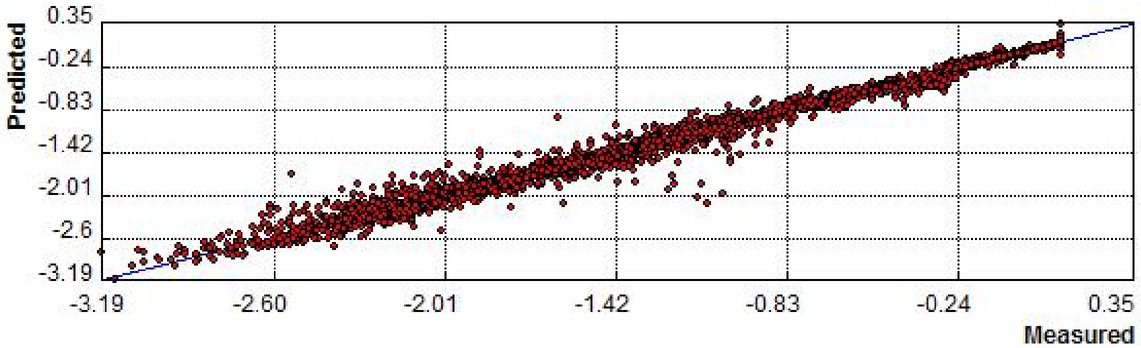
Ewe Island



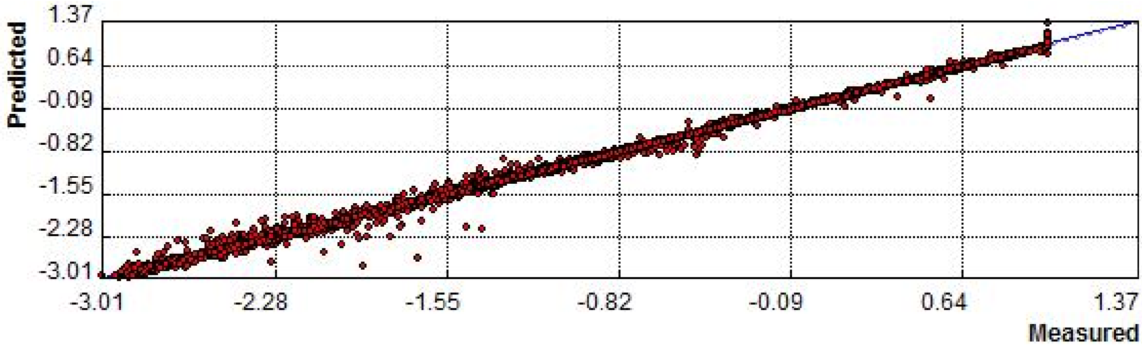
Barker Knoll



Mundoo Channel



Goolwa Channel



Appendix 5.1b: Cross validation results for the thin plate spline models at each site.

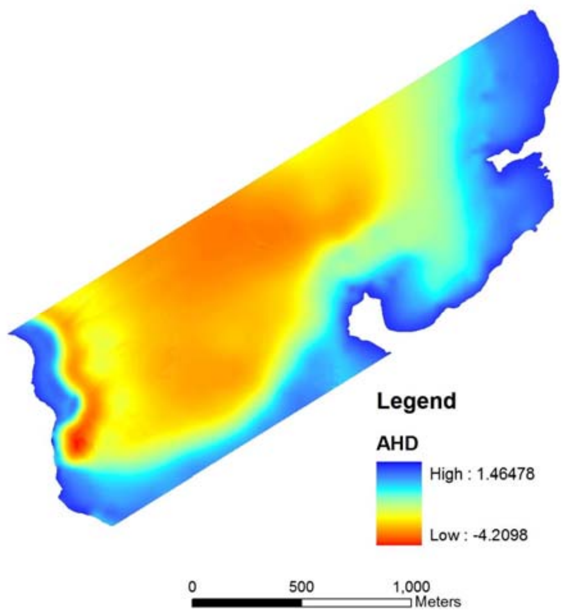
Reference Site Model	Number of Validation Points	Mean Error	RMS Error	Regression Function*
Salt Creek	704	0.0005	0.2548	0.962x + 0.021
Jack Point	602	-0.0014	0.1978	0.960x + 0.007
Villa dei Yumpa	628	-0.0063	0.2081	0.948x + 0.008
Parnka Point	868	-0.0120	0.4426	0.708x + 0.119
Noonameena	920	0.0003	0.0352	1.000x + 0.000
Long Point	713	0.0003	0.0642	0.999x - 0.004
Mark Point	2718	0.0001	0.0371	1.000x + 0.000
Pelican Point	1977	0.0001	0.0439	1.000x + 0.000
Ewe Island	13987	-0.0003	0.0701	1.000x + 0.000
Barker Knoll	3594	0.0008	0.1571	1.000x + 0.001
Mundoo Channel	9321	0.0001	0.0581	0.999x + 0.000
Goolwa Channel	7769	0.0001	0.0431	1.000x + 0.000

*Relationship between predicted (y) and actual (x) depths.

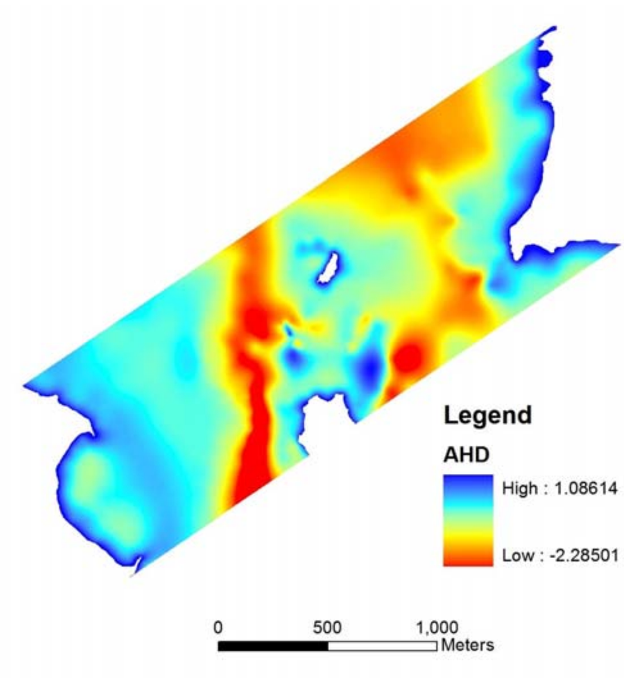
Appendix 5.2: High resolution surface models for each reference site.

Note differences in vertical scale between sites.

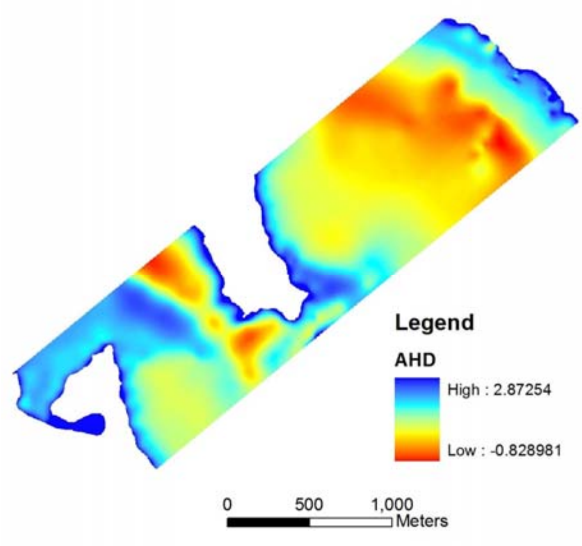
Salt Creek



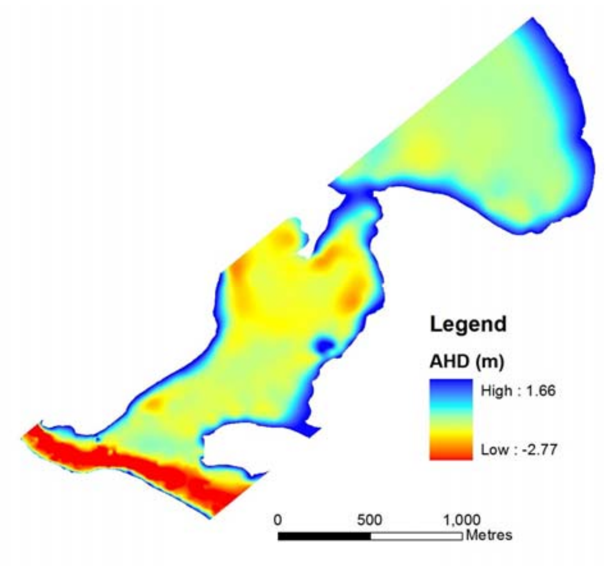
Jack Point



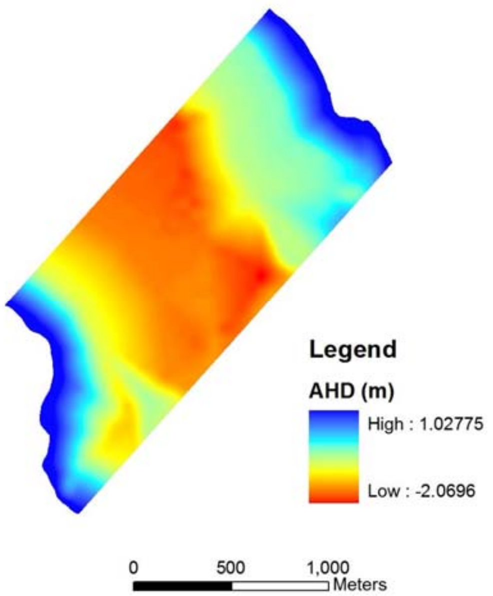
Villa dei Yumpa



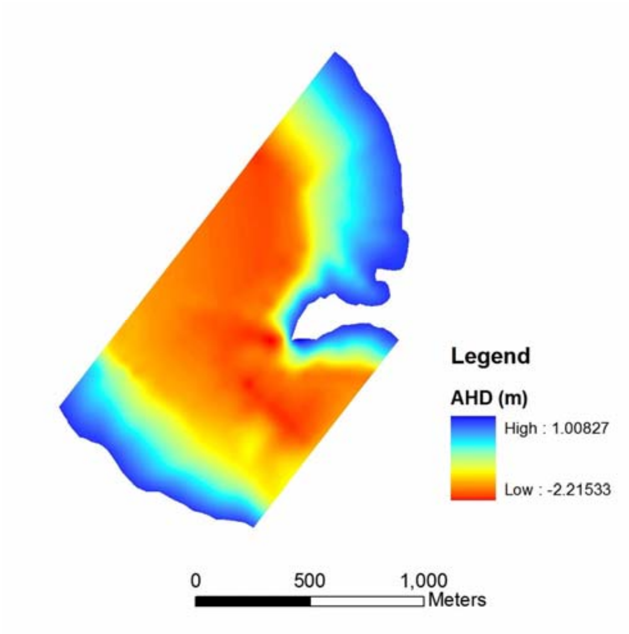
Parnka Point



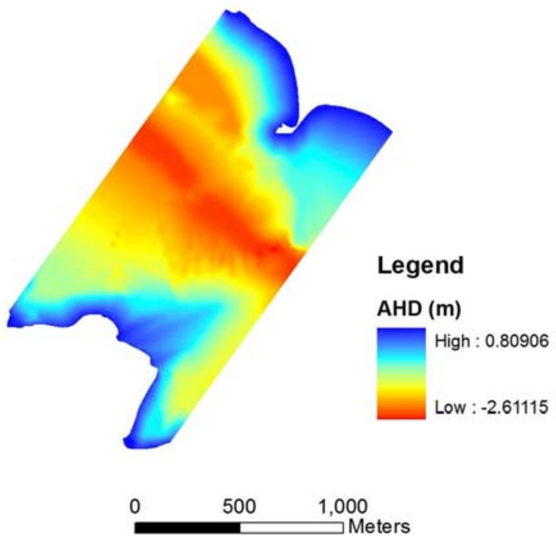
Noonameena



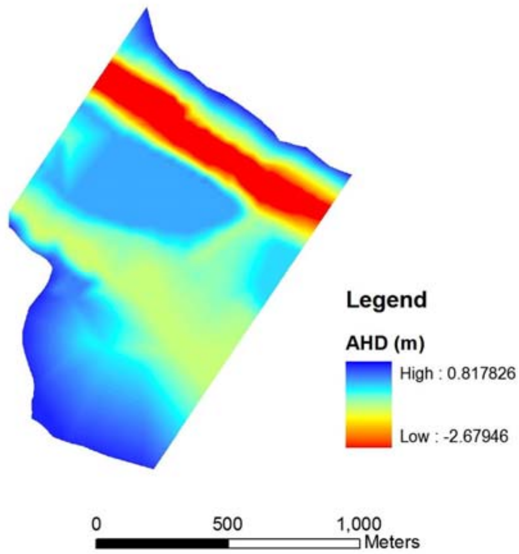
Long Point



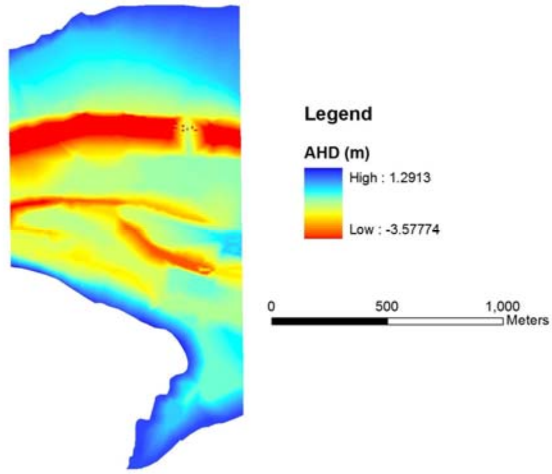
Mark Point



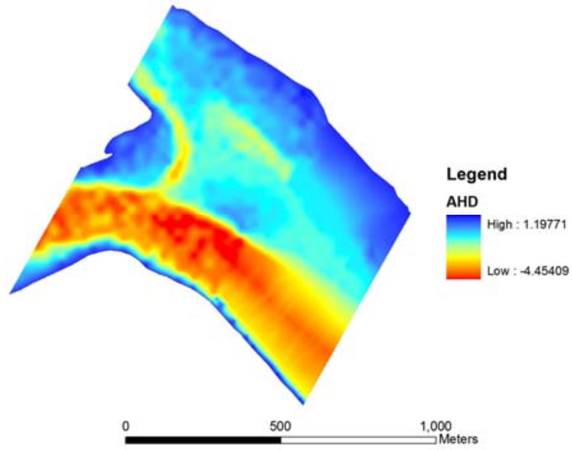
Pelican Point



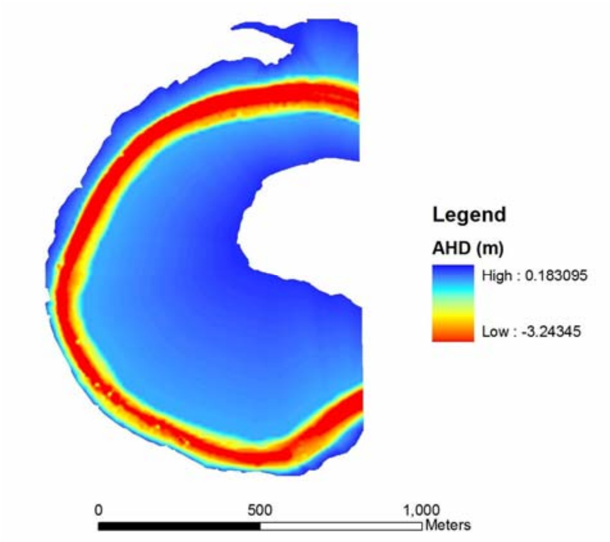
Ewe Island



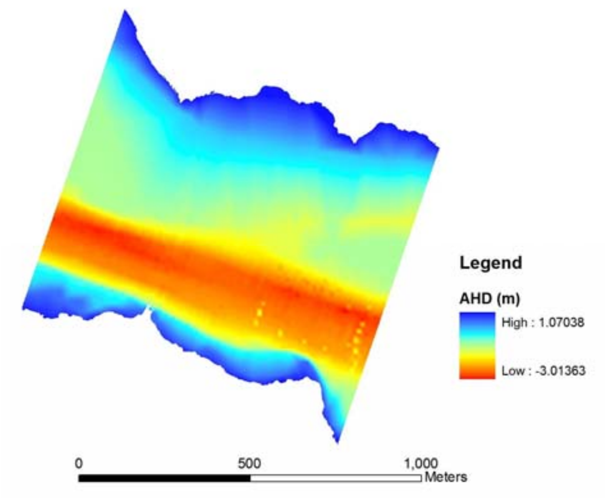
Barker Knoll



Mundoo Channel



Goolwa Channel



Appendix 5.3: General mudflat slope parameters at each reference site

Salt Creek		Slope in percent				
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	200106	0.00	14.23	14.23	1.16	1.08
0.0 to 0.5m	274669	0.00	14.26	14.26	0.88	0.84
0.5m to 1.0m	259725	0.00	8.46	8.46	0.76	0.65
1.0m to 1.5m	94444	0.01	8.00	8.00	0.62	0.50

Jack Point						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	710500	0.00	6.79	6.79	0.50	0.47
0.0 to 0.5m	945271	0.00	8.47	8.47	0.38	0.47
0.5m to 1.0m	154373	0.00	7.44	7.44	1.27	0.62
1.0m to 1.5m	4150	0.00	2.65	2.65	0.38	0.44

Villa dei Yumpa						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	1489699	0.00	3.50	3.50	0.21	0.22
0.0 to 0.5m	1004309	0.00	8.92	8.92	0.38	0.38
0.5m to 1.0m	114184	0.00	12.13	12.13	1.33	0.98
1.0m to 1.5m	12675	0.00	13.07	13.07	1.43	2.56

Parnka Point						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	137646	0.00	60.60	60.60	1.15	1.43
0.0 to 0.5m	1367330	0.00	75.01	75.01	0.31	0.69
0.5m to 1.0m	342823	0.00	55.95	55.95	1.22	1.28
1.0m to 1.5m	222285	0.00	30.77	30.77	1.14	1.04

Noonameena						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	324747	0.00	0.97	0.97	0.42	0.27
0.0 to 0.5m	177023	0.07	1.27	1.20	0.68	0.15
0.5m to 1.0m	201053	0.01	1.26	1.25	0.56	0.20
1.0m to 1.5m	1221	0.00	0.52	0.52	0.20	0.15

Long Point						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	188667	0.10	5.59	5.48	0.77	0.49
0.0 to 0.5m	231888	0.18	5.37	5.19	0.67	0.41
0.5m to 1.0m	145134	0.03	4.41	4.38	0.53	0.31
1.0m to 1.5m	12	0.49	0.53	0.04	0.50	0.01

Mark Point						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	239840	0.00	2.73	2.73	0.67	0.46
0.0 to 0.5m	175088	0.06	3.04	2.98	0.86	0.47
0.5m to 1.0m	102604	0.00	3.05	3.05	0.64	0.45
1.0m to 1.5m	0	0.00	0.00	0.00	0.00	0.00

Pelican Point						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	395667	0.00	4.63	4.63	0.57	0.62
0.0 to 0.5m	463754	0.00	3.97	3.97	0.39	0.48
0.5m to 1.0m	121506	0.00	1.97	1.97	0.41	0.39
1.0m to 1.5m	0	0.00	0.00	0.00	0.00	0.00

Ewe Island						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	310847	0.00	18.10	18.10	0.59	0.74
0.0 to 0.5m	210577	0.00	4.66	4.66	0.71	0.74
0.5m to 1.0m	174780	0.00	4.53	4.53	0.84	0.75
1.0m to 1.5m	16071	0.00	4.29	4.29	0.65	0.87

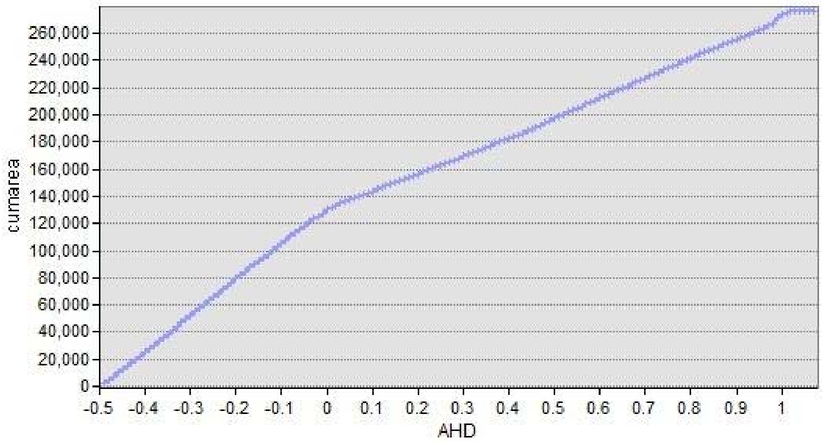
Barker						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	125549	0.00	26.29	26.29	1.57	2.48
0.0 to 0.5m	86103	0.01	23.42	23.41	1.91	2.45
0.5m to 1.0m	88209	0.00	20.06	20.06	1.55	1.74
1.0m to 1.5m	1815	0.01	8.46	8.46	1.11	1.16

Mundoo Channel						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	565357	0.00	10.47	10.47	0.41	0.95
0.0 to 0.5m	129737	0.00	7.24	7.24	0.23	0.31
0.5m to 1.0m	0	0.00	0.00	0.00	0.00	0.00
1.0m to 1.5m	0	0.00	0.00	0.00	0.00	0.00

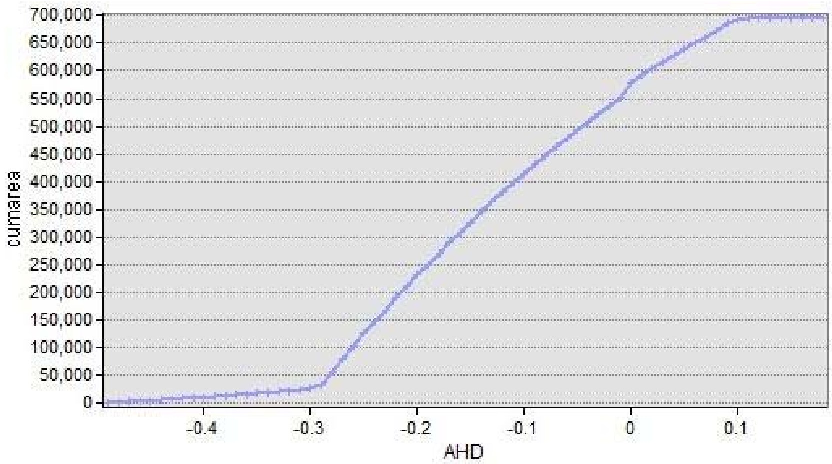
Goolwa Channel						
AHD	Area (m^2)	MIN	MAX	RANGE	MEAN	SD
-0.5 to 0.0m	128855	0.01	15.13	15.12	0.85	1.01
0.0 to 0.5m	66556	0.01	14.76	14.74	1.65	1.07
0.5m to 1.0m	75453	0.00	8.11	8.11	1.28	0.76
1.0m to 1.5m	5179	0.00	2.63	2.62	0.27	0.30

Appendix 5.4: Hypsometric Curves for the Reference Sites (cummulative area in m^2)

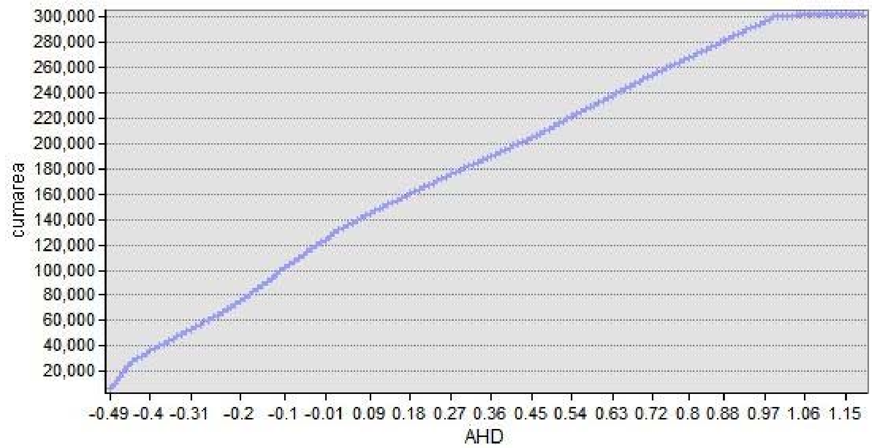
Goolwa Channel



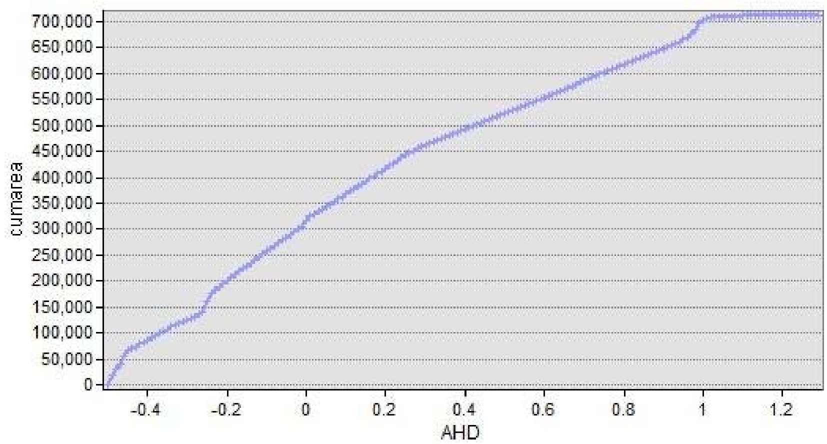
Mundoo Channel



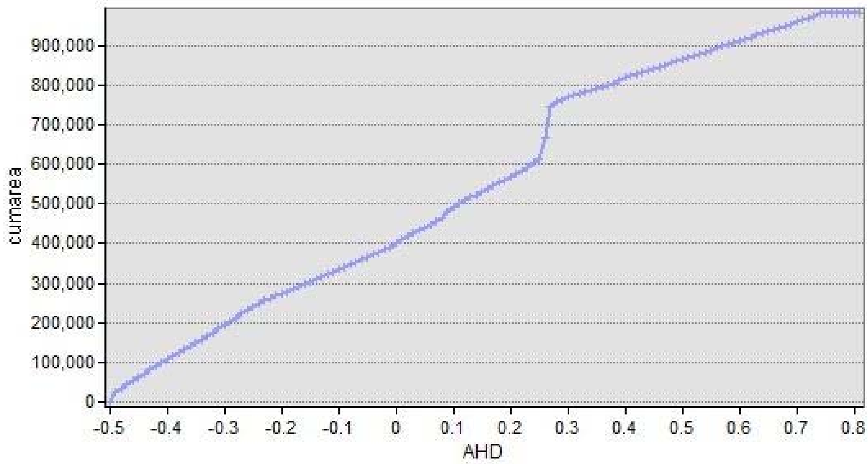
Barker Knoll



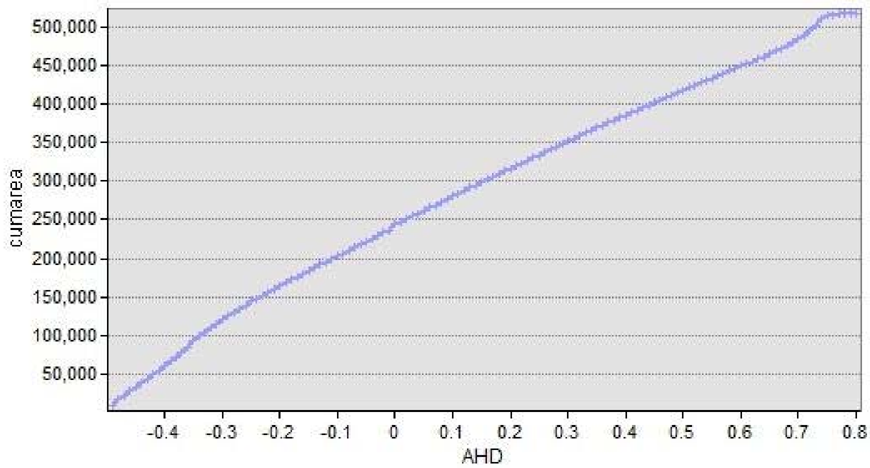
Ewe Island



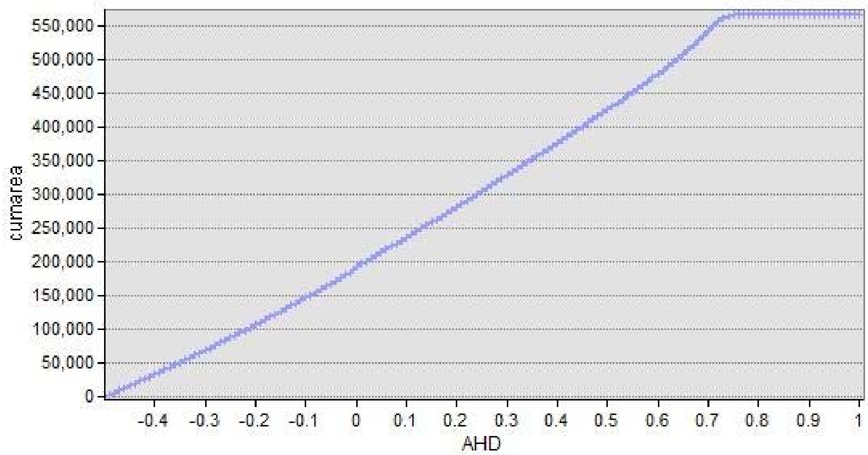
Pelican Point



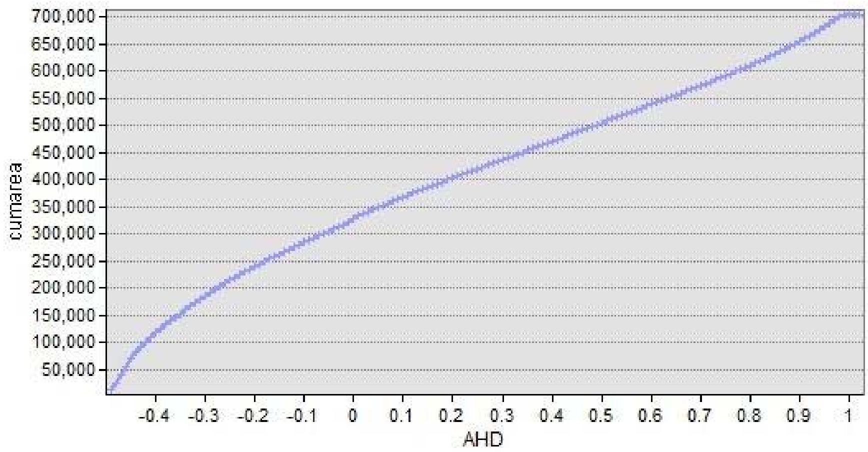
Mark Point



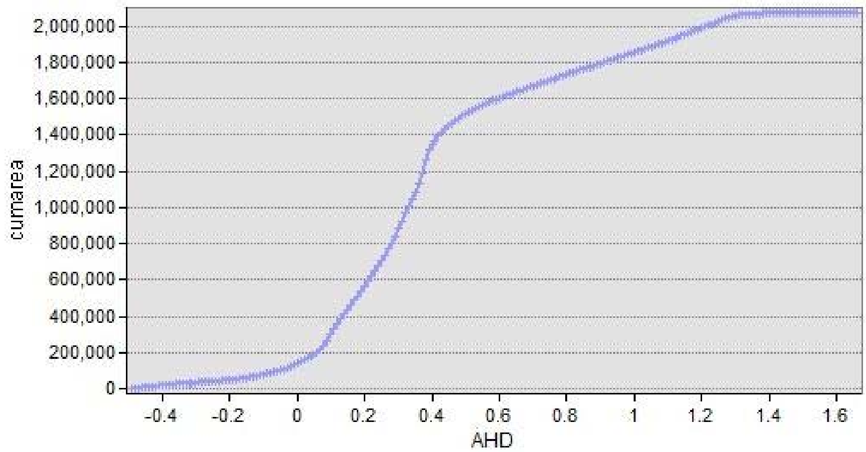
Long Point



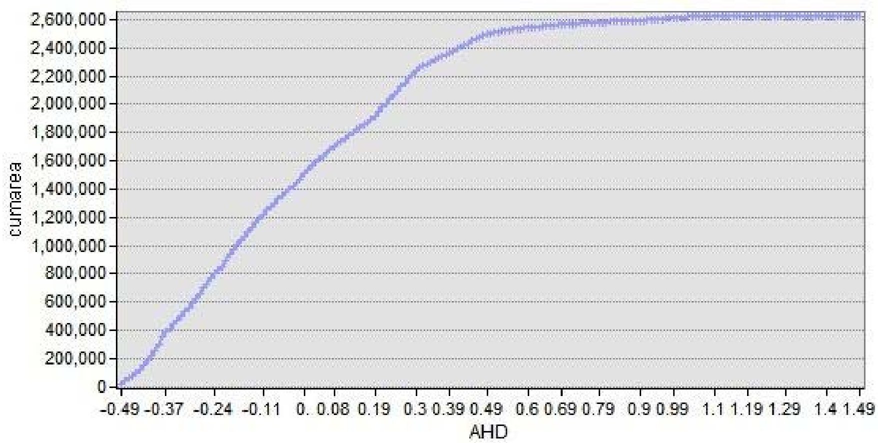
Noonameena



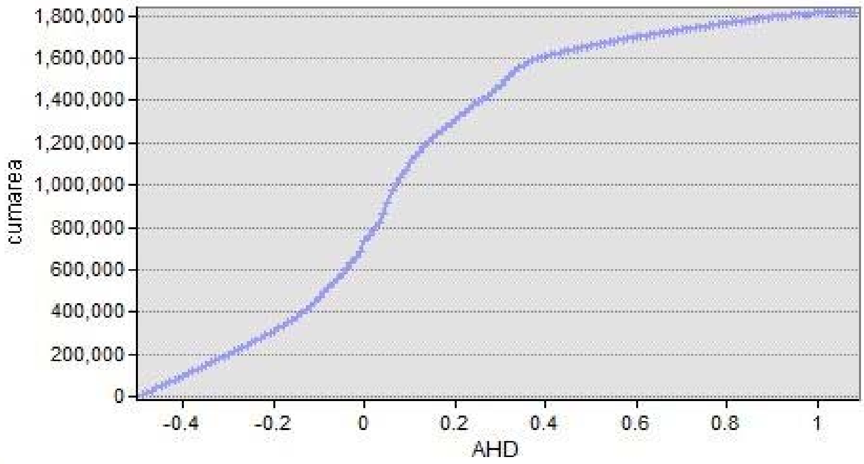
Parnka Point



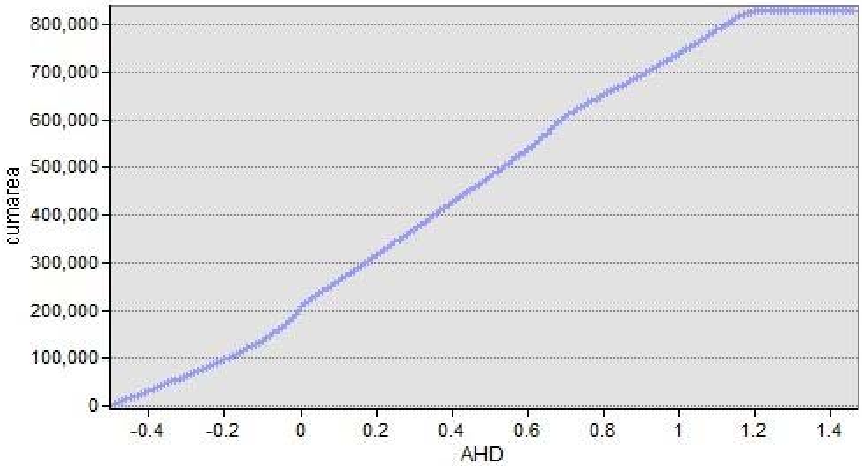
Villa dei Yumpa



Jack Point



Salt Creek



6. Spatial modelling of mudflat availability and fish habitat in the Coorong

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6.1. Executive Summary

Water level and salinity are the key ecological drivers in the Coorong. Water level determines the availability of mudflat habitats, which constitute vital habitat for many species of waterbirds, supporting highly productive foraging grounds. Salinity has long been acknowledged as the most significant water quality parameter directly influencing the distribution of all biological communities in the Coorong including fish, macrophytes and micro-invertebrates and indirectly influencing waterbird numbers through limiting food resources.

This report presents spatial models of mudflat and fish habitat to predict the availability of mudflats for the waterbirds and habitats for key fish species under a range of hydrodynamic scenarios using water level and salinity simulations. The first spatial model predicts the location and extent of mudflats, defined as soft sediment areas that are either immersed or covered by no more than 12 cm of water, where most waterbird foraging occurs. The second spatial model predicts occurrence probabilities of key fish species throughout the Coorong, based on the results of logistic regression modelling using observed presence from an extensive sampling effort carried out between 2006-08. Both models use water level data from the hydrodynamic model generated for the current climate (Scenario A) prescribed by the CSIRO Sustainable Yields project, while the second model also uses salinity data from the hydrodynamic model. The spatial models run continuously for the series of simulated water level and salinity data produced by the hydrodynamic model, and subsequently maps are generated for each scenario.

Three representative sites from the set of 12 used by CLLAMMecology, Barker Knoll, Noonameena and Salt Creek, were analysed for maximum and minimum water levels in two wet (1976 and 1993) and two dry (1988 and 2005) years, selected based on salinity levels in the South Lagoon. Mudflat availability varied spatially and temporarily along the Coorong, and is influenced by the primary factors of tide, wind, rainfall and evaporation, some of which are dependent on the distance from the Murray Mouth and are affected by seasonal variation. Underwater topography was also found to be significant for mudflat availability. The modelling of mudflats at different water levels suggests that an average water level of 0.12 mAHD (Australian Height Datum) gives the maximum average mudflat area in the three reference sites, with the majority of the mudflats located on the eastern shores.

Out of seven key fish species, Yelloweye Mullet (*Aldrichetta forsteri*), Smallmouth Hardyhead (*Atherinosoma microstoma*), Greenback Flounder (*Rhombosolea tapirina*) and Tamar River Goby (*Afurcagobius tamarensis*), demonstrated a significant relationship with salinity. Among the three different salinity gradient

scenarios examined, a salinity range from 5 to 90 g/L along the Lagoon was found to be the best in terms of the suitability of the entire Lagoon for these four key species, as well as for supporting other important biological communities including both macrophytes and infauna.

While this study suggests an appropriate water level and salinity gradient for maximizing available mudflat areas, as well as the "health" of biological communities in the Coorong, it is unable to provide advice on the amount and timing of barrage outflow to achieve them. Additional research and modelling considering all physical and hydrological factors may be able to provide an answer to the question: how much and how frequently does freshwater need to be released through the barrages to maintain an optimum water level and salinity gradient in the Coorong? Mixing mechanisms, groundwater inputs and local precipitation inputs for the Coorong remain unknown. However, from a management perspective, managers can use the spatial models developed through this study as management tools to instantly assess mudflat availability and the habitat suitability for these species for specified flow scenarios, and to assist informed decisions on barrage outflows, once the Lower Lakes recharge.

6.2. Introduction

The Coorong lagoonal system forms part of one of the largest estuaries in Australia and has been recognized nationally and internationally for its ecological, social and economic significance (Seaman 2003; Edyvane 1999). The ongoing drought conditions in the Murray Darling Basin have led to a situation where virtually no freshwater flows have entered the Lagoon since 2003 (CLLAMM 2008). The ecology of the Lagoon and surrounding region has been negatively affected by rising salinity and reduced water levels, particularly in the South Lagoon (Geddes 2005a; 2003). Consequently, ecosystem degradation in the Coorong is threatening many iconic bird and fish species. For example, salinities in the South Lagoon have risen to become hypersaline (100-160 g/L) in recent years, and key plant species like *Ruppia tuberosa* (Tuberous tassel) can no longer survive and have become restricted to the North Lagoon (CLLAMM 2008).

Before the recent ecological degradation, the Coorong supported a diverse array of interconnected habitats driven by salinity and water level. Lamontagne *et al.* (2004) acknowledged salinity and water level as the key ecological drivers of the system. Based on the salinity gradient, the habitats in the Coorong were differentiated into freshwater in the areas around the Murray Mouth, estuarine at the upper end and marine at the lower end of the North Lagoon and in the South Lagoon. Specific biological communities of macrobenthos, fish and phytoplankton colonised these habitats, depending on their salinity tolerance.

In the Coorong, water level and periodic inundation also play a key role in defining spatial extent for fish habitats as well as availability of mudflats. These mudflats constitute highly productive feeding grounds for wading birds and attract large numbers of local and intercontinental species (Rogers and Paton 2009a; Wilson 2001), resulting in the regions designation as a Ramsar listed wetland. As a consequnece, Australia is obligated to maintain the area in the state that it was in at the time of declaration. However, Wilson (2001) reported a drastic reduction in the number of waterbirds in the Coorong since early 1980s. In the past three decades, the largest flock of birds (234,543) counted in 1982 while 48,425 birds were counted in 2001. The number of Sharp-tailed Sandpipers, Red-necked Stints, Curlew Sandpipers, Red-necked Avocets and Red-capped plovers declined sharply over the period (Wilson 2001).

Restoration and conservation of all these habitats are considered highly significant for the biological diversity and ecological sustainability of the region. Freshwater inputs through the barrages that separate the Coorong and the Lower Lakes, and through the Upper South East Drainage (USED) scheme, are essential to maintain water level and salinity gradients as well as frequent inundation of mudflats. Precipitation and evaporation influence water level and salinity in the Coorong (Webster 2007), whereas tide and wind affect mudflat inundation and vary temporarily and spatially along the lagoon (see Chapter 5). The mudflats around the Murray Mouth are influenced by daily tidal routines whereas large tidal events such as king tides may inundate mudflats in areas beyond the Murray Mouth region. Spatio-temporal variation in all these factors impacts on salinity and water levels along the lagoon. In response to fluctuations in salinity and water levels, the available habitats are subjected to change, which ultimately affects the composition and productivity of biological communities.

The restoration of the diverse ecosystems of the Coorong is of utmost importance to maintain its status as a Ramsar Wetland of International Significance as well as its iconic site status under the Living Murray Initiative. It has been acknowledged that a detailed understanding of the ecology of the Coorong is necessary to prescribe a decision-support framework for an effective intervention, which would aim to restore the vital lagoonal ecosystem in the Coorong. The necessity of ecological knowledge at the local level and, in particular, understanding of the relationships between species and their environment, have been widely acknowledged by many ecologists as key to the successful conservation and management of ecosystems (Aber 2007; Carter *et al.* 2006; Gibson *et al.* 2004).

The accelerated degradation of ecosystems and biodiversity in the Coorong require a detailed understanding of the species-environment relationships for iconic bird and fish species to predict their habitats at varying salinity and water levels. Rogers and Paton (2009a) and Noell et al. (2009) conducted a detail on the waterbirds and fish species in the Coorong under the Key Species Project of the CLLAMMecology research cluster, respectively, and provide a summary of the important species present. The modelling of relationships enables us to predict habitat availability under changed climatic conditions. The Dynamic Habitat Project under the Coorong, Lower Lakes and Murray Mouth Ecology (CLLAMMecology) Research Cluster aims to develop spatial models to predict the habitats for waterbirds and key fish species under varying hydrodynamic scenarios. The first model predicts mudflat availability for waterbirds by quantifying available mudflat areas up to 12 cm water depth, where the majority of waterbird foraging occurs (Rogers, pers. comm.; Wildlife Habitat Management Institute 2000). The accessibility of mudflat for waterbirds is likely to be determined by their size. As the average size of the major waterbird species does not exceed 21 cm (for Sharp-tailed Sandpiper), the shallower mudflat areas are generally available for foraging. However, in a recent study, Rogers and Paton (2009a) found that the foraging behaviour of waterbirds is influenced by the water depth and foraging grounds are likely to be inaccessible below 20 cm depth in the Coorong. The second model predicts occurrence probability for key fish species including four commercially important species: Black Bream (*Acanthopagrus butcheri*), Greenback Flounder (*Rhombosolea tapirina*), Yelloweye Mullet (*Aldrichetta forsteri*) and Mulloway (*Argyrosomus hololepidotus*), two common small-bodied estuarine fish: Smallmouth Hardyhead (*Atherinosoma microstoma*) and Tamar River Goby (*Afurcagobius tamarensis*) and one species of conservation significance: Congolii (*Pseudaphrites urvillii*), based on salinity levels along the lagoon. Both models use water level data from the hydrodynamic model developed for the Coorong (Webster 2007) generated for the current climate (Scenario A) as prescribed by the CSIRO Sustainable Yields project (Chiew *et al.* 2008), and the second model also uses salinity data generated from the hydrodynamic model.

The first model compliments the study on mudflat geomorphology and availability at different water levels in the Coorong described in Chapter 5. Chapter 5 discusses the geomorphological characteristics of mudflats at the 12 CLLAMMecology reference sites and presents an analysis of mudflat availability at varying water depths in these sites. The model in the current study integrates digital elevation models (DEMs) described in the previous chapter and hourly water level data from Webster's (2007) model to predict foraging ground up to 12 cm water depth; a part of the mudflat specifically utilized by waterbirds in the Coorong. The model generates mudflat habitat maps for hourly water level data showing the availability of mudflats in the eastern (landward), western (seaward) sides of the Coorong and in the channel areas. The second model predicts the occurrence probability of the key fish species in relation to the salinity levels in the Coorong.

Both habitat models are developed within a GIS framework in ArcGIS (ver. 9.3) and iteratively apply hourly water level and salinity data generated by the hydrodynamic model. These models are not truly dynamic process models as they neither simulate the physical process for predicting habitat change nor use outputs of previous iterations as input to the subsequent iteration (Environmental Systems Research Institute 2006). However, these models use hourly data on water level and salinity from the hydrodynamic model and deliver hourly habitat maps depicting the dynamic influence of these ecological factors on habitat availability in the Lagoon.

6.3. Methods

6.3.1 Datasets

Bathymetry for the reference sites

The bathymetry generated for studying mudflat geomorphology and availability over the 12 Coorong reference sites (see Chapter 5 in Appendix 5.2) was used in these models. Depth data for the North Lagoon were collected by the South Australia Water Corporation (SA Water) by using an echo-sounder and GPS mounted on a boat. However, such a survey was not feasible in the South Lagoon due to the shallow water depth (Miles 2006). Hence, depths at four reference sites in the South Lagoon were measured manually using a combination of techniques (see Chapter 5). The bathymetry for all reference sites was derived by interpolating the depth data using Radial Basis Functions available in the Geostatistical Analyst extension in ArcGIS (ver. 9.3) (Environmental Systems Research Institute 2001). The bathymetry represented the topography at these reference sites in metres (m) in relation to Australian Height Datum (AHD) with 1 m horizontal resolution and 0.001 m vertical resolution. The process of bathymetry development for the reference sites in the Coorong is described in Chapter 5 and the resultant models for the 12 reference sites are also illustrated there.

Hydrodynamic model: water level and salinity data

Webster (2007) developed a hydrodynamic model which simulates water levels and salinity within the Coorong as these respond to barrage flows, USED flows, sea level changes, wind, evaporation, precipitation and exchange through the Murray Mouth. This one-dimensional model outputs time series of simulated water level and salinity for each of 102 and 14 cells, respectively, along the centreline of the Coorong between the Murray Mouth and the southern end of the Lagoon. Water level is output at one km intervals, whereas salinity is output at intervals of 5 to 10 km (Figure 6.1).

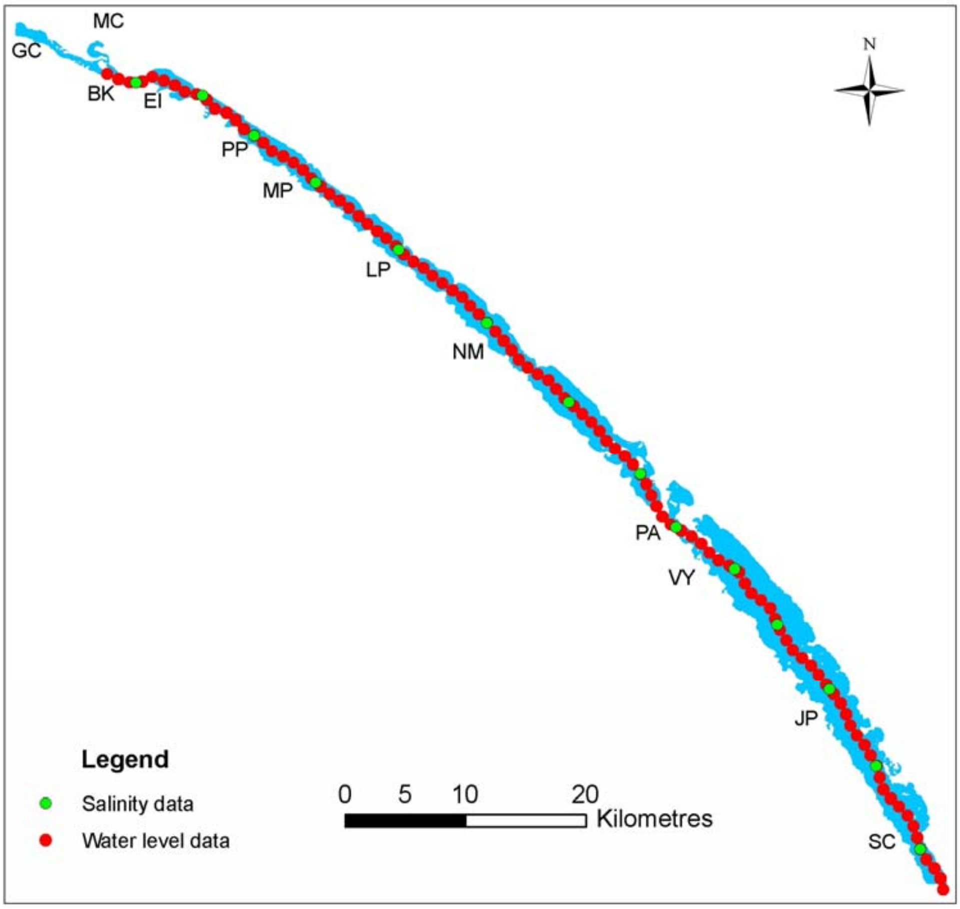


Figure 6.1. Locations of water level and salinity data points generated through the hydrodynamic model in relation to the CLLAMMecology reference sites. (GC = Goolwa Channel; MC = Mundoo Channel; EI = Ewe Island; BK = Barker Knoll; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa; JP = Jack Point and SC = Salt Creek.

The hydrodynamic model was run using barrage flows derived for a single climatic and development scenario from the CSIRO Sustainable Yields (SY) Project. These flows were made available by the Murray-Darling Basin Authority (MDBA) and are based on SY simulations that have been modified by the Victorian 2030 climate approach. Synthetic time series of flows were constructed by analysing the daily time series of climatic data for the period 1891-2008 in combination with an inflow model run using the current state of agricultural development and specifically current water management rules. This analysis is being used to assess the current and likely future water availability in the Murray-Darling Basin (Chiew *et al.* 2008). The scenario we use develops a flow time series using the historical climate sequence and inflows adjusted to the current level of development. This represents the baseline scenario.

For habitat modelling of the Coorong, we chose to predict habitat availability for the baseline scenario (Scenario A). The hydrodynamic model simulates water level and salinity for 117 years (the period between 1891 and 2008). Salinity in the South Lagoon was found to be a good indicator of very wet and dry years as this part of the Coorong better reflected the influence of consecutive wet and dry conditions producing ‘very low’ or ‘very high’ salinities compared to the North Lagoon. Two ‘very wet’ and ‘very dry’ years in the past decades were selected for a comparison of habitat availability under these conditions. Based on the simulated daily average salinities for 1891-2008 under scenario A, we identified 1976 and 1993 as wet years; and 1988 and 2005 as dry years. The hydrodynamic model was run for these years using scenario A. Water level and salinity data were linked to the geographical coordinates of the respective points.

Other GIS layers

The site boundary up to the high water mark level was digitised from the 2003 orthorectified airphoto to specify the area for analysis. The high water mark signifies the edges on the eastern and western shores of the lagoon. In order to specify the mudflats on either side of the shores, masking layers were created for the eastern and the western shores and applied in the model.

Fish Catch Data

The fish habitat modelling described in section 6.3.2 used fish catch data and salinity as the only predictor variables. These data were collected along the Coorong between October 2006 and July 2008. A detailed description of the sampling methods used is described in Noell *et al.* (2009).

6.3.2 Spatial Model Development

Modelling mudflat availability

A spatial model for predicting mudflat availability under various flow scenarios was developed by integrating the water level output from the hydrodynamic model with the fine resolution bathymetry. The model was initially developed in ModelBuilder within the ArcGIS platform utilizing functionality and tools available in ArcToolBox including spatial analyst, data management, conversion and analysis tools. Once the model was run successfully and delivered desirable outputs, the model was exported as a python script. The script was modified to incorporate looping ability so that hourly water level from the hydrodynamic model could be used to generate maps for mudflat availability at the same interval. The model development processes for both models are described in the following sections.

Model for single run developed in ArcGIS Model Builder platform

The fine resolution bathymetry (1x1 m), water level data from the hydrodynamic model and a boundary layer covering up to the high water mark level were integrated into ArcGIS ModelBuilder to predict the spatio-temporal availability of mudflat habitats in the Coorong. The entire model is shown in Figure 6.2 and the four parts of the model are illustrated in Figures 6.3-6.6. The model is composed of six model parameters (blue ovals) and uses 12 processes (yellow rectangles) and generates 12 outputs (green ovals) including 9 intermediate and 3 final outputs.

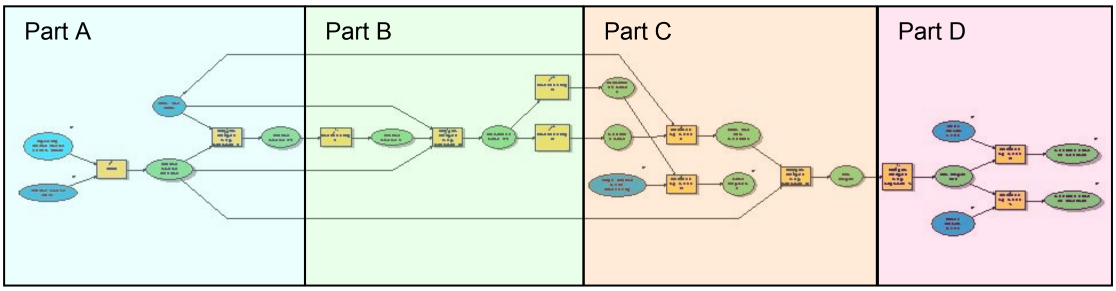


Figure 6.2. Overall model for predicting mudflat availability in the Coorong. Each part is presented in detail in Figures 6.3-6.6. Dark blue ovals represent input data or layer, light blue oval represents parameter input, yellow rectangles represent processes and green ovals represent model intermediate and final outputs.

The water level data from the hydrodynamic model contained hourly time series data for 102 points distributed linearly along the Lagoon. These data points were first assigned geographic coordinates and a field name was given to each column of water level data. The water level data from the hydrodynamic model were interpolated using the inverse distance weighted (IDW) interpolation in the Spatial Analyst extension in ArcGIS (ver 9.3) (Environmental Systems Research Institute 2009). IDW applies an inverse power weighting function to the distance of the measured points. Nearby points have higher weights and influence than points located at greater distance (De Smith *et al.* 2006). The goodness of fit of the models generated by IDW and other methods were compared using the Geostatistical Analyst extension in ArcGIS. Although Radial Basis Functions are considered to be the best method for topographical surface interpolation with dense sampling data (Environmental Systems Research Institute 2001), in this case the IDW produced the lowest root mean square error. Kriging produced the highest root mean square error of all three methods. Hence, the IDW was used for interpolating water level data at specified times to generate a two dimensional water level surface of 1 x 1 m grid cells (Water Level Raster). The area of interest for raster interpolation was specified by setting the extent to the boundary layer in the model properties. The water level surface (Water Level Raster) was applied to the DEM of the site (DEM site) to derive an output (Water Level Mask 01) with values 0 and 1 using Map Algebra (1). In the output raster, a value of 1 signifies a 'true' condition and represents the area less than or equal to the water level while the 0 value indicates a 'false' condition and represents the area above the water level.

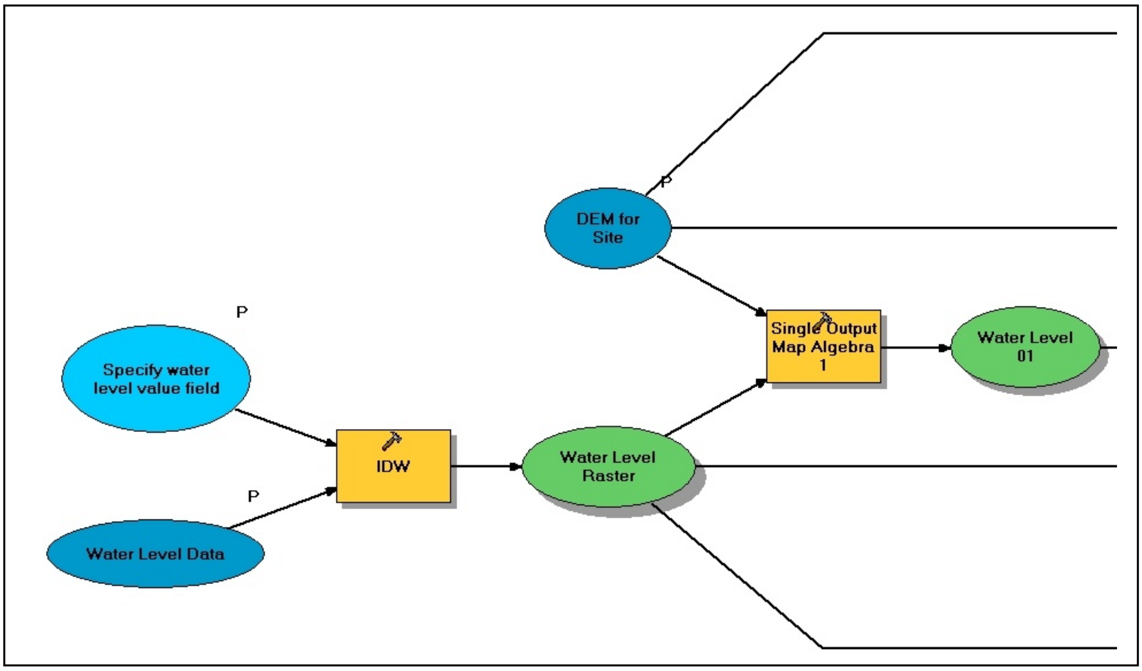


Figure 6.3. Mudflat habitat model part (A).

A raster mask was required to delineate the area at the specified water level for identifying the mudflat area used by waterbirds. In the model part B (Figure 6.4), the output of the model part A (Water Level Mask 01) was assigned 1 to 0 and 0 to NoData (Reclassify 1) to generate a raster mask with 0 value (Water Level Mask 1). In the Map Algebra (2), the water level raster (Water Level Raster) and raster mask (Water Level Mask 1) were applied together with water depth up to 12 cm from the water level to the DEM of the site. The water depth up to 12 cm was used to extract the mudflat area utilized by waterbirds in this case. However, this value could be changed to suit the various depths and mudflat areas utilized by different species of waterbirds. In the output raster (Subtidal Mudflat area 01), a value of 1 indicates the area up to 12 cm water depth and 0 signifies the subtidal area deeper than 12 cm water depth. Reclassify (2) was applied to Subtidal Mudflat area 01 to assign both values 0 and 1 to NoData (Exposed area) for identifying the exposed mudflat area above the water level whereas reclassify (3) excluded the mudflat area with 1 value and the rest to NoData (Mudflat area). The outputs of both reclassify (2) and (3) are shown in the model part C (Figure 6.5).

The first output of the model, exposed area between the water level and the high water mark boundary, was obtained by employing an ‘extraction by mask’ operation. This operation uses the high water mark boundary layer as an input layer and the raster specifying the area below water level as a mask (Exposed area). Similarly, another ‘extraction by mask’ operation was applied to the DEM of the site by using the Mudflat area raster to obtain the DEM for the mudflat area up to 12 cm water depth from the water level (Mudflat DEM). The DEM for the mudflat area (Mudflat DEM) changed from floating point to integer data type (DEM integer) and would be the input for the model part D (Figure 6.6).

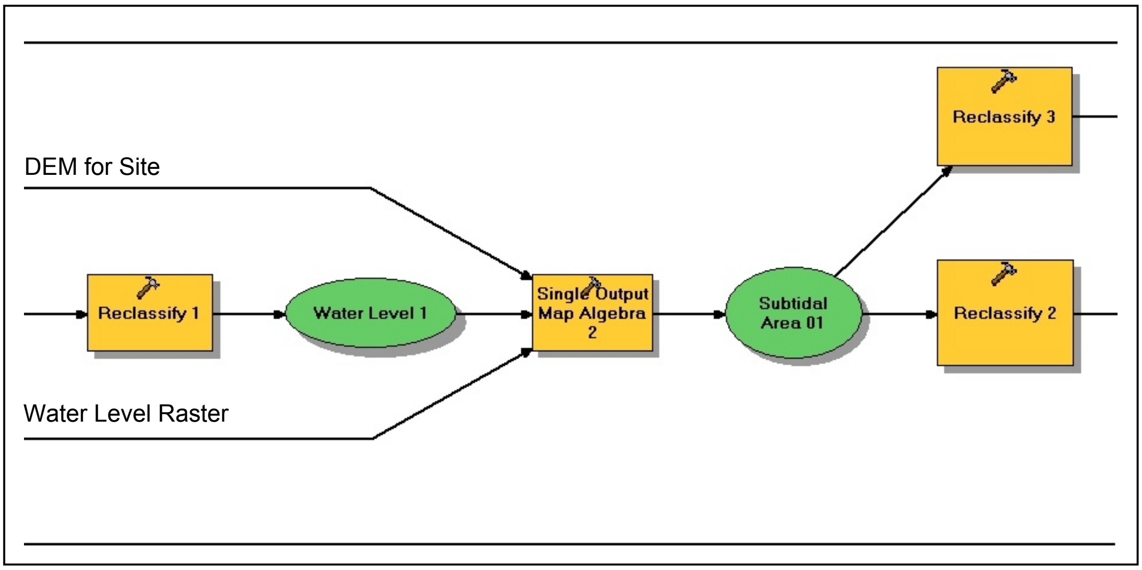


Figure 6.4. Mudflat habitat model part (B).

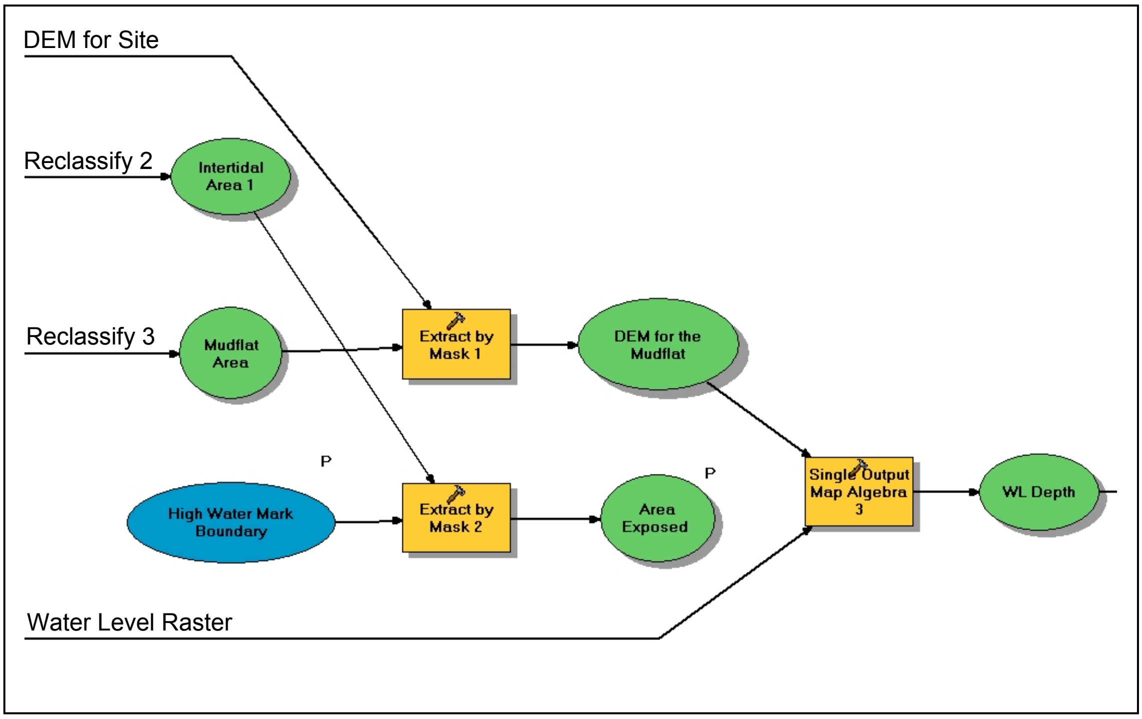


Figure 6.5. Mudflat habitat model part (C).

In the model part D (Figure 6.6), the mudflat areas were segregated into the eastern shore (landward) and the western shore (seaward) by applying the extracting mask for the east shore and mask for the west shore, respectively. These outputs were the final outputs from this model and they show the mudflat availability at 1 cm vertical resolution up to 12 cm depth on both shores of each reference site.

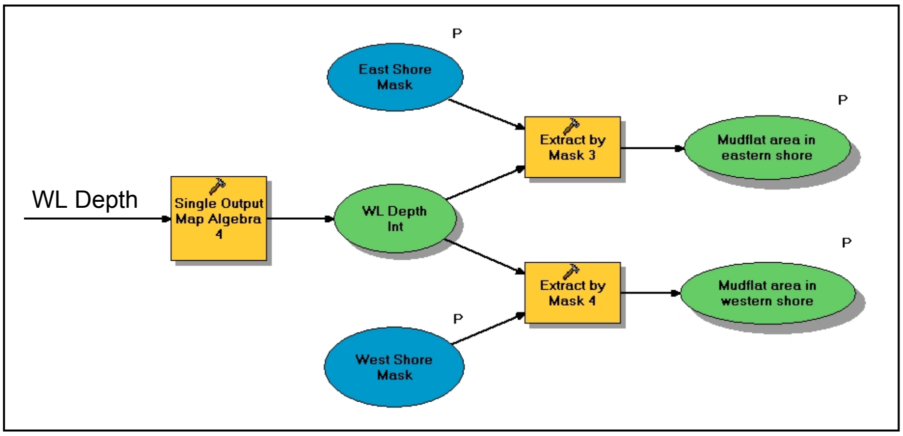


Figure 6.6. Mudflat habitat model part (D).

Figure 6.7 provides the model interface for running the model where the model parameters, input files and the location and names of the three final outputs are specified. The input files are comprised of four feature shape files and one DEM for any given reference site. The water level dataset supplies the water level data at 102 points and these data are interpolated to generate a water level surface. Since the model predicts the mudflat availability for water level at one point in time, it requires specifying the water level data point from the attribute table of water level dataset to be used for running the model. The high water mark boundary, and masks for the east and west shores, are used to generate three output files: exposed mudflat area between the water level and the high water mark boundary and available mudflats on the eastern and the western shores.

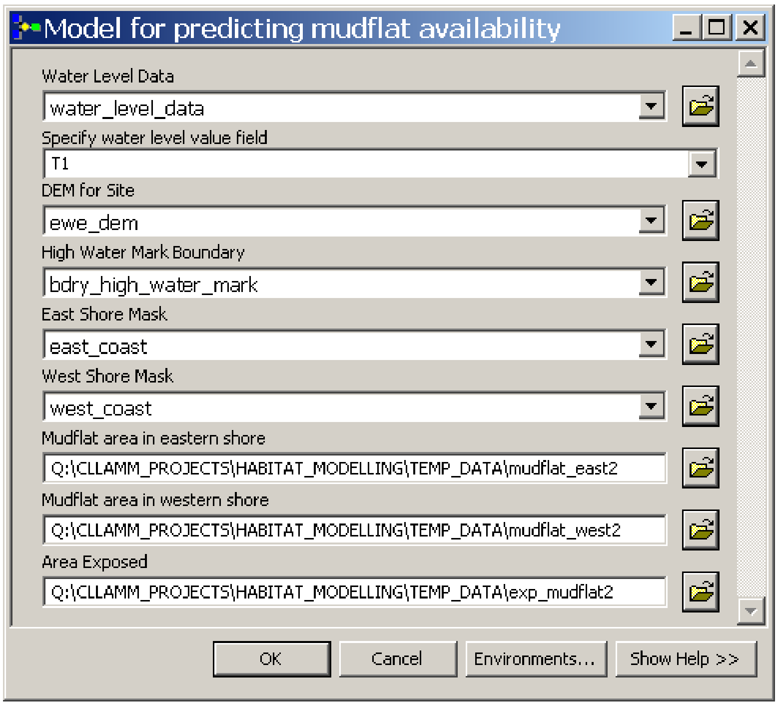


Figure 6.7. Interface for implementing the model in ArcGIS.

Dynamic model for predicting mudflat availability

The above model was developed in the ModelBuilder platform in ArcGIS and runs for one sequence of water level data at one point in time. The model requires specifying the water level data to be used for modelling each time. Since the hydrodynamic model simulates water level data every hour for the specified flow and physical scenario, a model was written in geo-processing python script for automating the execution using a series of water level data in the dataset. The model terminates only at the end of the water level data in the dataset and generates three outputs for each water level time step. The python script for the model is given in Appendix 6.1.

For assessing the spatial variability in the habitats along the Coorong, three sites, one close to the Murray Mouth (Barker Knoll), a second near the middle of the North Lagoon (Noonameena) and the third near the end of the South Lagoon (Salt Creek) were chosen from the 12 reference sites used by CLLAMMecology. Seasonal variations were taken into account by analysing habitat availability in January and July, representing two extreme seasonal conditions in summer and winter, respectively. The daily averages for minimum and maximum water levels were used to cover the full spectrum of water level variations in these two months. The days with the minimum and maximum daily average water levels were chosen for both wet and dry years. The model was implemented for the simulated hourly water level data between 6:00 AM to 8:00 PM and analysed for temporal variation in mudflat availability at the three sites. This time period was chosen to approximate maximum daylight (summer) hours when foraging by waterbirds would be likely to occur.

Modelling fish habitat

Spatial model for predicting fish habitat

Logistic regression was applied within a GIS framework for predicting the probability of occurrence of key fish species in the Coorong. This method has been used for spatial modelling of habitat suitability (Gross *et al.* 2002; Shriner *et al.* 2002) and environmental management (Mathew *et al.* 2007; Xie *et al.* 2005; Álvarez-Arbesú and Felicísimo 2002). Logistic regression is a general linear regression method and is developed to explore the relationship between a discrete response variable (especially binary form data such as presence and absence) and independent variables (Hosmer *et al.* 1989). A general formula for a logistic regression is similar to that of a linear regression and is shown as equation 6.1.

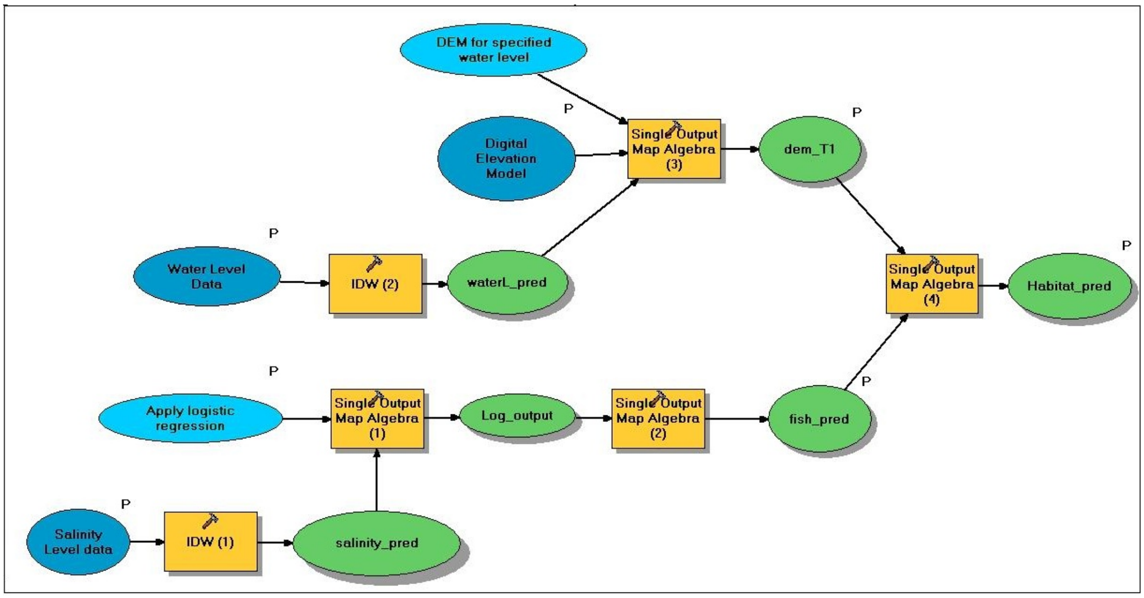


Figure 6.8. Predicting fish habitat based on fish occurrence probability using logistic regression.

$$Y_f = b_{0f} + b_{1f}\,x_{1f} + b_{2f}\,x_{2f} + \ldots\ldots.. + b_{nf}\,x_{nf} \qquad (6.1)$$

Where Y_f is the linear value for species “f”, b_{0f} is the coefficient for the intercept, b_{1f}, b_{2f}, to b_{nf} are variable coefficients and x_{1f}, x_{2f} to x_{nf} are the independent variables.

The species occurrence probability is predicted based on the linear value (Y_f) derived from equation 6.1 for the associated significant predictor variables and the formula is given as equation 6.2.

$$\text{Probability of Occurrence} = (1 / (1 + \exp(-Y_f))) \qquad (6.2)$$

The probability values range between 0 and 1. A value close to 1 represents higher occurrence probability.

A spatial model was developed to predict the probability of occurrence of fish species based on salinity levels using logistic regression in ArcGIS (ver. 9.3) (Figure 6.8). In addition to salinity, other water quality variables including water temperature, pH, dissolved oxygen and secchi depth may also be used in the model. However, salinity is the only variable generated by the hydrodynamic model, and thus is the only variable against which predictions can be made under the flow scenario examined here. Both of the outputs from the hydrodynamic model: salinity and water level, and also the full Digital Elevation Model (DEM) for the Coorong (see Chapter 3) were used in the model.

The salinity level data was interpolated for the Coorong using the inverse distance weighted (IDW) method. The coefficients derived from the logistic regression for the intercept and salinity specific to each fish species were used in equation 6.1 to obtain linear prediction value for the species. Subsequently, the linear value for the species was transformed to a probability value using equation 6.2 in the single output map algebra function.

The water level data obtained from the hydrodynamic model were also interpolated and integrated with the DEM of the Coorong to derive the water surface for the Lagoon at the specified water level. The resultant water surface map is a binary map, where 1 signifies the area under water and 0 signifies the area above the specified water level. Finally, the output for the occurrence probability was combined with the water level surface. The final map illustrated the probability of occurrence of fish species based on the salinity level and water level generated by the hydrodynamic model.

Figure 6.9 provides the model interface for implementing the logistic model for predicting the occurrence probability of fish species in the Coorong. The input files included salinity data, water level data, the DEM and the Lagoon boundary layer. The coefficients specific to individual fish species derived from the logistic regression must be entered to calculate the occurrence probability. The probability map and the water surface layer are integrated into the final output specifying the habitat with varying probability for specified salinity and water levels.

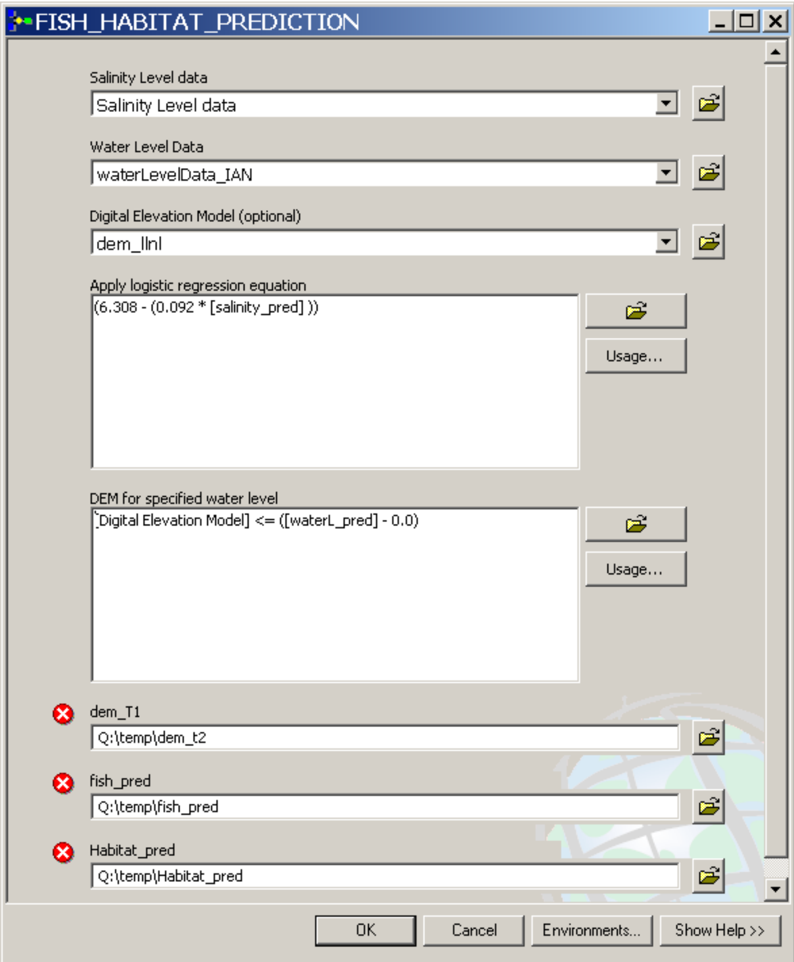


Figure 6.9. Interface for implementing the model in ArcGIS.

Dynamic model for predicting fish habitat

A spatial model for predicting fish habitat at varying salinity and water levels was developed in the ModelBuilder platform in ArcGIS 9.3 and runs for one sequence of water level and salinity data at one point in time. The model requires specification of the salinity and water level data to be used for modelling each run. Since the hydrodynamic model simulates salinity and water level data every hour for the specified flow and physical scenario, a model was written in geo-processing python script for automating the execution using a time-series of salinity and water level data available from the hydrodynamic model. The dynamic fish habitat model terminates only at the end of salinity and water level data in the dataset and generates an occurrence probability map for each hourly time step. The python script for the model is given in Appendix 6.2.

Fish catch data (number) were converted into binary data (1 for presence and 0 for absence) for the key fish species in the Coorong. Out of 94 data samples, about 70% of the data (65 samples) were randomly selected for modelling the relationship between the species and salinity whereas the remaining data (29 samples) were used for validating the relationship in SPSS 16.0 (SPSS Inc). For classification, cases with a predicted value above a cut-off value of 0.5 were classified as ‘present’ and below 0.5 were classified as ‘absent’.

The predictive power of the models was evaluated by using the validation dataset, and analysed for accurate classification of the data into presence and absence against true presence and absence. The models were also analysed for Receiver Operator Characteristic (ROC) curves in SPSS 16.0 (SPSS Inc.). The ROC curve is widely used as a tool for measuring the accuracy of a model by evaluating the model performance in classifying a variable into two possible outcomes (Gönen 2006). The curve is a graphical representation of the probability of a true positive against a false positive at the specified cut-off value. The sensitivity is used to represent the probability of correctly classified data (true positive) and is plotted on the y-axis. The specificity implies the probability of the correct classification of absence data and is plotted on the x-axis of the ROC curve. The area under the curve represents the probability estimated by the model that a randomly chosen presence case will exceed the probability prediction for a randomly chosen absence case. Thus, the ROC curve is considered as an important tool for measuring of the accuracy of the model. A large area under the curve implies a high level of accuracy in the model.

The average monthly salinity representing a low, medium and high range, as derived from the hydrodynamic model, were chosen for predicting the probability of occurrence of the key fish species in the Coorong. The monthly average salinity was low in July 1976, medium in July 1988 and high in January 2005.

6.4. Results

6.4.1 Spatial and temporal variation in water level and salinity in the Coorong

The monthly average water levels were higher in July than in January for 1976, 1988, and 2005, but not for 1993 (Figure 6.10). Relatively high rainfall and low evaporation during the winter months contributed to high water levels in July. The monthly average water level reached a maximum along the Lagoon and steadily rose between Tauwitchere Channel (0.77 mAHD) and Salt Creek (0.87 mAHD) in July 1976. Water levels were reduced along the Lagoon during January, particularly in dry years. Less rainfall (<22 mm at Meningie) and rising evaporation in the summer months (above 225 mm for the lakes during December and January) resulted in significant loss of water, which was complimented by lower or no freshwater inputs over the barrages, resulting in drastically lower water levels in the Lagoon. The monthly average water levels were reduced more markedly in the South Lagoon than in the North Lagoon with average differences in water levels of 0.27 mAHD and 0.17 mAHD in January 1988 and 2005, respectively.

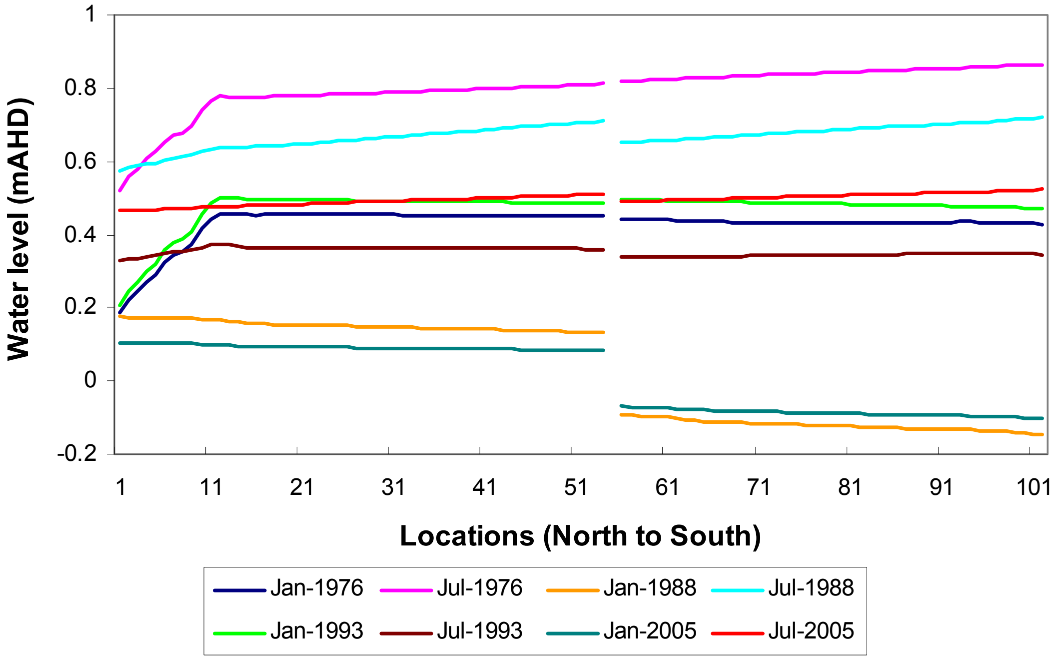


Figure 6.10. Monthly average water level along the Lagoon in the summer (January) and winter (July) months for the wettest years (1976 and 1993) and driest years (1988 and 2005) in the past four decades. The hydrodynamic model does not predict the water level for Parnka Point (location 55).

The three selected reference sites also followed the same general pattern for the monthly average water levels. The water levels were consistently lower in January than July in 1976, 1988 and 2005. However, higher water levels were predicted for January than July in 1993 at Noonameena and Salt Creek (Figure 6.11 and 6.12). At all three sites, the average water levels exceeded 0.51 and 0.57 mAHD in July 1976 and 1988, respectively. Salt Creek had the lowest average water level of -0.13 mAHD in January 1988 and of -0.09 mAHD in January 2005 (Figure 6.12). At Barker Knoll, the average water level was 0.17 mAHD in January, while it reached above 0.57 mAHD in July 1988. The hydrodynamic model predicts hourly as well as daily variations in the water level along the Coorong. Generally, water levels subsided during the night and rose to maximum levels in the afternoon, primarily due to wind effects. The daily variation in water levels at Barker Knoll, Noonameena and Salt Creek for January and July of 1976, 1988, 1993 and 2005 are presented in Appendix 6.3.

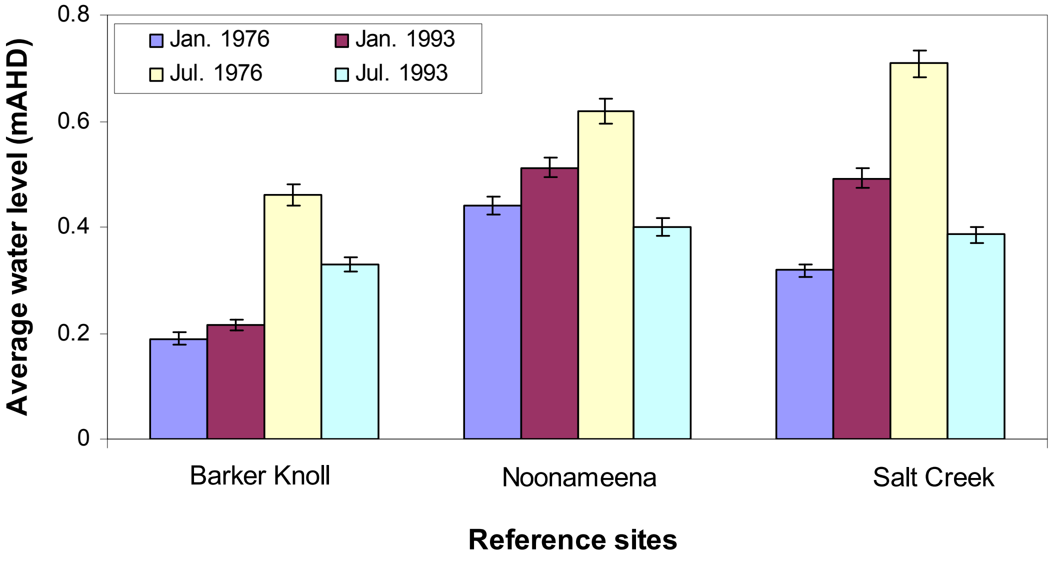


Figure 6.11. Monthly average water level at three reference sites for January and July in the wettest years (1976 and 1993).

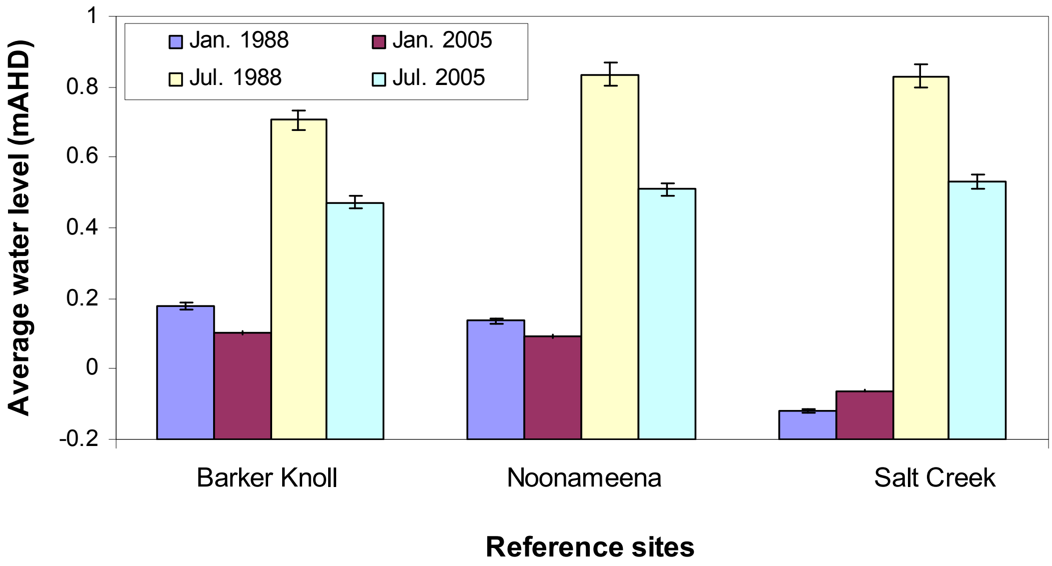


Figure 6.12. Monthly average water level at three reference sites for January and July in 1988 and 2005.

Higher water levels generally coincided with lower salinity and vice versa. For example, the lowest average salinity of 18.2 g/L was predicted for July 1976 when the monthly average water level was at its highest (0.8 mAHD) along the Lagoon. Similarly, the highest average salinity (85.5 g/L) was predicted at the lowest average water level (0.18 mAHD) in January 2005 (Figure 6.13). The Lagoon had the lowest salinity range of ~ 2 – 48 g/L in July 1976 and reached the highest range of ~41 – 125 g/L in January 2005. Predicted salinities in the North Lagoon were consistently lower than in the South Lagoon.

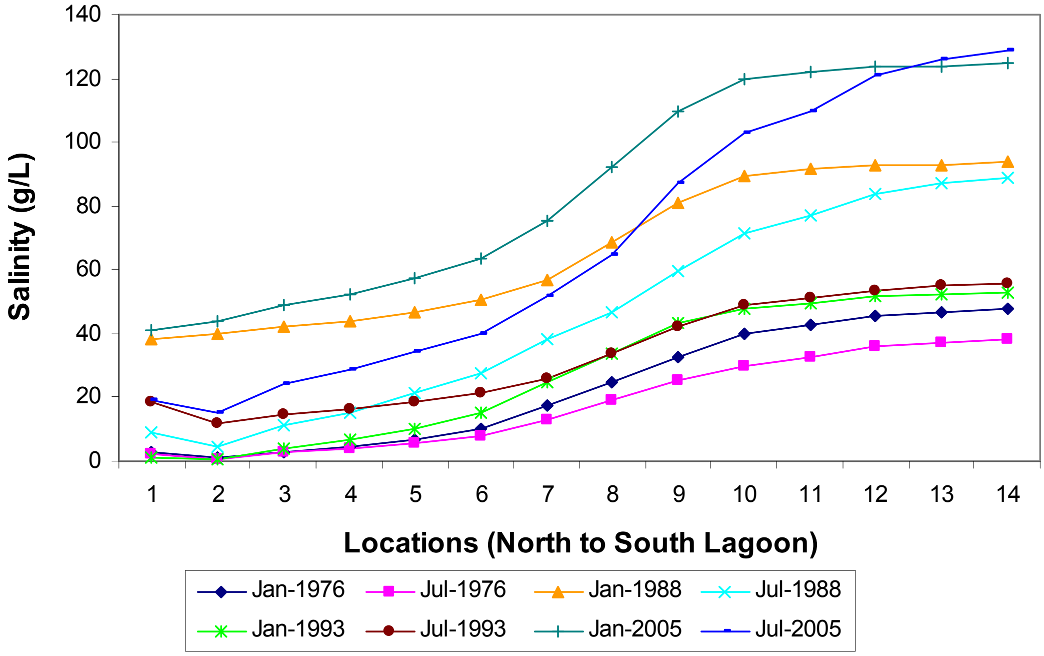


Figure 6.13. Monthly average salinity levels along the Lagoon in the summer (January) and winter (July) months for the wettest years (1976 and 1993) and driest years (1988 and 2005) in the past four decades.

The average salinity was predicted to be below 15 g/L in the northern part of the Lagoon and did not exceed 50 g/L in the South Lagoon in 1976 and 1993 (Figure 6.14). The average salinity was above 40 g/L at Barker Knoll, 50 g/L at Noonameena and 89 g/L in Salt Creek in January 1988 (Figure 6.15). The salinity further increased and reached approximately 125 g/L at Salt Creek in January 2005. Raised water levels in July 1988 and July 2005 had some influence on salinity with levels reduced to almost half those in January. The daily variation in salinity for these three sites for January and July of 1976, 1988, 1993 and 2005 is presented in Appendix 6.4.

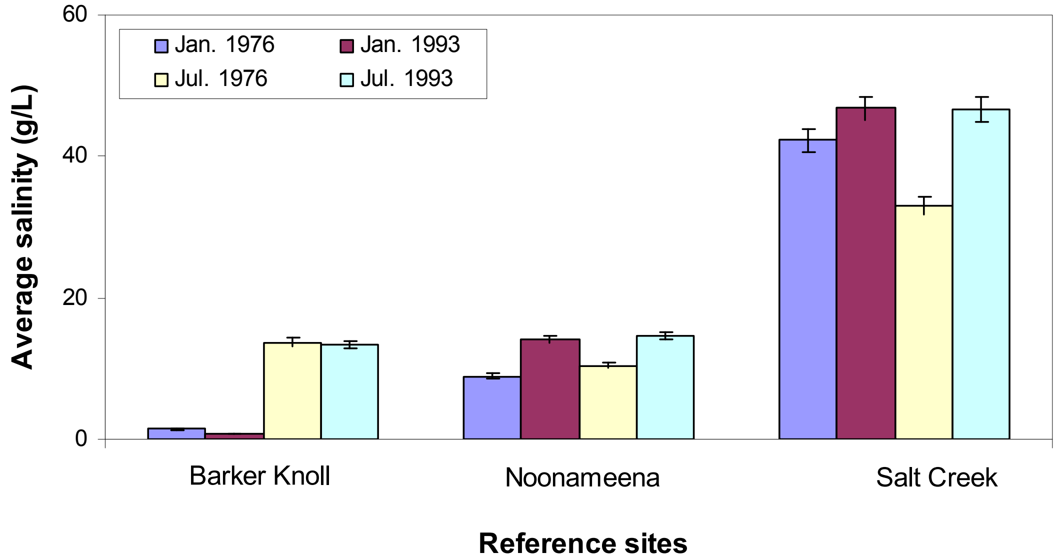


Figure 6.14. Monthly average salinity (g/L) at three reference sites for January and July in 1976 and 1993.

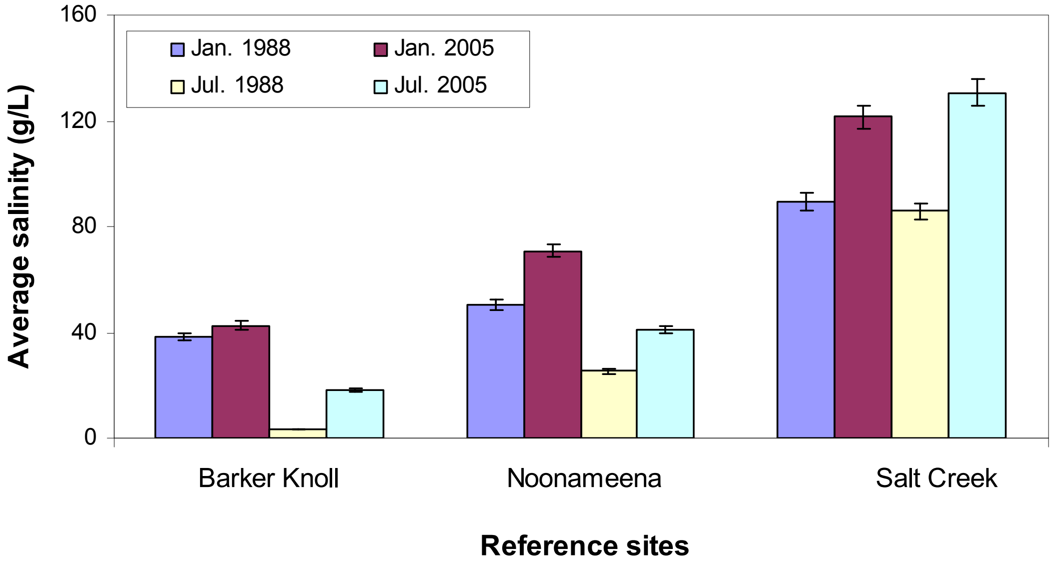


Figure 6.15. Monthly average salinity (g/L) at three reference sites for January and July in 1988 and 2005.

6.4.2 Mudflat availability at the reference sites

Of the three reference sites modelled for this study, the mudflat habitats were available primarily on the eastern and western shores of Noonameena and Salt Creek (Figure 6.16 and 6.17) while some mudflats also appeared within the channel at Barker Knoll (Figure 6.18). The majority of mudflat areas were present on the eastern shore at Barker Knoll and Salt Creek whereas both shores had similar mudflat areas at Noonameena. These maps present spatial as well as temporal variations in the amount of mudflat areas available to waterbirds with changes in water levels. A detailed analysis of the distribution of mudflats at the maximum and minimum water levels in the winter (July) and summer (January) months of the wet and dry years between 6:00 to 20:00 is presented below.

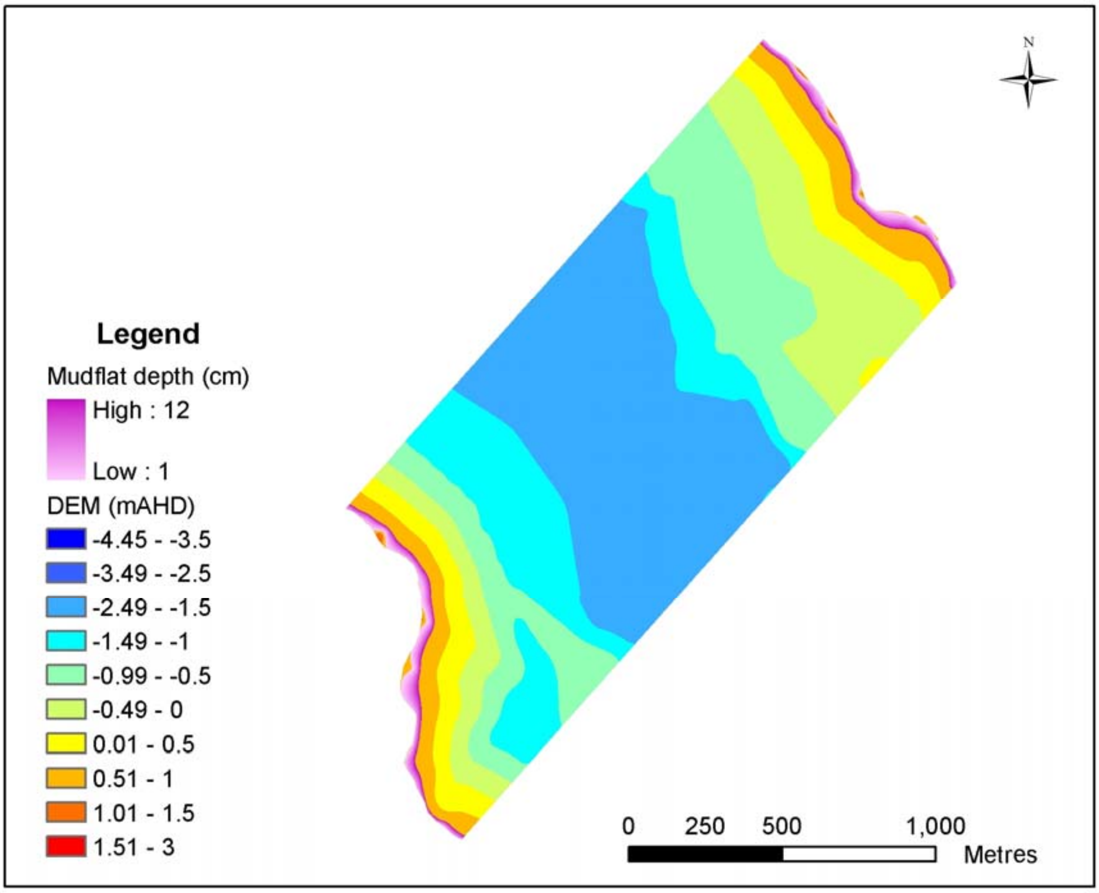


Figure 6.16. Map of mudflat availability generated by the spatial model at Noonameena on 22 July 1988 at 12:00 PM: an example.

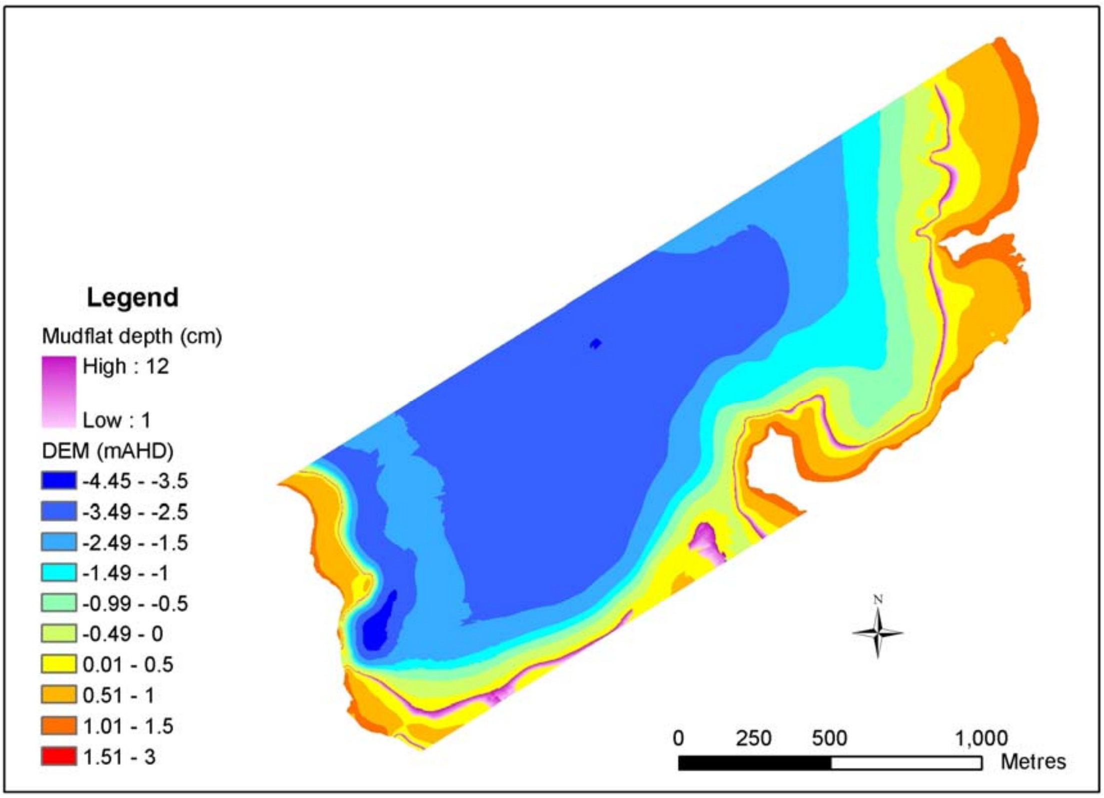


Figure 6.17. Map of mudflat availability generated by the spatial model at Salt Creek on 9th July 1993 at 7:00 AM: an example.

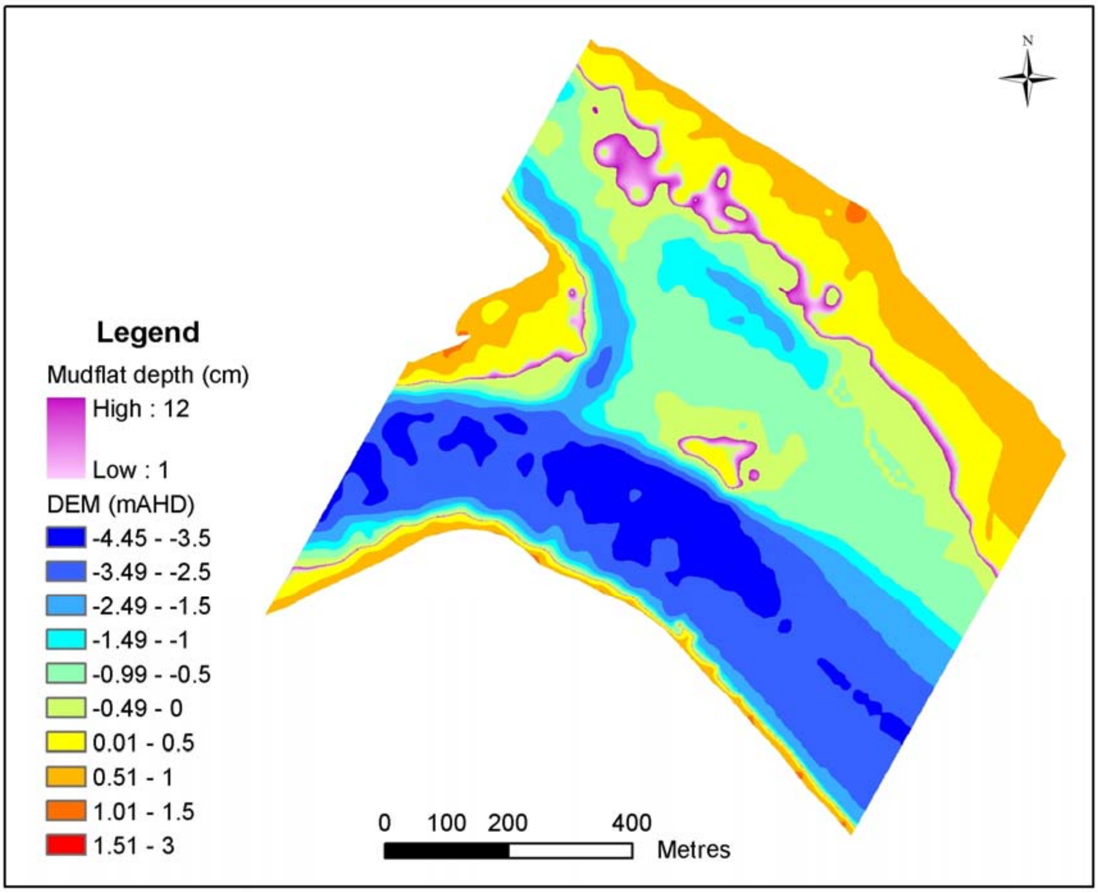


Figure 6.18. Map of mudflat availability generated by the spatial model at Barker Knoll on 8th January 1988 at 9:00 AM: an example.

Mudflat availability at different water levels

At Barker Knoll, the maximum mudflat habitat (around 3.2 ha) became available at a mean water level of -0.066 mAHD with around 2.4 ha located on the eastern shore. The mudflat declined sharply beyond 0.90 mAHD and did not occur above 1.24 mAHD, as the edge of the shores had been reached (Figure 6.19). When the mean water level was 0.99 mAHD at Noonameena, the mudflat area reached its maximum (around 6.4 ha) with about 2.9 ha and 3.5 ha on the eastern and the western shores, respectively. Below 0.8 mAHD, the mudflat areas did not change much (around 4.4 ha) and were almost equally distributed on both shores. The mudflat areas were reduced dramatically with an increase in the mean water level above 1.0 mAHD and no mudflats were found above 1.4 mAHD at Noonameena (Figure 20). At Salt Creek, the maximum mudflat area of around 6.2 ha occurred at mean water level between 0.26 to 0.29 mAHD. The western shores offered less mudflat areas above 0.29 mAHD, while the mudflat habitat area increased on the eastern shore above 0.29 mAHD, except for water levels between 0.54 and 0.89 mAHD. Above 0.93 mAHD, the mudflat area gained on the eastern shore was more than the loss of habitat on the western shore resulting in a net increase in the mudflat areas above 0.93 mAHD at Salt Creek (Figure 6.21).

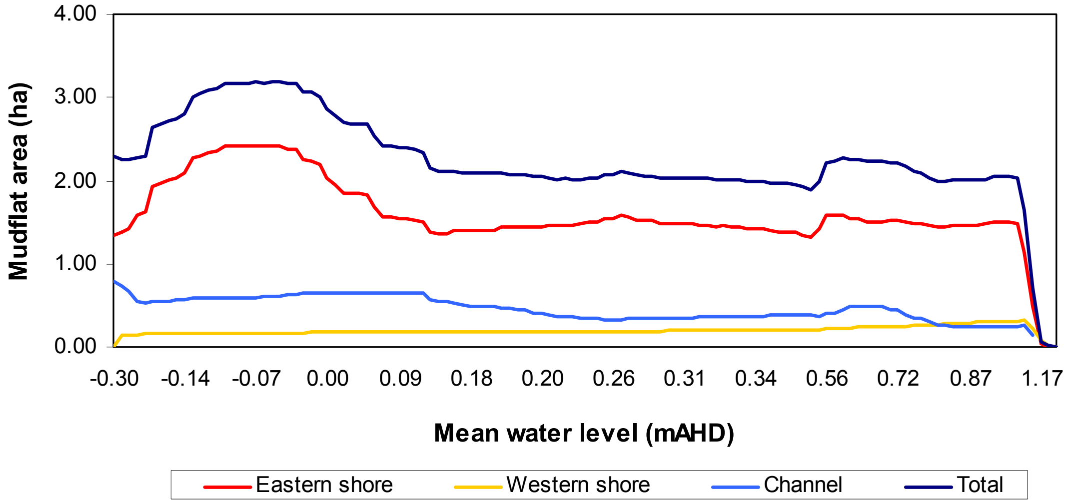


Figure 6.19. Mudflat availability on the eastern shore, western shore, channel and the total areas at different water levels at Barker Knoll.

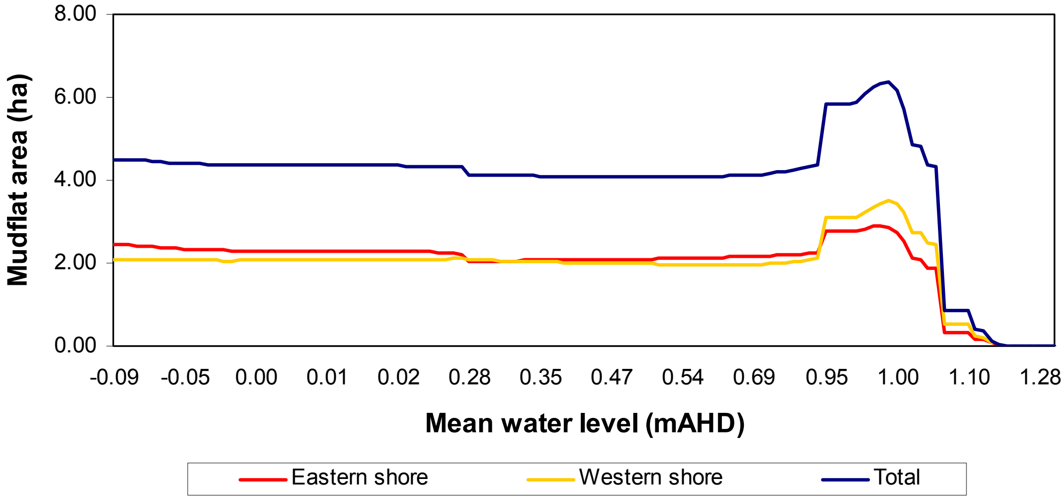


Figure 6.20. Mudflat availability on the eastern shore, western shore and the total areas at different water levels at Noonameena.

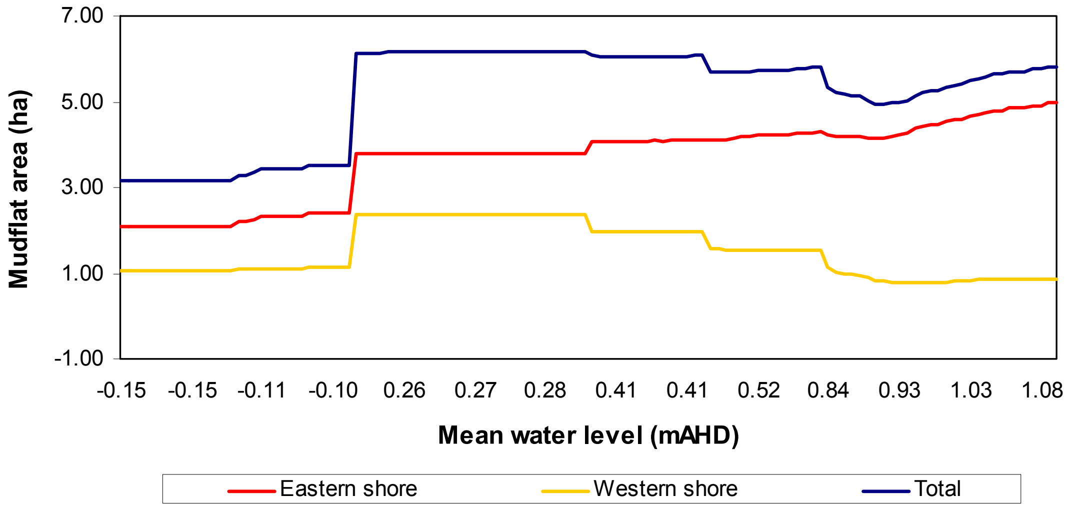


Figure 6.21. Mudflat availability on the eastern shore, western shore and the total areas at different water levels at Salt Creek.

Spatial and temporal variation of mudflat area

The mean water levels and corresponding mudflat areas available between 6:00 to 20:00 are presented in Figures 6.22 to 6.29 for the day on which the average water level reached the minimum or maximum in each of January and July of the two dry and wet years at the selected reference sites. The availability of mudflat on the eastern and western shores, and also in the channel in the case of Barker Knoll, for these water levels is illustrated in Appendix 6.5.

Barker Knoll, being closest to the Murray Mouth, experienced high variability in water levels during the day in both summer and winter months, which greatly affected mudflat availability. On the day the water level reached its maximum in January for the two wet years (22^{nd} January 1976), the water level at Barker Knoll followed a typical diurnal pattern due to tidal influence. The water level dropped initially to 0.19 mAHD and then rose to 0.30 mAHD at 13:00. In the afternoon, the water level reduced gradually to the lowest level of 0.05 mAHD at 17:00 and again increased to 0.21 mAHD. The mudflat availability did not follow exactly the same pattern and variability. However, the mudflat areas generally expanded with reducing water levels. Thus, the maximum areas of mudflat (around 2.5 ha) were observed at the mean water level, 0.05 mAHD in the late afternoon (at 17:00), and the minimum areas (around 1.89 ha) occurred in the morning (at 7:00) at 0.40 mAHD.

Although the water level dropped gradually from around 0.8 to 0.62 mAHD, throughout the day, there was not much change in mudflat area (around 4.1 to 4.4 ha) at Noonameena. On the same day, Salt Creek had the highest mudflat area of around 6.0 ha while the mean water level was almost static at 0.41 mAHD (Figure 6.22).

On the day the water level reached its minimum in January in the wet years (31^{st} January 1976), the water level at Barker Knoll decreased from -0.017 mAHD at 6:00 to the lowest level of -0.30 mAHD at 11:00 and gradually increased to 0.17 mAHD at 20:00. The mudflat area increased to around 3.2 ha at -0.066 mAHD in the late afternoon (at 17:00) at Barker Knoll (Figure 6.23). At Noonameena, the water level slightly reduced from -0.02 mAHD at 6:00 to -0.09 mAHD at 20:00 while the mudflat area increased by 0.2 ha over the period from 4.3 ha to 4.5 ha. The water level was almost static at around 0.27 mAHD throughout the day at Salt Creek, with an available mudflat area of around 6.17 ha.

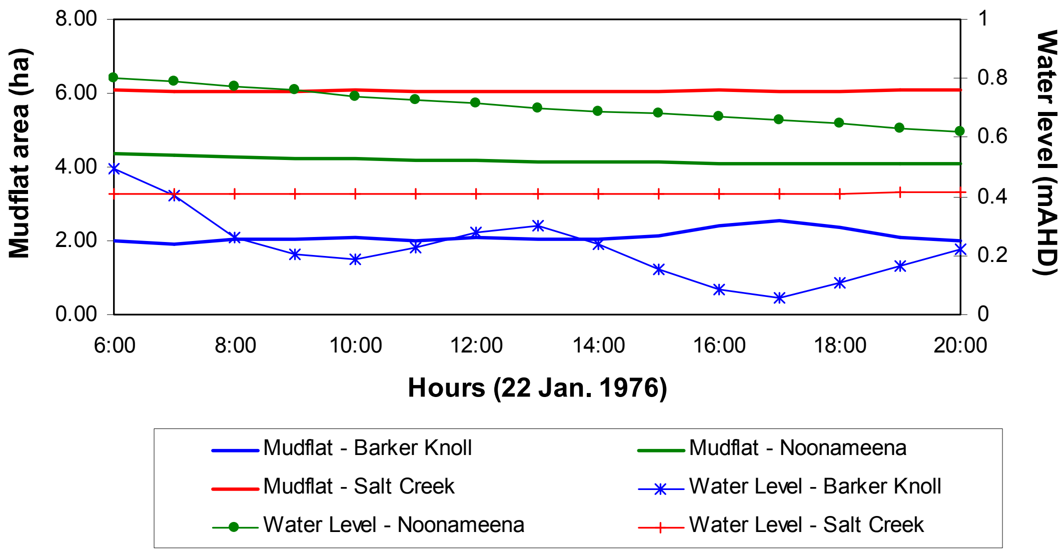


Figure 6.22. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 22 Jan. 1976. The average water level was at its maximum for January in the two wet years on this day.

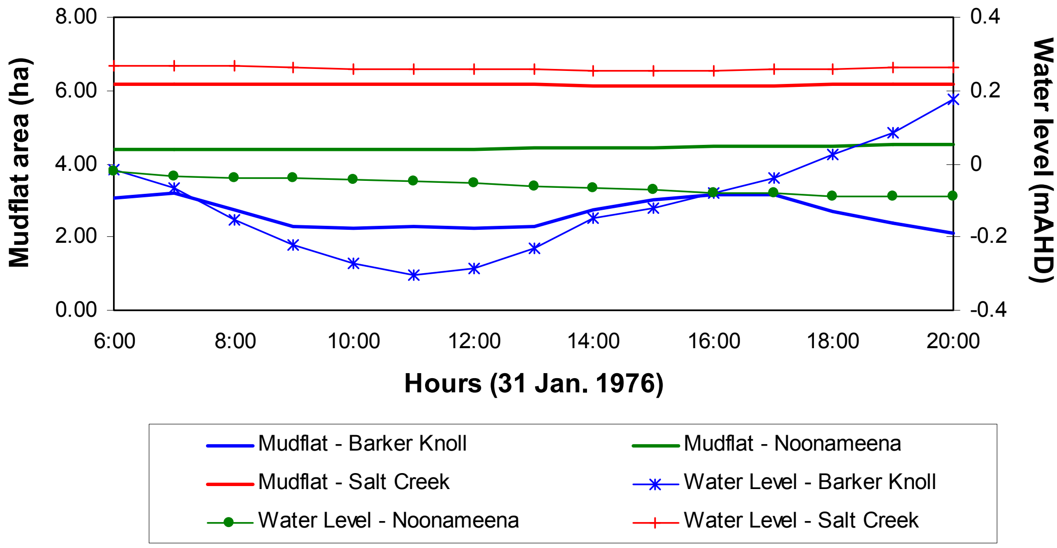


Figure 6.23. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 31 Jan. 1976. The average water level was at its minimum for January in the two wet years on this day.

The average water level reached a July maximum for the two wet years on 21st July 1976 in the Lagoon. The water level increased gradually from 0.56 mAHD at 6:00 to 1.24 mAHD at 15:00 and subsequently dropped to 0.84 mAHD at 20:00 at Barker Knoll. Although there was a continuous increase in water level, the mudflat area peaked at 2.27 ha at a water level of 0.59 mAHD (at 8:00). Further rises in the water level above 0.65 mAHD after 9:00 reduced the mudflat habitat gradually up to a water level of 0.90 mAHD. Water levels above 1.17 mAHD covered almost all the mudflat, and no mudflat became available between 14:00 to 16:00. As the water receded, the water level dropped below 0.90 mAHD, thus resulting in about 2.0 ha of mudflat at Barker Knoll (Figure 6.24). At Noonameena, the water level stayed above 1.1 mAHD throughout the day. At the minimum water level (1.1 mAHD) between 8:00 to 11:00, the maximum mudflat area available was around 0.86 ha. At water levels above 1.19 mAHD, all mudflats were submerged under greater than 12 cm of water and not accessible for foraging by the majority of wading birds for the rest of the day. At Salt Creek, the water level increased by around 0.60 mAHD in July 1976 compared to January 1976, to around 1.0 mAHD and fluctuated very little for the whole day. However, there was a slight change in mudflat availability ranging between 5.3 and 5.8 ha.

The minimum July water level for the two wet years occurred on 9th July 1993. The water levels were steady at Noonameena and Salt Creek, but varied at Barker Knoll. At Barker Knoll, the water level was -0.056 at 6:00 and dropped to -0.12 at 8:00 before rising to 0.37 mAHD at 16:00, and then decreasing to 0.012 mAHD at 20:00. The availability of mudflat was a maximum at around 3.2 ha at a water level of -0.056 mAHD and slightly decreased with decreasing water level. Water levels above -0.056 mAHD also decreased mudflat availability and reached a minimum of 1.95 ha at the maximum water level of 0.37 mAHD at 16:00. At Noonameena, the water level fluctuated between -0.009 and 0.082 mAHD, with only a slight impact on mudflat availability (4.33 and 4.36 ha). The water level at Salt Creek was around 0.28 mAHD, about 0.7 mAHD below the water level on 21st July 1976. However, mudflat availability increased by about 0.8 ha and reached around 6.16 ha (Figure 6.25).

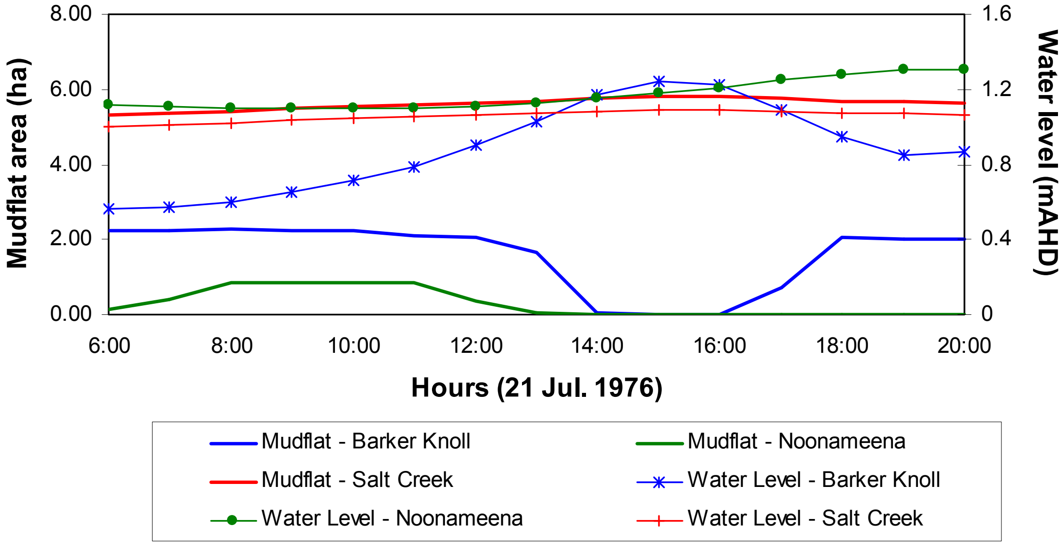


Figure 6.24. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 21 Jul. 1976. The average water level was at its maximum for July in the two wet years on this day.

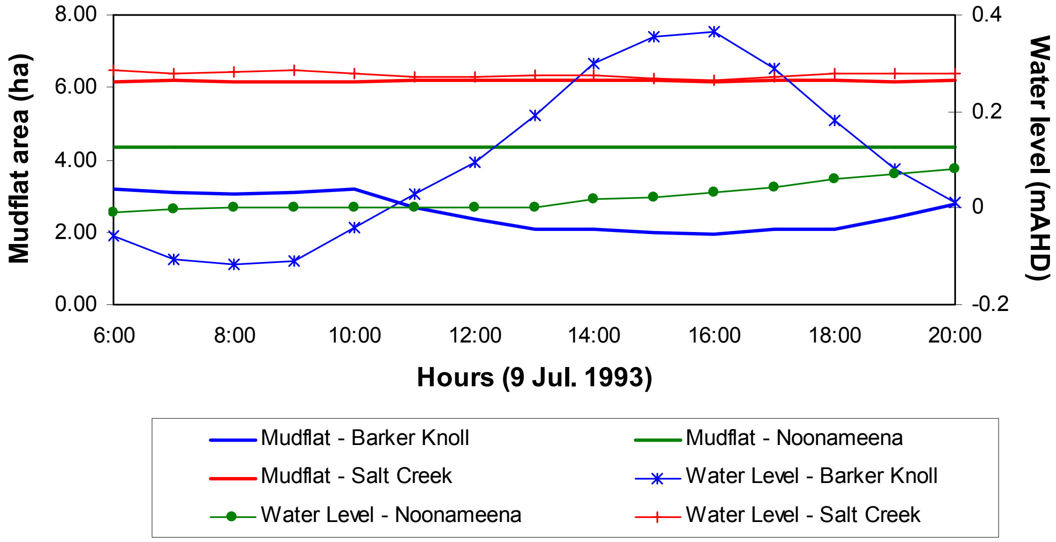


Figure 6.25. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 9 Jul. 1993. The average water level was at its minimum for July in the two wet years on this day.

In January of the dry years, the Lagoon experienced the maximum and minimum water levels on the 17th and 8th January 1988, respectively. On the 17th, at Barker Knoll there was slight reduction in the water level in the morning from 0.31 mAHD at 6:00 to 0.17 mAHD at 14:00 and it then gradually rose to a maximum of around 0.36 mAHD at 20:00. Mudflat availability was a maximum of 2.1 ha at the minimum water level of 0.17 mAHD and a minimum of 1.96 ha at the maximum water level of 0.36 mAHD. At Noonameena, the water level reached a maximum of 0.39 mAHD at 7:00 and gradually dropped to minimum of 0.28 mAHD at 20:00. Similar to Barker Knoll, the minimum and maximum mudflats of 4.12 ha and 4.09 ha were available at maximum (0.39 mAHD) and minimum (0.28 mAHD) water levels, respectively. At Salt Creek, the water level remained at 0.15 mAHD and did not change throughout the day. Likewise, the mudflat area was stable at around 3.15 ha (Figure 6.26).

When the water level was at a minimum on 8th January 1988, it progressively decreased from a maximum of 0.163 mAHD at 6:00 to the local minimum of -0.09 mAHD at 11:00 and rose to 0.029 mAHD at 15:00 before dropping to the lowest level of -0.17 mAHD at 19:00 at Barker Knoll. Mudflat availability was 2.11 and 2.68 ha at the maximum and minimum water levels, respectively. However, the maximum mudflat availability of 3.19 ha was reached at water levels around -0.05 mAHD at midday (12:00). At Noonameena, water levels varied between -0.02 mAHD at 6:00 and 0.02 mAHD at 18:00. These water level changes had very little influence on the mudflat availability, which ranged between 4.34 ha at the maximum water level and 4.36 ha at the minimum water level at 6:00. Water levels ranged between -0.10 mAHD and -0.13 mAHD at Salt Creek with the maximum mudflat availability of 3.53 ha at the lowest water level of -0.10 mAHD in the late morning to afternoon between 11:00 and 16:00 (Figure 6.27).

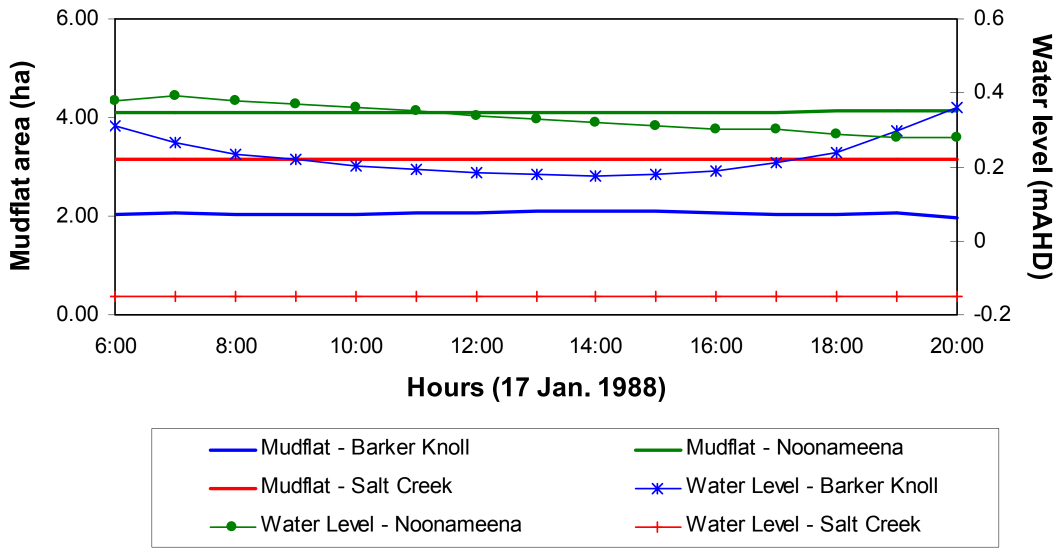


Figure 6.26. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 17 Jan. 1988. The average water level was maximum for January in the two dry years on this day.

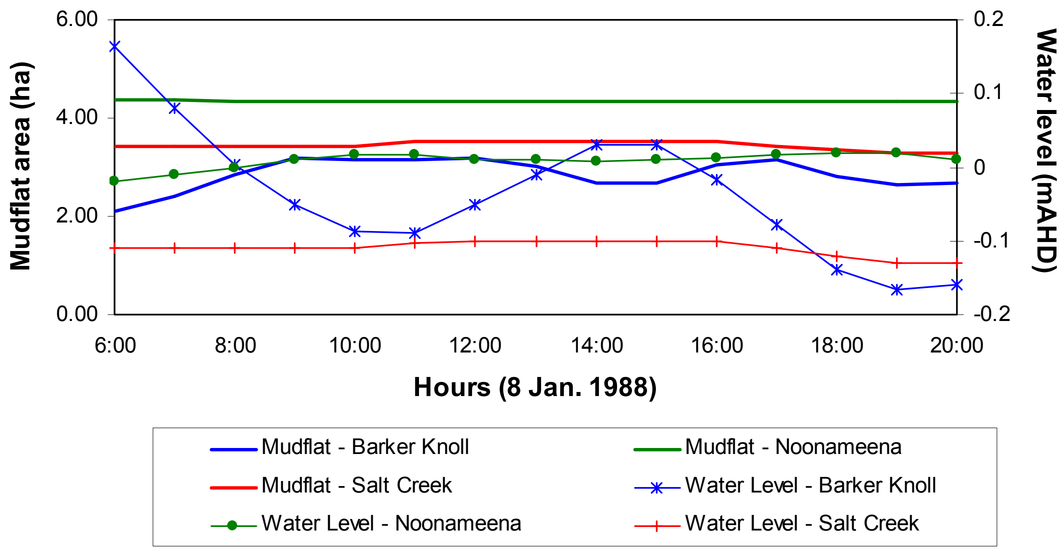


Figure 6.27. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 8 Jan. 1988. The average water level was minimum for January in the two dry years on this day.

In July of the dry years, the Lagoon had maximum and minimum average water levels on the 22nd and 8th July 1988, respectively. On 22nd July, at Barker Knoll, there was a slight reduction in the water level in the morning from 0.65 mAHD at 6:00 to 0.63 mAHD at 8:00 which gradually rose to maximum water level around 0.92 mAHD at 16:00. The mudflat availability fluctuated between 2.05 ha and 2.26 ha with the changing water level. The maximum available mudflat area of 2.26 ha occurred at the minimum water level around 0.63 mAHD in the morning. At Noonameena, the maximum water level of 1.04 mAHD was reached in the morning at 7:00 and it gradually dropped to 0.95 mAHD at 16:00 and did not change thereafter. The available mudflats at the maximum and minimum water levels were 4.34 ha and 5.85 ha, respectively. However, the maximum mudflat area of 6.39 ha was available at a water level around 0.99 mAHD at noon (12:00). At Salt Creek, the water level was a maximum 0.99 mAHD at 7:00 and progressively dropped to around 0.84 mAHD at 20:00 on the day. The mudflat area was a minimum of 5.27 ha at the maximum water level and a maximum of 5.35 ha at the minimum water level (Figure 6.28).

On 8th July 1988, the water level was at the minimum. At Barker Knoll, the water level only changed slightly during the day between 0.31 mAHD (10:00) and 0.38 mAHD (6:00). The mudflat area reached a maximum of 2.034 ha at the minimum water level and minimum mudflat area of 1.92 ha occurred at the maximum water level. At Noonameena, the water level gradually increased from 0.45 mAHD at 6:00 to 0.54 mAHD at 19:00. However, there was little variation in mudflat availability, which only ranged between 4.07 ha and 4.09 ha. At Salt Creek, the water level ranged between 0.49 mAHD at 6:00 and 0.54 mAHD at 16:00. Unlike Barker Knoll and Noonameena, the maximum mudflat area of 5.82 ha coincided with the maximum water level of 0.54 mAHD (Figure 6.29).

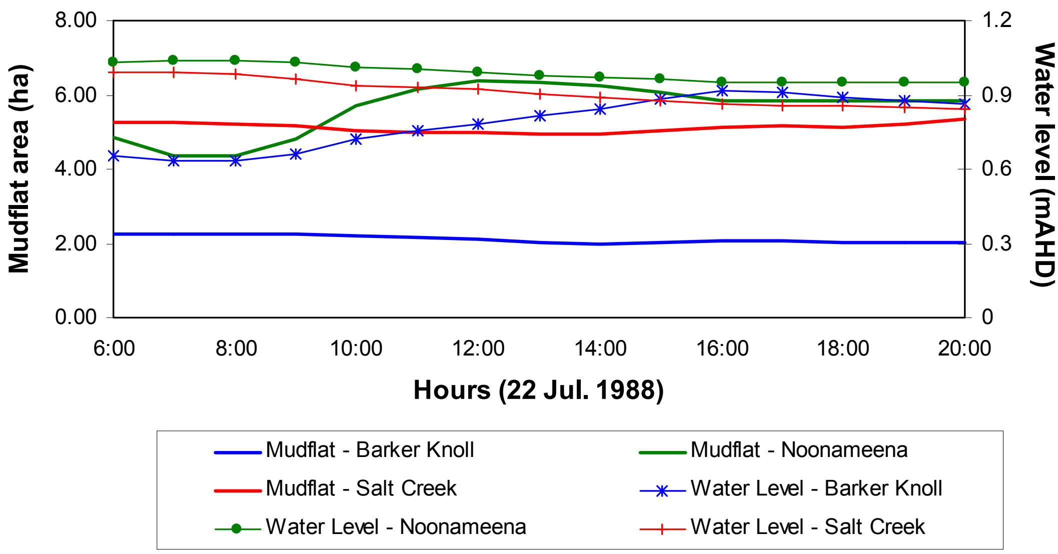


Figure 6.28. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 22 Jul. 1988. The average water level was at its maximum for July in the two dry years on this day.

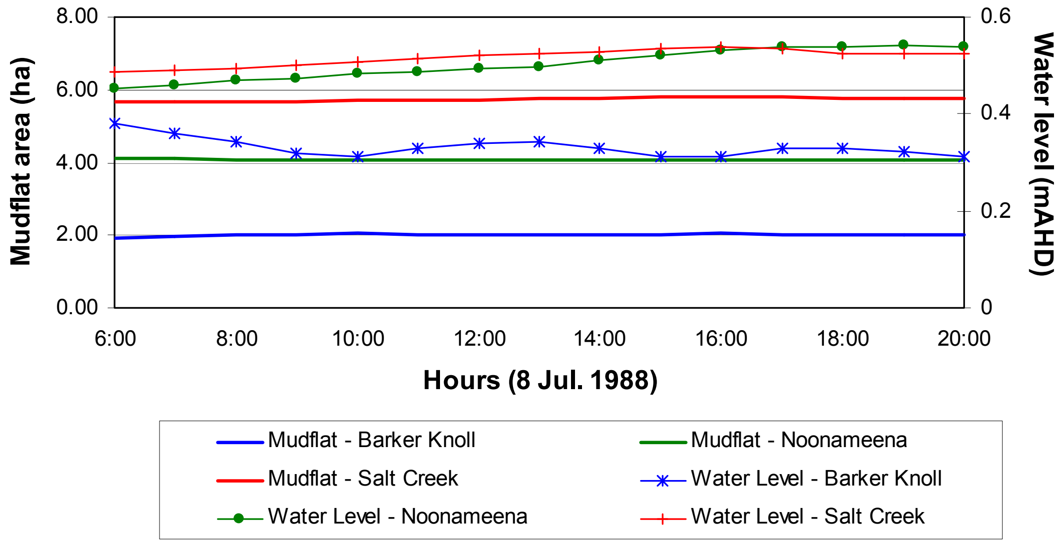


Figure 6.29. Mudflat availability and water levels between 6:00 - 20:00 at three reference sites on 8 Jul. 1988. The average water level was at its minimum for July in the two dry years on this day.

6.4.3 Modelling fish habitats using logistic regression

The key fish species of the Lagoon were modelled against salinity as the only predictor variable using logistic regression. A summary of the model parameters for all seven key species is given in Table 6.1. Salinity was only a significant predictor of the presence of four species: Yelloweye Mullet, Smallmouth Hardyhead, Greenback Founder and Tamar River Goby. Salinity was not a significant predictor for the other three species, Black Bream, Congolii and Mulloway, although this could be due to the rare occurrence of these species in the data. In the entire 94 sampling attempts, each of these species were reported less than seven times.

Table 6.1. Model coefficients and parameters for seven key species in the Coorong.

Variables	β	S.E.	df	Sig.
Yelloweye Mullet				
Salinity	-0.135	0.038	1	**0.000**
Constant	9.854	2.624	1	**0.000**
Smallmouth Hardyhead				
Salinity	0.054	.025	1	**0.035**
Constant	-1.226	1.078	1	0.255
Greenback Founder				
Salinity	-0.078	0.019	1	**0.000**
Constant	4.829	1.055	1	**0.000**
Tamar River Goby				
Salinity	-0.081	0.033	1	**0.013**
Constant	2.906	1.342	1	**0.030**
Black Bream				
Salinity	-0.051	0.039	1	0.194
Constant	-.172	1.593	1	0.914
Congolii				
Salinity	-0.027	.021	1	0.213
Constant	-0.789	1.022	1	0.440
Mulloway				
Salinity	-0.083	.054	1	0.124
Constant	1.022	2.018	1	0.613

β = Estimated coefficient; S.E. = Standard Error of estimates; df = degree of freedom; Sig. = Significance value and values > 0.05 are bold.

The prediction of presence and absence cases at the 0.5 cut off value for the selected (training) dataset for the four species is summarised in Table 6.2. The overall prediction accuracy was found to be above 70% for all four species. The model for Yelloweye Mullet accurately classified 46 out of 47 presences and 17 out of 18 absences, and had the highest overall prediction accuracy of 96.7 %. For Smallmouth Hardyhead, the model correctly classified 50 out of 51 presences. However, the overall prediction accuracy of the model was only 76.9% as the model failed to classify any of the absence data (14) accurately. The model for Greenback Flounder correctly classified 37 out of 40 presences, but only 8 of the 25 absences, again suggesting a patchy distribution or that an important constraining variable is absent from the model. Although the model for Tamar River Goby had a prediction accuracy of 72.3%, the model failed to classify 13 out of 20 presences accurately.

Table 6.2. Classification summary for the selected dataset by the models.

Fish species	Original data		Classification by the model				Overall prediction accuracy %
	1	0	1-1	0-0	1-0	0-1	
Yelloweye Mullet	47	18	46	17	1	1	96.9
Smallmouth Hardyhead	51	14	50	0	1	14	76.9
Greenback Flounder	40	25	37	17	3	8	83.1
Tamar River Goby	20	45	7	40	13	5	72.3

The cut-off value was 0.50. 1 = species presence; 0 = species absence;1-1= true presence; 0-0= true absence; 1-0 = False-negative and 0-1 = False-positive.

6.4.4 Validation of the models

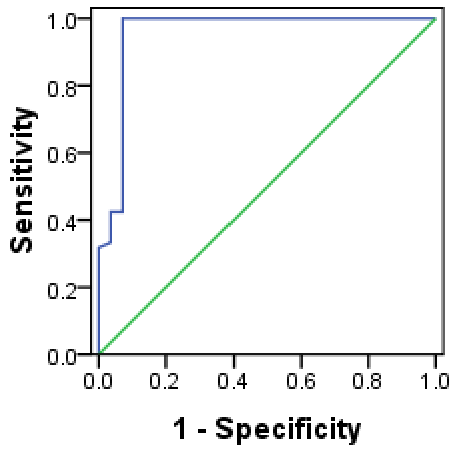
The accuracy of the models was assessed by using the component of the data set aside for validation. The models predicted occurrence with > 96% success for Yelloweye Mullet, > 89% for Greenback Flounder, and > 79% for Smallmouth Hardyhead and Tamar River Goby. The slightly lower prediction accuracies of the models for Smallmouth Hardyhead and Tamar River Goby were due to the inability of the model to classify 6 absences for the former and 6 presences for the latter. The classification summary and prediction accuracies of the models for the four species are shown in Table 6.3.

Table 6.3. Classification summary for the unselected (validation) dataset by the models.

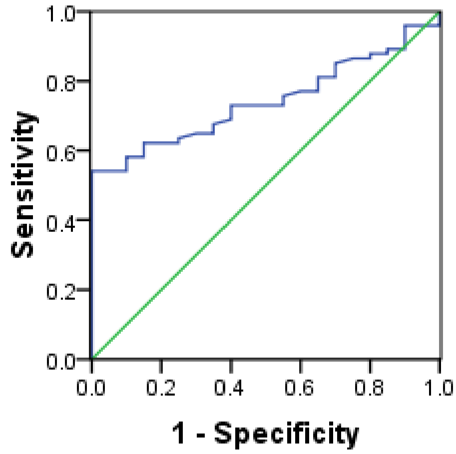
Fish species	Original data		Classification by the model				Overall prediction accuracy %
	1	0	1-1	0-0	1-0	0-1	
Yelloweye Mullet	20	9	19	9	1	0	96.6
Smallmouth Hardyhead	23	6	23	0	0	6	79.3
Greenback Flounder	17	12	17	9	0	3	89.7
Tamar River Goby	6	23	0	23	6	0	79.3

The cut-off value was 0.50. 1 = species presence; 0 = species absence; 1-0 = False-negative and 0-1 = False-positive.

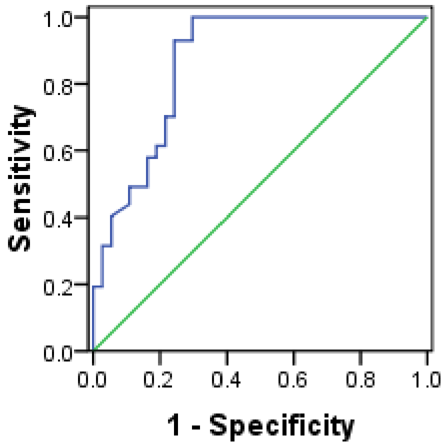
The ROC curves, which illustrate the accuracy of models, are given in Figure 6.30. The model for Yelloweye Mullet had the highest area (0.955) followed by Greenback Flounder with 0.867, and Smallmouth Hardyhead and Tamar River Goby, both with 0.741. These values correspond to 95.5%, 86.7% and 74.1% accuracy, respectively (Table 6.4).



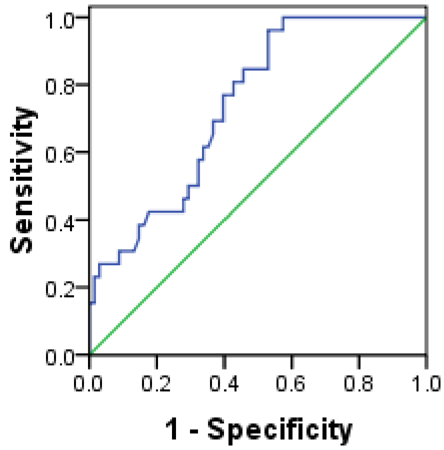
(a). Yelloweye Mullet



(b). Smallmouth Hardyhead



(c). Greenback Flounder



(d). Tamar River Goby

Figure 6.30. Receiver Operator Characteristics (ROC) curve for four species.

Table 6.4. Statistical parameters for Receiver Operator Characteristic (ROC) curves for the logistic models of four fish species.

Species	Area	Std. Error[a]	Asymptotic Sig.[b]	Asymptotic 95% Confidence Interval	
				Lower Bound	Upper Bound
Yelloweye Mullet	0.955	0.031	0.000	0.895	1.016
Smallmouth Hardyhead	0.741	0.050	0.001	0.644	0.838
Greenback Flounder	0.867	0.042	0.000	0.786	0.949
Tamar River Goby	0.741	0.052	0.000	0.640	0.843

6.4.5 Habitat prediction for the key fish species

The predicted occurrence along the Coorong of the four key fish species significantly related to salinity is presented in Figures 6.31 to 6.34. In July 1976, the Lagoon had an estuarine condition (with salinity < 35 g/L) up to Parnka Point and was marine (salinity between 35 to 47 g/L) in the South Lagoon (Appendix F). The models predicted a very high probability (> 75%) occurrence of Yelloweye Mullet and Greenback Flounder in the entire Lagoon (Figures 6.31 and 6.32). Smallmouth Hardyhead had a very high probability of occurrence in the South Lagoon between

Jack Point and Salt Creek and a high probability to the south of Noonameena down to Jack Point. The species had a moderate probability of occurrence in the North Lagoon, except around Ewe Island (Figure 6.33). Tamar River Goby had a very high probability of occurrence up to midway between Noonameena and Parnka Point, a high probability (50 – 75%) up to Villa dei Yumpa and a moderate probability (25 – 50%) to the south of Villa dei Yumpa (Figure 6.34).

In July 1988, the salinity levels were elevated by about three times in the North Lagoon and two and half times in the South Lagoon relative to the salinity level in July 1976 (Appendix 6.6). The salinity ranged between 5 g/L around the Murray Mouth and 89 g/L at Salt Creek in the South Lagoon. High salinity levels impacted on the occurrence probability of the key fish species along the Lagoon. Very high occurrence probabilities of Yelloweye Mullet and Greenback Founder were restricted to north of Villa dei Yumpa and Parnka Point in the South Lagoon, respectively, with a low probability of occurrence to the south of Jack Point due to high salinity levels. Tamar River Goby was also impacted negatively, with a very high probability of occurrence limited to north of Long Point. In contrast, the rising salinity level favoured Smallmouth Hardyhead and the area with a very high probability included the entire North and South Lagoon.

Salinity rose to extremely high levels in January 2005 with a minimum of 42 g/L around the Murray Mouth and a maximum of 124 g/L at Salt Creek in the South Lagoon (Appendix 6.6). High salinity levels in the North Lagoon favoured a very high probability of occurrence for Smallmouth Hardyhead throughout the entire Coorong except for the area around the Murray Mouth, which had a high probability. Tamar River Goby was restricted to a moderate probability of occurrence in the North Lagoon, and low south of Pelican Point. Yelloweye Mullet and Greenback Founder both had a low probability of occurrence from about 10 kilometres south of Noonameena including the South Lagoon. However, Yelloweye Mullet had a very high probability of occurrence north of Noonameena whereas Greenback Flounder had a very high occurrence probability between Goolwa Channel and Ewe Island and a high occurrence probability to the south of Long Point. Table 6.5 summarises the probability of occurrence for the key fish species and their relationship with salinity.

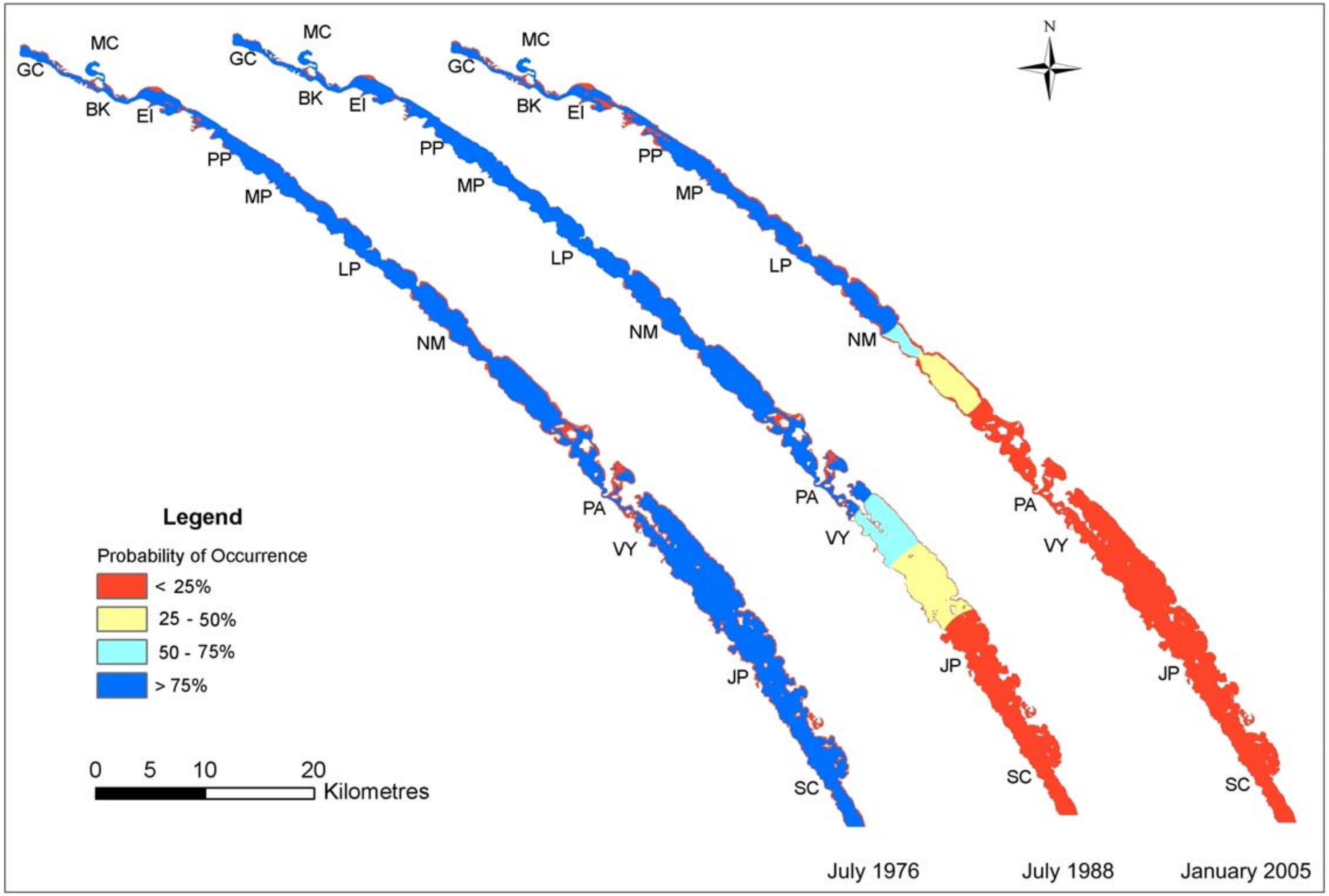


Figure 6.31. Habitat prediction for Yelloweye Mullet in July 1976, July 1988 and January 2005. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa, JP = Jack Point and SC = Salt Creek.

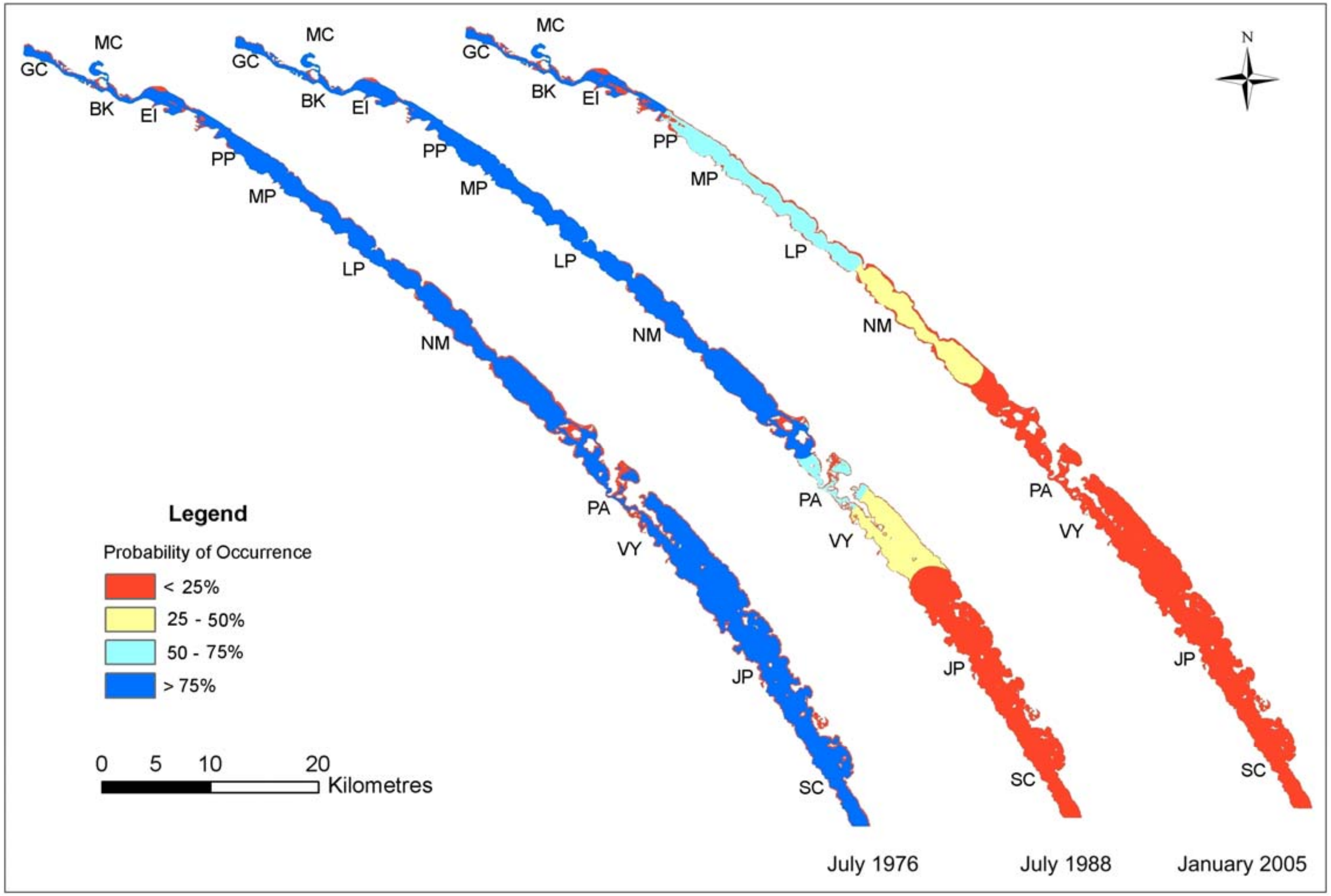


Figure 6.32. Habitat prediction for Greenback Flounder in July 1976, July 1988 and January 2005. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa, JP = Jack Point and SC = Salt Creek.

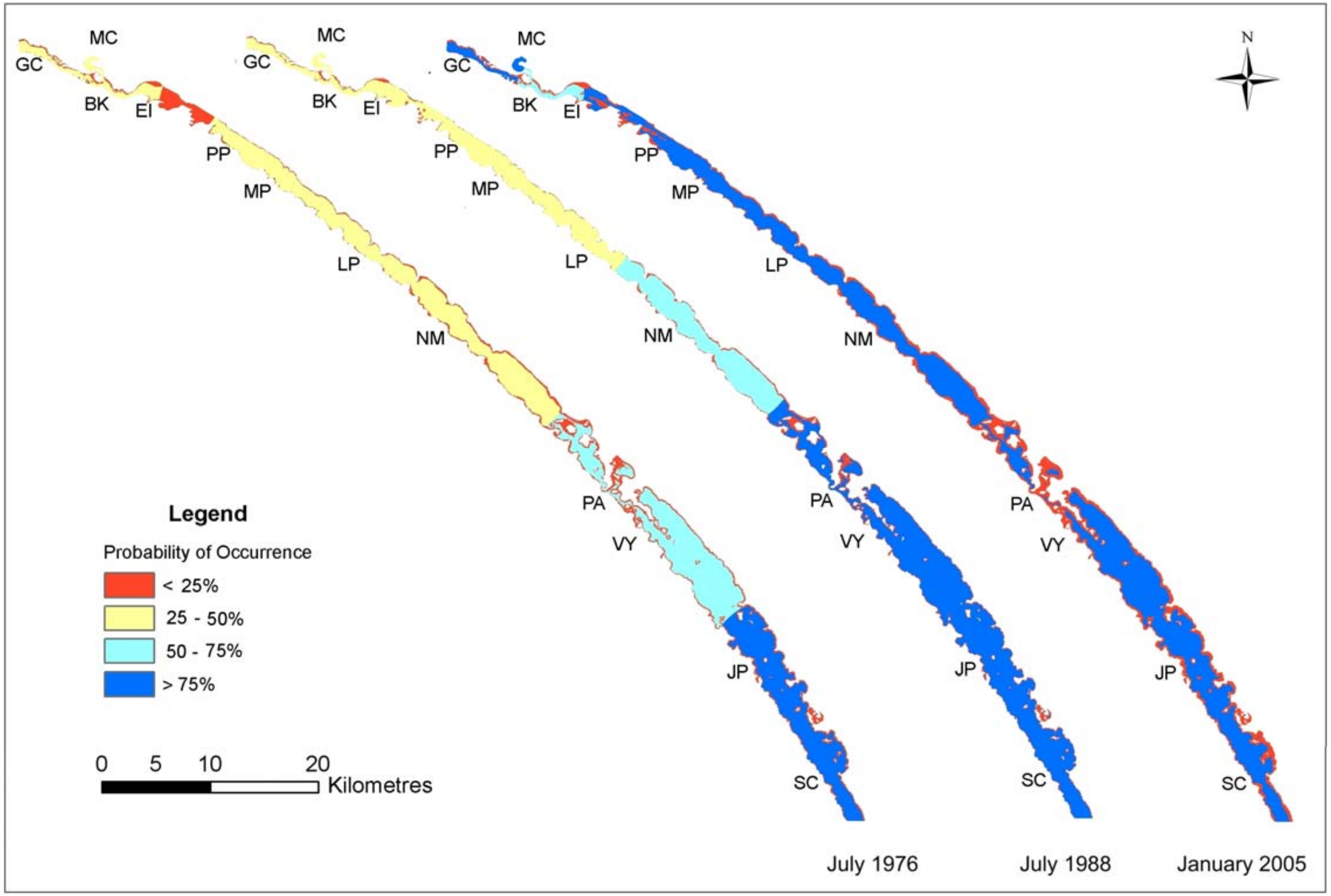


Figure 6.33. Habitat prediction for Smallmouth Hardyhead in July 1976, July 1988 and January 2005. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa, JP = Jack Point and SC = Salt Creek.

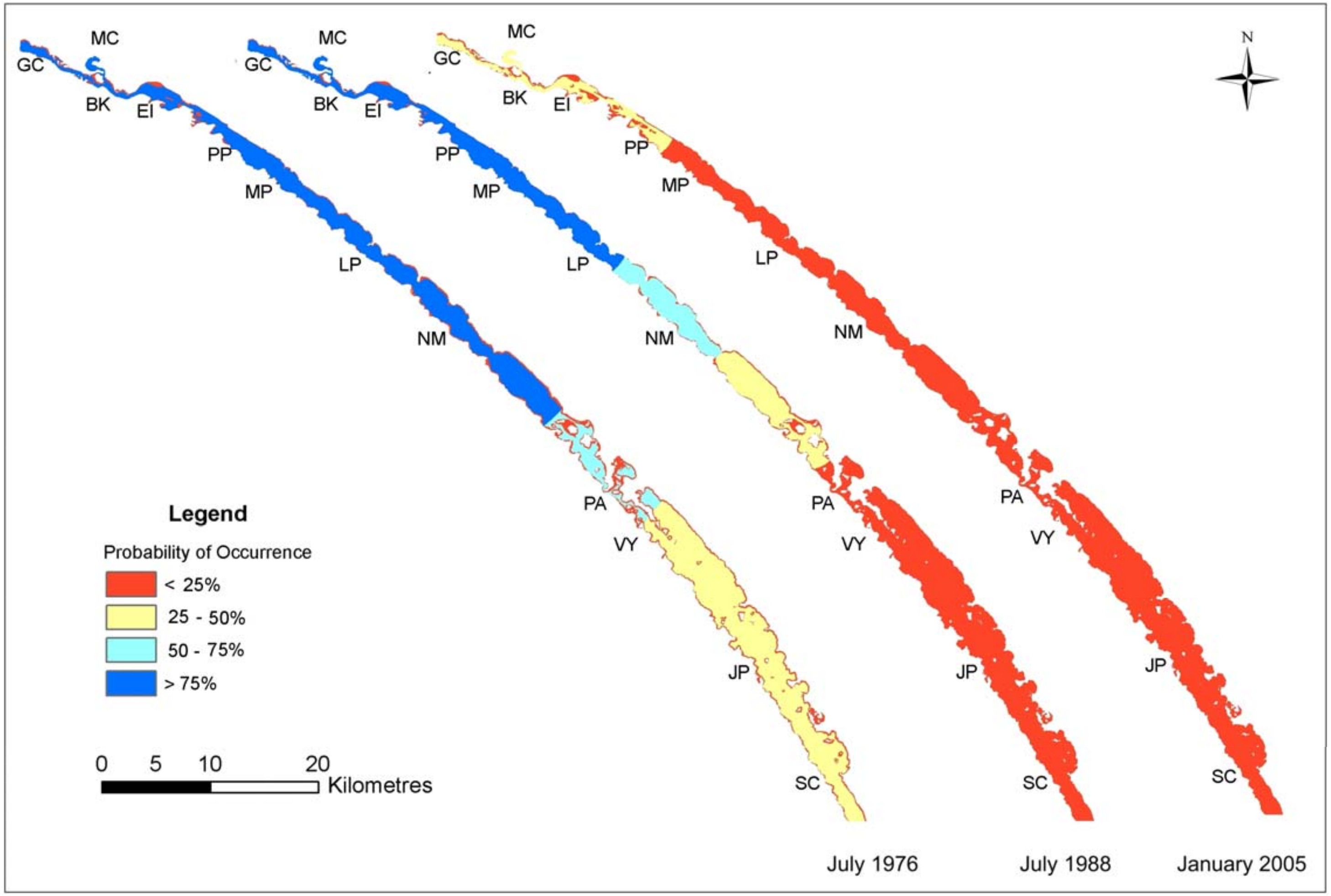


Figure 6.34. Habitat prediction for Tamar River Goby in July 1976, July 1988 and January 2005. GC = Goolwa Channel; MC = Mundoo Channel; BK = Barker Knoll; EI = Ewe Island; PP = Pelican Point; MP = Mark Point; LP = Long Point; NM = Noonameena; PA = Parnka Point; VY = Villa dei Yumpa, JP = Jack Point and SC = Salt Creek.

Table 6.5. Salinity level and occurrence probability for the four key fish species.

Key Fish Species	Occurrence Probability/ Salinity (g/L)			
	< 25%	25 – 50%	50 – 75%	> 75%
Yelloweye Mullet	> 80	72 - 80	64 - 72	< 64
Smallmouth Hardyhead		< 22	22 - 43	> 43
Greenback Founder	> 75	61 - 75	47 - 61	< 47
Tamar River Goby	> 49	35 - 49	22 - 35	< 22

6.5. Discussion

6.6.1 Water level and salinity variations in the Coorong

Water level and salinity are the key ecological drivers in the Coorong, and influence the overall distribution of biological communities and the state of the ecosystem as a whole. Changes in water level influence the availability of mudflat habitats for waterbirds (Rogers and Paton 2009a) and their main food source by impacting on distribution of *Ruppia tuberosa* (Rogers and Paton 2009b) and macroinvertebrates. Salinity has been recognized as the most critical factor for the ecological sustainability of the Coorong, impacting directly on the aquatic biological communities (fish, vegetation and macroinvertebrates) and indirectly on the waterbirds through influencing their primary food source (*R. tuberosa*) (Rogers and Paton 2009b; Rolston and Dittmann 2009).

Variations in water level are primarily attributed to the timing and volume of freshwater input over the barrages, Upper South East Drainage (USED) flow, and the opening of the Murray Mouth (Webster 2005, 2007). The seasonal variation in water levels is mainly caused by rainfall and evaporation, while wind and tide have a higher frequency temporal effect. In the summer, the Coorong and surrounding region receive low rainfall (average <22 mm per month at Meningie) with very high evaporation (average > 225 mm per month for the Lakes) compared to the winter season rainfall (average >40 mm per month at Meningie) and evaporation (average < 60 mm per month for the Lakes). High rainfall with less evaporation in July is likely to favour higher water levels than in January. On a shorter time-scale, the tide has diurnal or semi-diurnal effects in areas around the Murray Mouth and up to 15 km from the Mouth in the North Lagoon, whereas wind influences water levels both in the North and South Lagoon (Webster 2007). Although the volume of the water inputs, season (time), rainfall, evaporation, tide and wind all act together to determine water level at any point in time, the seasonal variation in the water levels is due primarily to rainfall and evaporation in no/low flow situations, resulting in high and low water levels in winter and summer, respectively

The monthly barrage flow data used for the scenario modelling (Appendix 6.7) showed large fluctuations in the quantity of water released into the Coorong in the past decades. Among the four selected years, the predicted average water level was higher in July than in January except for 1993. High water levels in January 1993 were attributed to almost five times more water volume (2199 GL) released into the Coorong than in July. Although the amount of water had a large impact on the water level, it was not possible to find a fixed relationship between the volume of water and the water level in the Coorong. For example, the model predicted a higher water level with about 73 GL released in July 2005 than in July 1993 with 433 GL of water released. Therefore, other hydrodynamic factors present in the Lagoon such as water flow out from the Lagoon, underground leakage, etc. could also play a significant role in determining the water levels in the Coorong.

The water levels vary longitudinally in the Lagoon due to the main hydrological drivers; water volume, timing, Murray Mouth opening and environmental variables such as rainfall, precipitation and evaporation. The average water level in the South

Lagoon was predicted to be as high as 8 cm above the water level in the North Lagoon during barrage flows. However, in the summer without barrage flows, the water level in the Lagoon is entirely influenced by sea level and the Murray Mouth opening and drops below 0 mAHD, causing a significant reduction in the water flow at Parnka Point and isolating the South Lagoon. Eventually, further loss of water due to evaporation lowers the water level in the South Lagoon below that of the North Lagoon (Webster 2007). The Coorong did not receive barrage flows in January 1988 or 2005, resulting in average water levels of around 0.12 mAHD in the North Lagoon and around -0.10 mAHD in the South Lagoon.

Salinity levels in the Coorong are influenced by a number of factors including; salty water inputs through the Murray Mouth and USED, their transport and mixing, and evaporation. Freshwater inputs through the barrages tend to raise the water level, compensating for evaporative water loss and eventually reducing salinity levels along the Lagoon if flows are large enough (Webster 2007). For example, about 30 to 40 GL of waterflow over the barrages restored estuarine conditions in areas up to 15 km from the Murray Mouth for about 20 days (Geddes 2005b).

During barrage flows in the four selected years, the salinity level was maintained below ~ 20 g/L in the Murray Mouth and in some areas in the North Lagoon, and it did not exceed 56 g/L in Salt Creek at the end of the South Lagoon. However, zero flows in January 1988 and 2005 doubled salinity levels along the Lagoon, reaching ~40 g/L around the Murray Mouth and ~ 126 g/L at Salt creek.

6.6.2 Mudflat availability at the reference sites

For this analysis, we designated mudflats up to 12 cm water depth as suitable for foraging by the majority of waterbird species (Rogers pers. comm., Wildlife Habitat Management Institute 2000). Analysis of mudflat availability was performed for the days with maximum and minimum water levels in both wet and dry years. Water level ranges between -0.30 to 1.25 mAHD, -0.09 to 1.30 mAHD and -0.15 to 1.09 mAHD were modelled for Barker Knoll, Noonameena and Salt Creek, respectively, although there was not a simple relationship between mudflat availability and water level.

The availability of mudflat areas accessible to waterbirds is governed by the underwater topography. For a given water level, relatively flat areas provide more available foraging area than steeply sloping areas (see Chapter 5). A study of the morphology of mudflats in the Coorong discussed the mudflat slopes (%) for all references sites (see Chapter 5), however, the slopes of the eastern and western shores were not differentiated. In the current study, mudflat areas are estimated as the sum of all areas available on the eastern and western shores, and in the channel in the case of Barker Knoll. Because of differences in the topography (slope), these areas offer varying amounts of mudflat for specified water levels. At Barker Knoll, the maximum area of mudflat (3.19 ha) was available at -0.05 mAHD with more than 75% of mudflat located on the eastern shore, implying the eastern shore is relatively flat compared to the western shore. Similarly the maximum mudflat area (6.17 ha) occurred at 0.27 mAHD at Salt Creek with more than 60% found on the eastern shore. However, the western shore has a lesser slope at Noonameena and thus contributed about 55% of the maximum mudflat area (6.38 ha). It should be noted here that the hydrodynamic model only gives water level along the centreline of the Lagoon, and we assume that this is representative of the entire width. In reality, wind is likely to bank water along one shore, resulting in changing water levels and mudflat availability across the Lagoon.

Temporal variation in mudflat area was evident at Barker Knoll due to diurnal or semi-diurnal tidal influences on the water level, whereas Noonameena and Salt Creek had very little change in mudflat area over the period of a day as water level varied little at this time-scale.

Although the topography of the Lagoon is a major factor for determining accessible mudflat areas in the Coorong, the water level is the variable that managers can manipulate to maximize mudflat availability. As the water levels vary longitudinally in the Lagoon, it is not possible to maximize mudflat area at all locations at the same time. Based on the three selected references sites, the highest average mudflat area was observed at an average water level of ~0.12 mAHD on the day with minimum water level in January 1976. The highest mudflat area of 6.17 ha occurred at Salt Creek at 0.26 mAHD followed by Noonameena with 4.43 ha at -0.06 mAHD and the lowest area of 2.64 ha at Barker Knoll at -0.11 mAHD.

6.6.3 Habitat modelling and prediction for key fish species

Salinty has been recognized as the most significant ecological variable for the distribution of biological communities including key fish species in the Coorong (Noell *et al.* 2009; Geddes 1987). The occurrence of the key fish species was modelled against salinity using logistic regression. The model found a significant relationship between salinity and the occurrence of four key species: Yelloweye Mullet, Smallmouth Hardyhead, Greenback Flounder and Tamar River Goby in the Coorong. However, the model for Smallmouth Hardyhead failed to classify any of the absent data accurately, suggesting that an important environmental variable constraining the presence of this species was absent from the model, or that distribution within suitable habitat is patchy. Smallmouth Hardyhead was found to be the most salt tolerant species, and was collected from the South Lagoon at 149‰ total dissolved solids (TDS) (~ 130 g/L) in 1984 (Geddes 1987) and up to 133.5 g/L in December 2006 (Noell *et al.* 2009). According to the species-salinity relationship established by the model, this species is highly likely to occur above 43 g/L to the maximum salinity level (125 g/L) predicted for January 2005. In contrast to Smallmouth Hardyhead, other key species preferred low salinity. Geddes (1987) reported Yelloweye Mullet, Black Bream and Congolii from the South Lagoon at salinities below 55‰TDS. For Yelloweye Mullet, salinities below 64 g/L offer a high likelihood of occurrence in the Coorong. Habitat modelling of Yelloweye Mullet using Non Parametric Multiplicative Regression (NPMR) (McCune 2006) also demonstrated salinity as the major predictor variable for this species along with water temperature, and it is likely to occur with consistent probability of occurrence of > 90 % at salinity < 64 g/L (Sharma *et al.* 2009). Greenback Flounder was reported in the list of commonly found fish species in the North Lagoon during 1984, when the salinity ranged from 5 to 65 g/L (Geddes 1987). However, the model found Greenback Flounder to be less salinity tolerant than Yelloweye Mullet and predicted a high likelihood of occurrence at salinities below 47 g/L.

Another key fish species of the Coorong, Tamar River Goby, which has an estuarine life cycle (Noell *et al.* 2009), was not reported in the study by Geddes (1987). However, it was collected in 26 samples out of 94 during sampling undertaken in 2006-08. This species had the lowest salinity tolerance of the four key species and is only highly likely to occur at salinities below 22 g/L.

The prediction maps for these key species were generated by applying the regression coefficients in a model in a GIS platform. The probability of occurrence was estimated based on the species-salinity relationship. The model consistently made accurate predictions of where species would occur, although it was slightly less accurate at predicting where they would be absent. Salinities between < 10 to 50 g/L favoured the low salinity tolerant species; Tamar River Goby, Greenback Flounder and Yelloweye Mullet. However, Smallmouth Hardyhead had a low probability (< 25 %) of occurrence in the North Lagoon where salinity was below 30 g/L. In January 2005, habitat suitability for Smallmouth Hardyhead increased, with an elevated salinity range between 40 to 125 g/L, at the expense of other key species. As salinity in the North Lagoon increased above 40 g/L, Greenback Flounder was restricted to the north of Pelican Point in the North Lagoon while Tamar River Goby had a low probability of occurrence (< 25 %) in most of the Lagoon except to the north of Pelican Point where probability of occurrence ranged between 25 to 50 %. However, salinity in July 1988 ranged around 5 to 90 g/L and offered suitable habitat for low salinity tolerant key species (Tamar River Goby) to the north of Long Point and Greenback Flounder had high probability to the north of Parnka in the North Lagoon. Yelloweye Mullet, with slightly higher salinity tolerance to Greenback Flounder, had a high probability of occurrence north of Villa dei Yumpa, while the high salinity tolerant species, Smallmouth Hardyhead, had a high probability of occurrence in the salinity range 43 to 89 g/L, between 9 km north of Parnka Point in the North Lagoon to the southern end of the South Lagoon.

6.6.4 Barrage outflow, water level and salinity in the Coorong

The quantity, frequency and duration of the freshwater outflow over the barrages greatly influence salinity levels and the ecological health of the Coorong (Geddes 1987; 2003; 2005a; 2005b) while also influencing the water level in both lagoons (Webster 2005, 2007). Managers are interested to know how much and how frequently freshwater should be released into the Coorong to maintain the optimum water level which maximizes mudflat habitat for the waterbirds and the best range of salinity for supporting maximum diversity of biological communities. The analysis of mudflat availability at three representative sites and the modelling of the key fish species-salinity relationships suggests that an average water level of 0.12 mAHD is required to secure maximum mudflat area whereas a salinity range of 5 to 90 g/L, as occurred in January 1988, provides the most suitable salinity conditions for these key species. At this time, the North Lagoon had an estuarine condition (< 30 g/L) around the Murray Mouth south to Noonameena, and a marine condition (30 to 50 g/L) to the north of Parnka Point. In the South Lagoon, the salinity ranged from hypersaline with 50 to 65 g/L to the north of Villa dei Yumpa, to highly hypersaline with 65 to 80 g/L to the north of Jack Point and extremely hypersaline with 80 to 90 g/L to the south of Jack Point. Maintaining an estuarine condition in the North Lagoon also offers a suitable habitat for a wide range of micro-benthic species (Geddes 1987; Rolston and Dittmann 2009) and the macrophyte *Ruppia megacarpa* (Geddes 1987). *Ruppia megacarpa* is believed to have become extinct from the system in 1990s due to elevated salinities in the Coorong (Nicol 2005). A salinity range of 50 to 90 g/L in the South Lagoon provides suitable habitat for high salinity tolerant fish species (Smallmouth Hardyhead), macro-invertebrates such as *Capitella capitata*, *Australonereis* spp., *Simplisetia* and insect larvae (Rolston and Dittmann 2009), and the macrophyte *Ruppia tuberosa* (Paton 2005).

An investigation of the barrage outflows used in the hydrodynamic modelling for predicting water level and salinity was not helpful for prescribing an appropriate volume and frequency for water inputs into the Coorong. However, Geddes (1987) noted that volumes above 1000 GL released into the Coorong for three consecutive months between August to October 1983 eventually reduced the salinity range from 40 to 130‰TDS to 25 to 60‰TDS in the North Lagoon and about 70‰TDS in the South Lagoon. The measured salinity range of ~ 40 to 105 g/L in the Coorong in October 2008 was similar to the salinity condition prior to barrage outflows in 1983. This suggests that initially we require a similar volume of water for a few months to substantially reduce the salinity in the system, although this is unimaginable under current conditions in the Murray Darling Basin. Once the salinity is in the appropriate range, barrage outflows would be required to mitigate the impact on salinity of sea water incursion and to compensate for the evaporative loss of water, particularly in summer months. Management of the Coorong is a very complex issue and requires further research and modelling taking into account the current situation in the Lagoon and the dynamics of environmental as well as physical factors like opening of the Murray Mouth, sea water incursions, etc.

6.6. Summary, Conclusions & Management Implications

A spatial approach to modelling mudflat availability and key fish species habitats in the Coorong is used to understand and visualise the spatio-temporal variations in these habitats for a given hydrodynamic situation. The spatial models developed as part of this study run continuously for several series of simulated water level and salinity data and subsequently maps are generated for each scenario.

The mudflat habitat was taken to constitute the mudflat area up to 12 cm depth below water level, representing accessible foraging ground for most species of waterbirds, and having a high abundance of macro-invertebrates under moderate salinities. The areas close to the Murray Mouth (Barker Knoll) are often influenced by diurnal or semi-diurnal tidal effects resulting in short-term temporal variation as well as frequent inundation of mudflats, supporting a high diversity and density of macro-invertebrates. However, the temporal variation at the other two sites at Noonameena and Salt Creek was not as evident as it was at Barker Knoll unless there was a significant change in the water level due to strong wind or water released through the barrages or the Upper South East Drainage scheme.

Along the Lagoon, the availability of mudflat is determined by the water level and the underlying topography. Flatter areas tend to offer more mudflat at a given water level. The eastern shore is flatter than the western shore in the Coorong. For this reason, the eastern shore offered more mudflat than the western shore among the three selected sites. The topography of the Lagoon is relatively stable over short periods of time, apart from areas directly adjacent to the Murray Mouth. However, managers could manipulate or control the water level through opening or shutting of barrages in order to maximize availability of mudflat in the Coorong. An analysis of mudflat availability at different water levels suggests that an average water level of 0.12 mAHD gives the maximum average mudflat area in the three reference sites.

The first spatial model generates maps for mudflat areas in the eastern and western shores and the channel (if any) and also the exposed mudflat areas above the waterline. The maps depict the mudflat areas up to 12 cm depth at 1 cm resolution. However, waterbirds are specific in their prey and are specialized in their use of mudflats under different water depths (Australian Online Coastal Information 2009). The 1 cm depth resolution maps allow a detailed analysis of mudflats at different depths, and would be very useful to understand the relationship between different waterbirds and their requirement of mudflat at particular depths. Importantly, although model results for only three selected sites are presented here, the model can be run for any given flow scenario over any time period for any of the 12 reference sites along the Coorong. The model could also be modified in the future to take into account the time since drying/wetting, which may be important for some macrophytes and macroinvertebrates.

The second spatial model used species-specific relationships between the fish distribution and salinity to predict the likelihood of occurrence of fish under different salinity regimes. Out of seven key fish species, Yelloweye Mullet, Smallmouth Hardyhead, Greenback Flounder and Tamar River Goby demonstrated a significant relationship with salinity levels. Among the three different salinity gradients examined, the salinity range from 5 to 90 g/L along the Lagoon was found to give the greatest representation of these four key species, and is also known to support other important biological communities including both macrophytes and infauna.

Although this study was able to suggest appropriate water levels and salinity gradients to maximize mudflat areas and biological communities in the Coorong, we were not able to define the volume and frequency of water to be released through the barrages or Upper South East drainage scheme. This requires further research and hydrodynamic analysis considering all physical and hydrological factors.

It is important for managers to understand the influence of both water level and salinity on mudflat habitats as well as the aquatic habitats for fish, macrophyte and infauna. The spatial models developed for this study allow managers to readily quantify these habitats for specified flow scenarios, and support informed decisions on the amount and frequency of barrage outflows once the Lower Lakes are recharged and excess water is available for the Coorong.

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6.8. Appendices

Appendix 6.1: Script used for modelling mudflat habitat.

```
# bird_habitat.py
# Created on: Fri Feb 27 2009 10:24:35 AM
#   (generated by ArcGIS/ModelBuilder)
# Usage: bird_habitat_finer <DEM_for_the_site>
<Specify_the_mean_water_level_for_the_site> <Site_boundary_to_high_water_mark_level>
<Change_the_mean_water_level_in_the_expression> <West_shore_line_mask>
<East_shore_line_mask> <Available_mudflat_area>
<Area_Exposed_between_high_water_mark_and_the_shoreline>
<Mudflat_area_in_eastern_shore> <Perimeter_of_the_eastern_shore>
<Mudflat_area_in_western_shore> <Perimeter_of_the_western_shore>
# ---------------------------------------------------------------------------
# Import system modules
import sys, string, os, arcgisscripting, math
# Create the Geoprocessor object
gp = arcgisscripting.create()
# Check out any necessary licenses
gp.CheckOutExtension("spatial")
# Load required toolboxes...
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Conversion Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management
Tools.tbx")
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx")
# Set the Geoprocessing environment...
gp.outputCoordinateSystem =
"PROJCS['GDA_1994_MGA_Zone_54',GEOGCS['GCS_GDA_1994',DATUM['D_GDA_1994',
SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degre
e',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Eastin
g',500000.0],PARAMETER['False_Northing',10000000.0],PARAMETER['Central_Meridian',14
1.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter
',1.0]]"
gp.extent =
"Q:\CLLAMM_PROJECTS\HABITAT_MODELLING\BIRD_HABITAT\\ewe_bdry.shp"
# Local variables...
water_level =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\water_level_data.dbf"
DEM_site =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\ewe_dem"
bdry_site =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\ewe_bdry.shp"
west_coast =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\west_coast.shp"
east_coast =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\east_coast.shp"
bdry_high_water_mark =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\bdry_high_water_mar
k.shp"
modelPath =
"Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\OUTPUT_BIRD_HABI
TAT\\"
# setting workspace
gp.workspace = modelPath
try:
   # Get list of fields for looping
```

```
    fields1 = gp.ListFields
("Q:\\CLLAMM_PROJECTS\\HABITAT_MODELLING\\BIRD_HABITAT\\water_level_data.dbf"
, "T*")
    fields1.reset()
    # Get the first field and start loop
    field1 = fields1.Next()
    while field1:
        wLevel = field1.Name
        print "Water level in the list is: ", str(wLevel)
        #output 1: A raster from water level data
        wl_IDW = modelPath + wLevel + "_IDW"
        #output 2: DEM for the subtidal_area extracted by using average water level value
        wl_Site = modelPath + wLevel+ "_site"
        #output 3: DEM for the subtidal_area extracted by using average water level value
        wl_DEM = modelPath + wLevel+ "_dem"
        #output 4: Generating mask for the subtidal area
        wl_Mask = modelPath + wLevel+ "_mask"
        #output 5: Total mudflat area in the site both up to 12 cm  (0) and below 12 cm (1) depth
        wl_totalArea = modelPath + wLevel+ "_totalArea"
        #output 6: Available mudflat area in the site with less than 12 cm depth
        wl_MF = modelPath + wLevel + "_MF"
        #output 7: DEM for the Available mudflat area
        wl_MFDEM = modelPath + wLevel+ "_MFDEM"
        #output 8: Available mudflat area in the east coast
        wl_MFEast = modelPath + wLevel +"_MFEast"
        #output 9: Available mudflat area in the east coast
        wl_DEPTH = modelPath + wLevel +"_DEPTH"
        #output 10: Available mudflat area in the east coast
        wl_DEPTHint = modelPath + wLevel +"_DEPTHint"
        #output 11: Available mudflat area in the wast coast
        wl_MFWest = modelPath + wLevel + "_MFWest"
        #output 12: Available mudflat area in the wast coast
        wl_MFExp = modelPath + wLevel + "_MFExp"
        #output 13: Available mudflat area in the wast coast
        wl_AreaExp1 = modelPath + wLevel + "_AreaExp1"
        #output 14: Available mudflat area in the wast coast
        wl_AreaExp = modelPath + wLevel + "_AreaExp"
        #Generating raster from water level data
        gp.Idw_sa(water_level, wLevel, wl_IDW, "1", "2", "VARIABLE 10", "")
        gp.AddMessage("Successful" + gp.GetMessages())
        print "Successful", gp.GetMessages()
        #Process: Extract water level rater with the site mask
        gp.ExtractByMask_sa(wl_IDW, DEM_site, wl_Site)
        #Raster properties: Getting the mean water level from the interpolated water level raster
        mean = str(gp.GetRasterProperties(wl_Site,"MEAN","0"))
        print "Mean is: ", mean
        InWhereClause = "value <= "+ mean +""
        #Process: Extracting the bathymetry below the mean water level
        gp.ExtractByAttributes_sa(DEM_site, InWhereClause, wl_DEM)
        print gp.GetMessages()
        #Generating a mask for the areas (subtidal) defined by the water level
        InExpression1 = wl_Mask + " = ( " + wl_DEM +" - "+ wl_DEM +")"
        gp.MultiOutputMapAlgebra_sa(InExpression1)
        print gp.GetMessages()
        #Applying 12 cm depth condition to the Mudflat bathymetry (wl_DEM) to areas
        #below 12 cm depth as ture (1) and areas upto 12 cm depth as false (0).
        InExpression2 = wl_totalArea+ " = ( " + wl_DEM + " <= ("+wl_Mask+" + "+ mean +" -
0.12))"
        gp.MultiOutputMapAlgebra_sa(InExpression2)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        # Process: Reclassify Mudflat area as 1 and the rest of area as Nodata
        gp.Reclassify_sa(wl_totalArea, "VALUE", "0 1;0 1 NODATA", wl_MF, "DATA")
```

```
        # Process: Extracting bathymetry for the Mudflat area
        gp.ExtractByMask_sa(DEM_site, wl_MF, wl_MFDEM)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        #Mudflat depth in cm from the water level down below derived from substracting
        #the mean water level. It means water depth at water level is 0 cm.
        InExpression3 = wl_DEPTH+ " = ( "+ mean +" - " + wl_MFDEM + " )"
        gp.MultiOutputMapAlgebra_sa(InExpression3)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        #Process: Converting Mudflat bathymetry to integer value.
        InExpression4 = wl_DEPTHint + " = Int(100 * " + wl_DEPTH  + ")"
        gp.MultiOutputMapAlgebra_sa(InExpression4)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        # Process: Extracting avialable Mudflat area in the eastern shore
        gp.ExtractByMask_sa(wl_DEPTHint, east_coast, wl_MFEast)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        # Process: Extracting avialable Mudflat area in the western shore
        gp.ExtractByMask_sa(wl_DEPTHint, west_coast, wl_MFWest)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        # Process: Reclassifying total area (areas below water level) as NODATA and
        #the rest of the areas, previously NODATA to 1.
        gp.Reclassify_sa(wl_totalArea, "VALUE", "0 NODATA;0 1 NODATA;NODATA 1",
wl_MFExp, "DATA")
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        # Process: Extracting areas exposed between the water level and the high water mark
level
        gp.ExtractByMask_sa(wl_MFExp, bdry_high_water_mark, wl_AreaExp1)
        gp.AddMessage("Successful" + gp.GetMessages())
        print gp.GetMessages()
        #Process: Cleanign the exposed area by using bathymetry dataset
        gp.ExtractByMask_sa(wl_AreaExp1, DEM_site, wl_AreaExp)
        #Delete intermediate layers
        gp.AddMessage ("Cleaning up ......." + gp.GetMessages())
        gp.delete(wl_IDW)
        gp.delete(wl_Site)
        gp.delete(wl_Mask)
        gp.delete(wl_DEM)
        gp.delete(wl_MFDEM)
        gp.delete(wl_MF)
        gp.delete(wl_totalArea)
        gp.delete(wl_DEPTH)
        gp.delete(wl_DEPTHint)
        gp.delete(wl_MFExp)
        gp.delete(wl_AreaExp1)
        print gp.GetMessages()
        # looping
        field1 = fields1.Next()
except:
    print gp.GetMessage(1)
```

Appendix 6.2: Script used for modelling fish habitat.

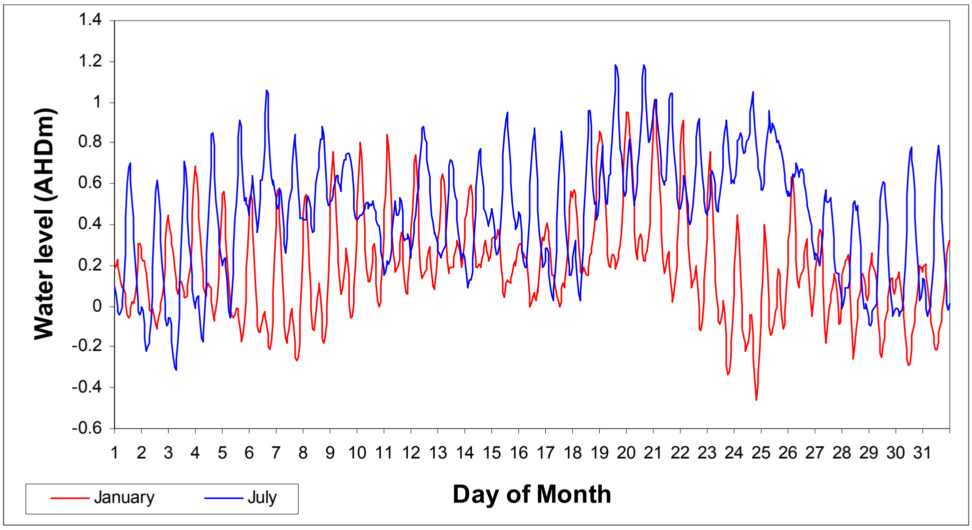
```
# ---------------------------------------------------------------------------
# Created on: Tue Apr 08 2008 10:47:39 AM
#   (generated by ArcGIS/ModelBuilder)
# ---------------------------------------------------------------------------

# Import system modules
import sys, string, os, arcgisscripting, math

# Create the Geoprocessor object
gp = arcgisscripting.create()

# Check out any necessary licenses
gp.CheckOutExtension("spatial")

# Load required toolboxes...
gp.AddToolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Spatial Analyst Tools.tbx")


# Set the Geoprocessing environment...
gp.outputCoordinateSystem =
"PROJCS['GDA_1994_MGA_Zone_54',GEOGCS['GCS_GDA_1994',DATUM['D_GDA_1994',
SPHEROID['GRS_1980',6378137.0,298.257222101]],PRIMEM['Greenwich',0.0],UNIT['Degre
e',0.0174532925199433]],PROJECTION['Transverse_Mercator'],PARAMETER['False_Eastin
g',500000.0],PARAMETER['False_Northing',10000000.0],PARAMETER['Central_Meridian',14
1.0],PARAMETER['Scale_Factor',0.9996],PARAMETER['Latitude_Of_Origin',0.0],UNIT['Meter
',1.0]]"
#gp.CellSize = "25"


# Local variables...
salinity_data = "Q:\\DATA_FOR_SCRIPT\\salinity4_test.dbf"

water_level = "Q:\\DATA_FOR_SCRIPT\\water_level4.dbf"

dem_10 = "Q:\\DATA_FOR_SCRIPT\\dem_10"

coorong_bdry = "Q:\\DATA_FOR_SCRIPT\\test10_bdry.shp"

#Output_variance_of_prediction_raster = ""


modelPath = "Q:\\DATA_FOR_SCRIPT\\"

# Setting workspace
gp.workspace = modelPath

try:
   # Get list of fields for looping
   fields1 = gp.ListFields ("Q:\\DATA_FOR_SCRIPT\\water_level4.dbf", "T*")
   fields1.reset()
   # Get the first field and start loop
   field1 = fields1.Next()

   fields2 = gp.ListFields ("Q:\\DATA_FOR_SCRIPT\\salinity4_test.dbf", "SAA*")
   fields2.reset()
   field2 = fields2.Next()


   while field1:
```

```
        wLevel = field1.Name
        print "Water level in the list is: ", str(wLevel)

        # output
        wl_output = modelPath + wLevel + "_IDW33"
        wl_dem = modelPath + wLevel + "_dem"
        # provide a default value if unspecified
        InExpression1 = wl_dem + " = (" + dem_10 + " < " + wl_output + ")"
        #gp.AddMessage("Working on + wLevel; interpolating by using IDW ....") +
gp.GetMessage())
        #print "IDW failed ", gp.GetMessages()
        # Process: IDW...
        #print "I am here."
        gp.Idw_sa(water_level, wLevel, wl_output, "25", "2", "VARIABLE 10", "")
        gp.AddMessage("Successful" + gp.GetMessages())
        print "Successful", gp.GetMessages()
        # Process: Single Output Map Algebra...
        gp.MultiOutputMapAlgebra_sa(InExpression1)
        # Delete intermediate layers
#        gp.AddMessage ("Cleaning up .......")
        gp.Delete (wl_output)

#        while field2:
        saLevel = field2.Name
        print "Salinity Level in the list is: ", str(saLevel)
        # output names
        sa_output = modelPath + saLevel + "_IDW1"
        sa_log1 = modelPath + saLevel + "_log1"
        sa_log2 = modelPath + saLevel + "_log2"
        sa_log3 = modelPath + saLevel + "_log3"
        YM_pred = modelPath + saLevel + "_YM1"
        # Give a name for the fish habitat raster output
        YM_habi = modelPath + saLevel + "_habitat"

# provide coeffecient values in InExpression2 for a fish species
        InExpression2 = sa_log1 + " = 4.574 - (0.074 * " + sa_output + ")"
            # Do not need to change the values
        InExpression3 = sa_log2 + " = ( "+ sa_log1 +" - (2 * " + sa_log1 + "))"
        InExpression4 = sa_log3 + " = exp(" + sa_log2 + ")"
        InExpression5 = YM_pred + " = (1 /(1 + (" + sa_log3 + ")))"
        InExpression6 = YM_habi + " = (" + wl_dem + " * " + YM_pred + ")"
    #gp.AddMessage("Working on + wLevel; interpolating by using IDW ....") +
gp.GetMessage())
# Process: IDW...
        gp.Idw_sa(salinity_data, saLevel, sa_output, "25", "2", "VARIABLE 10", "")
        gp.AddMessage("Successful" + gp.GetMessages())
        print "Successful", gp.GetMessages()
            # Process: Single Output Map Algebra...
        gp.MultiOutputMapAlgebra_sa(InExpression2)
        gp.MultiOutputMapAlgebra_sa(InExpression3)
        gp.MultiOutputMapAlgebra_sa(InExpression4)
        gp.MultiOutputMapAlgebra_sa(InExpression5)
        gp.MultiOutputMapAlgebra_sa(InExpression6)

        field2 = fields2.Next()


# Delete intermediate layers
        gp.AddMessage ("Cleaning up .......")
        gp.Delete (sa_output)
        gp.Delete (sa_log1)
        gp.Delete (sa_log2)
        gp.Delete (sa_log3)
```

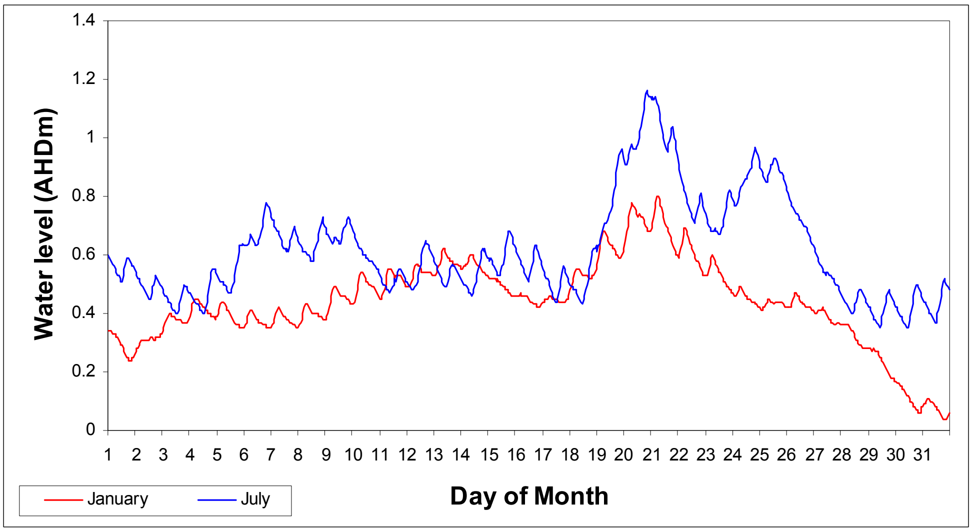
```
        gp.Delete (YM_pred)
        gp.Delete (wl_dem)

    # looping
        field1 = fields1.Next()


except:
    gp.AddMessage(gp.GetMessage(1))
    print gp.GetMessage(1)
```

Appendix 6.3: Hourly water level predictions for January and July of 1976, 1988, 1993 and 2005 at Barker Knoll, Noonameena and Salt Creek.

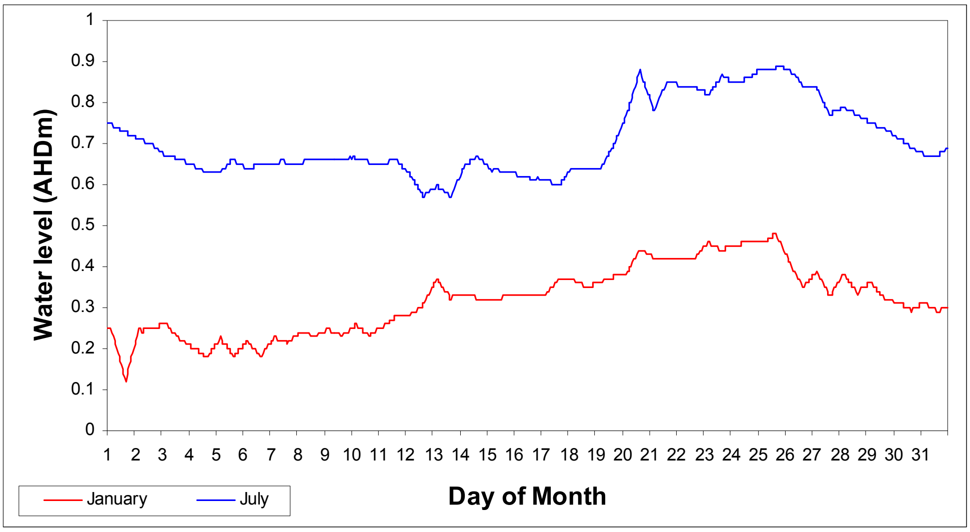
1. Barker Knoll 1976



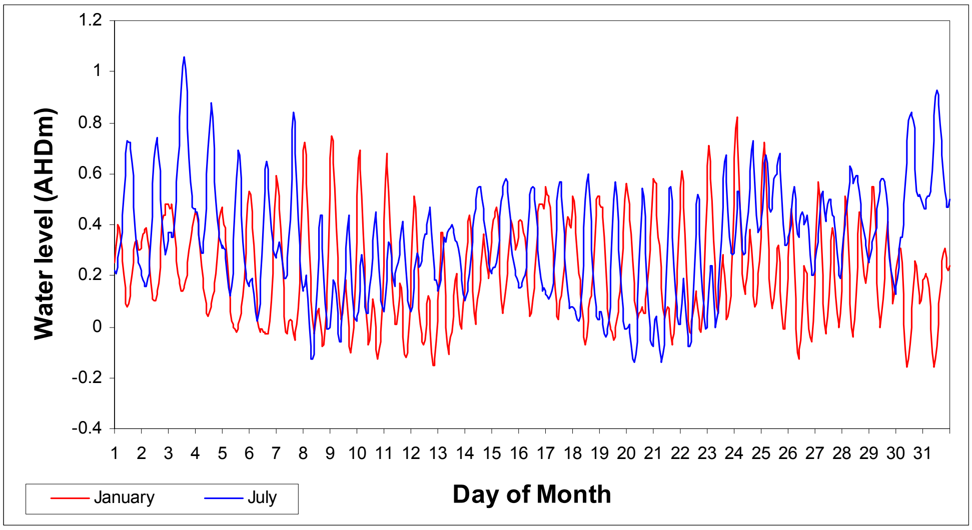
2. Noonameena 1976



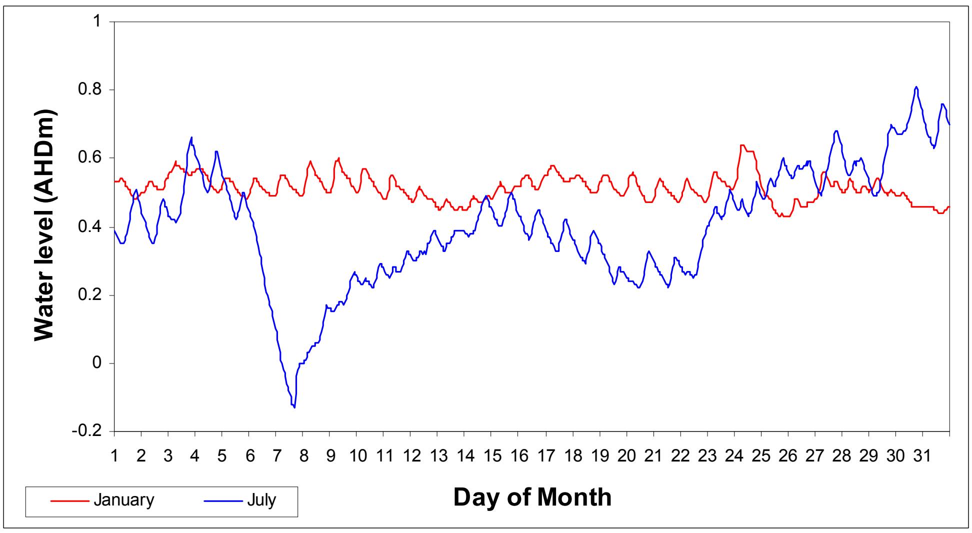
3. Salt Creek 1976



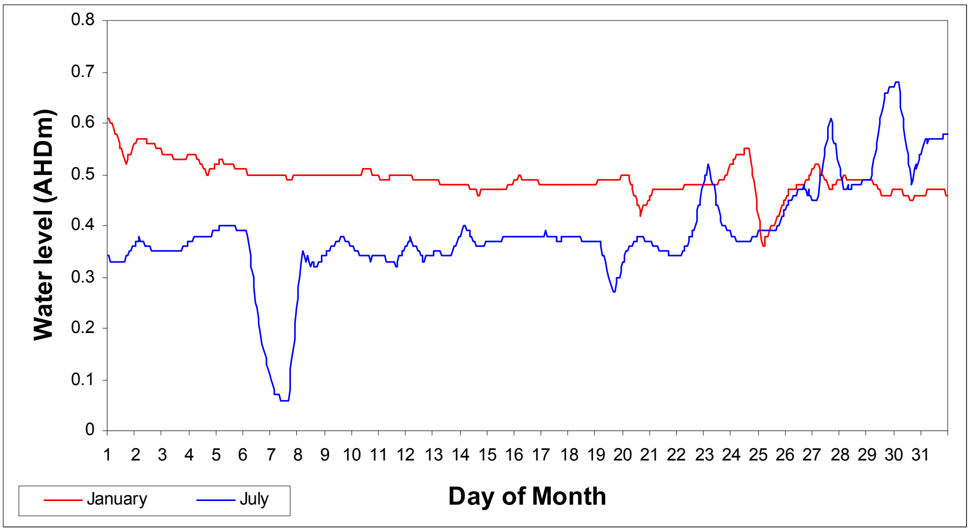
4. Barker Knoll 1993



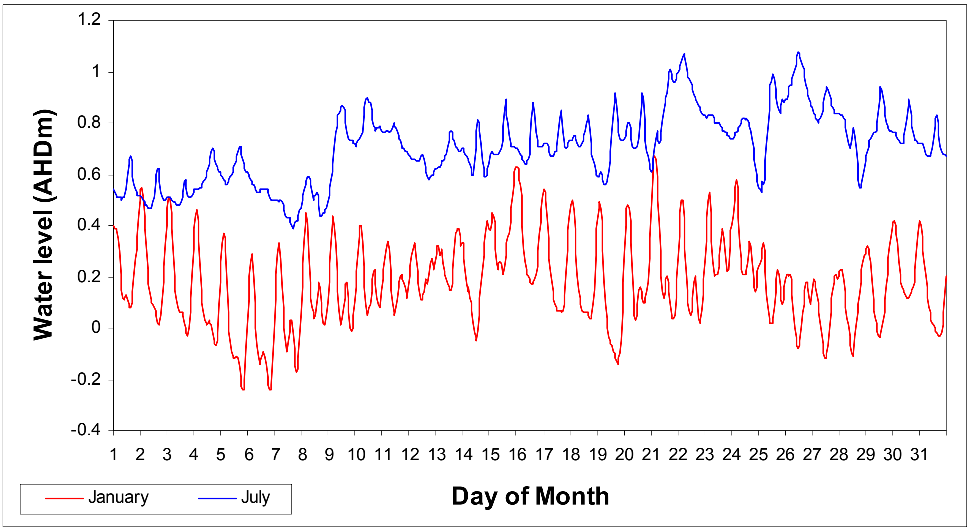
5. Noonameena 1993



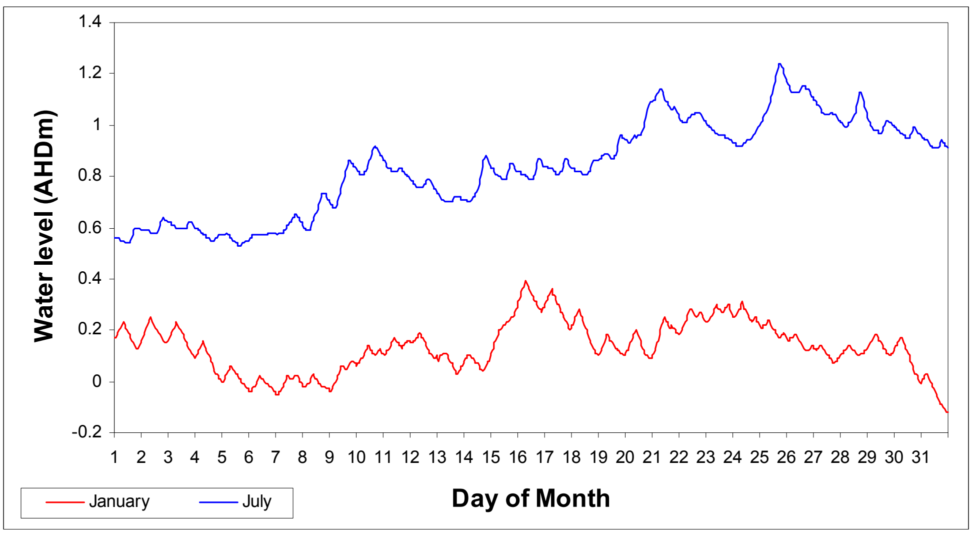
6. Salt Creek 1993



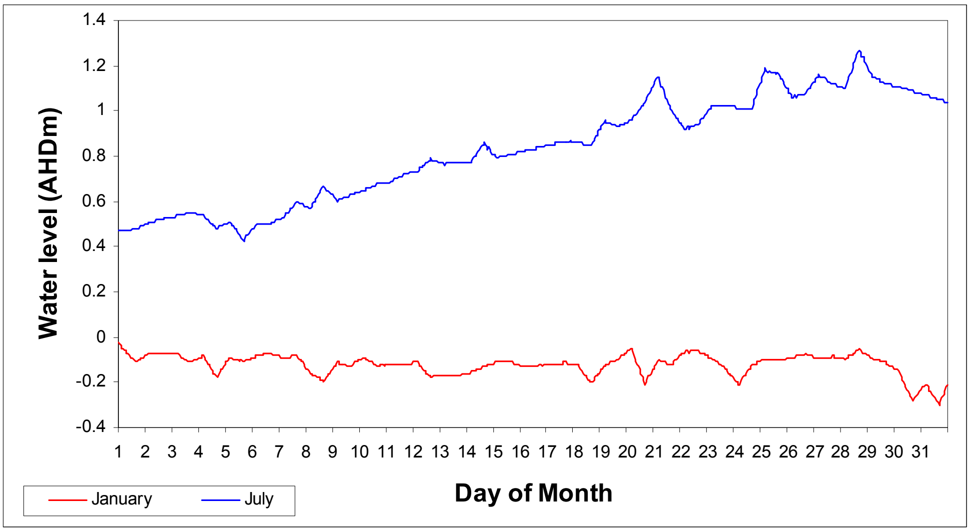
7. Barker Knoll 1988



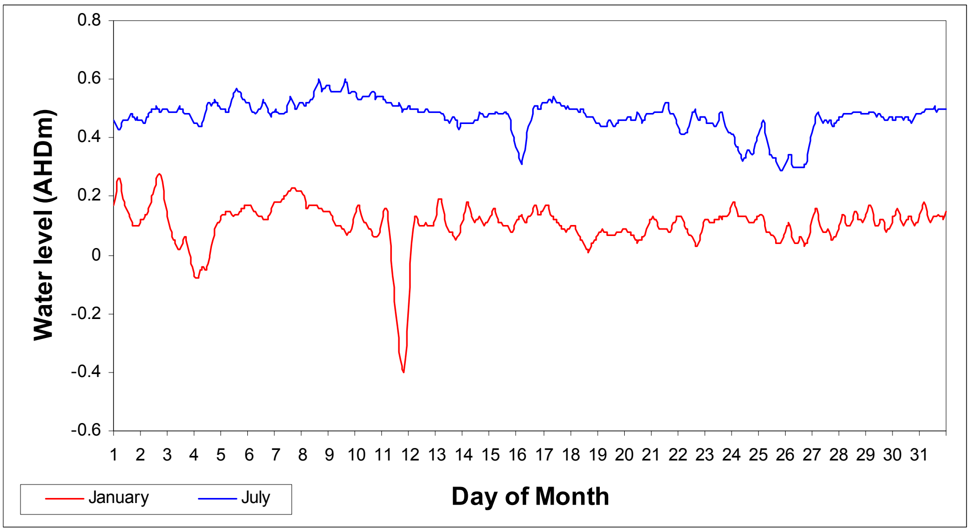
8. Noonameena 1988



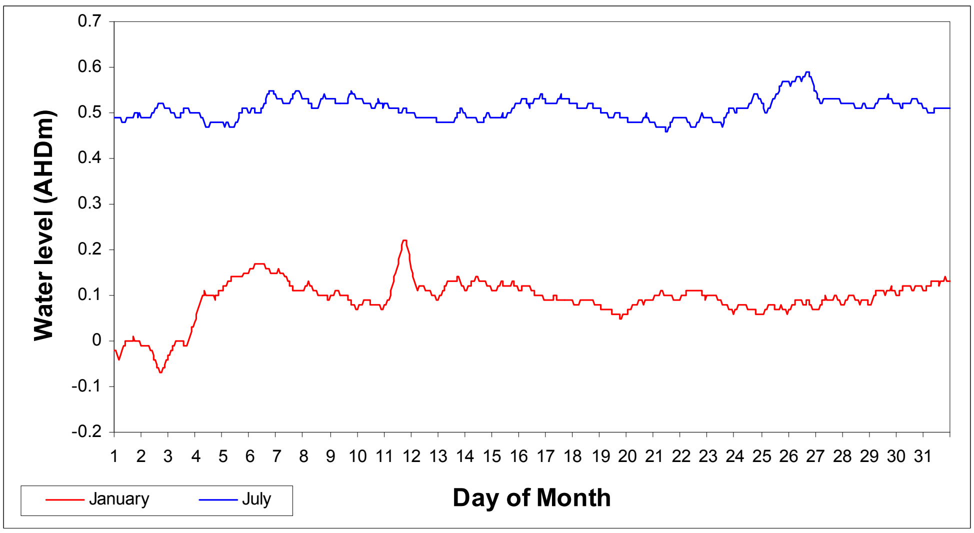
9. Salt Creek 1988



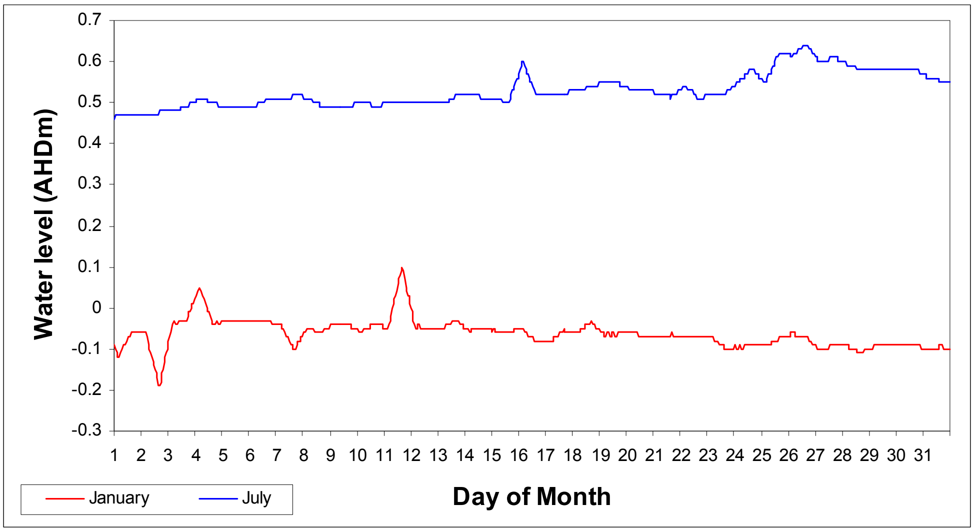
10. Barker Knoll 2005



11. Noonameena 2005

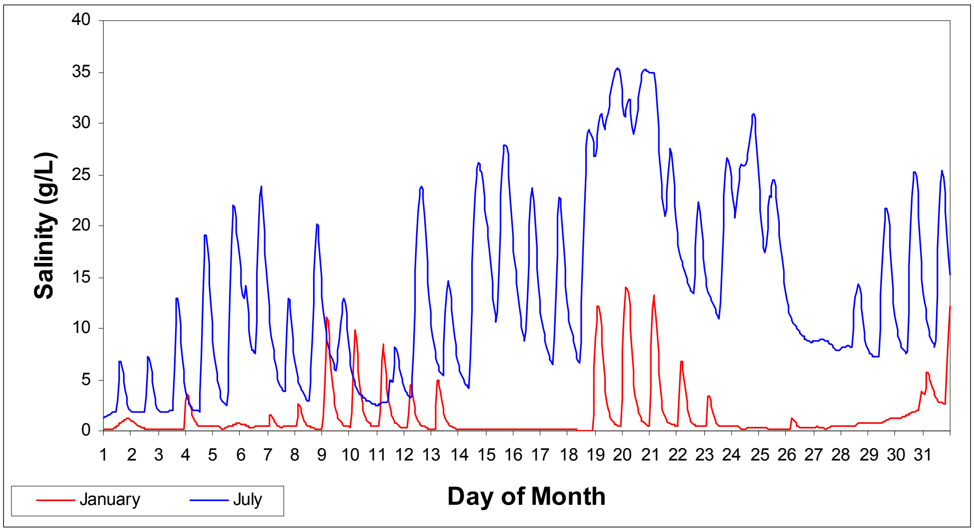


12. Salt Creek 2005

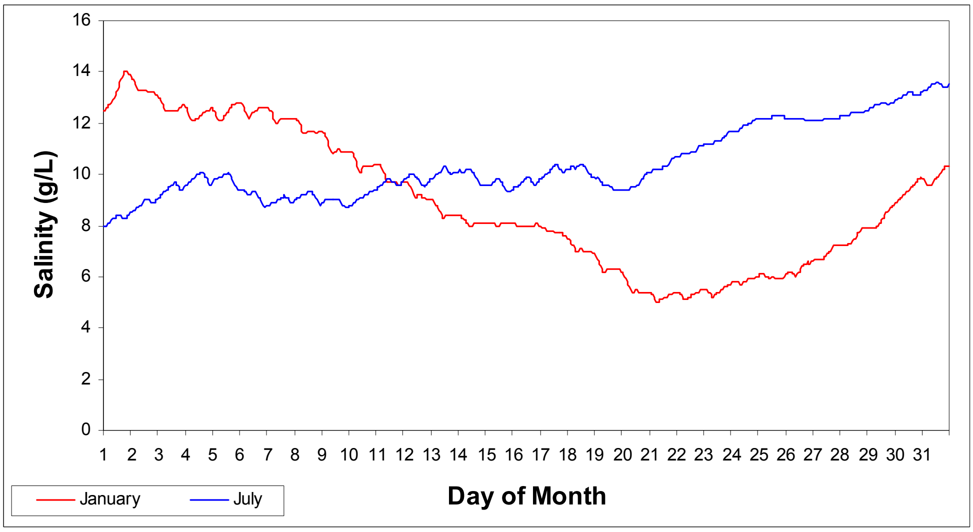


Appendix 6.4: Hourly salinity predictions for January and July of 1976, 1988, 1993 and 2005 at Barker Knoll, Noonameena and Salt Creek.

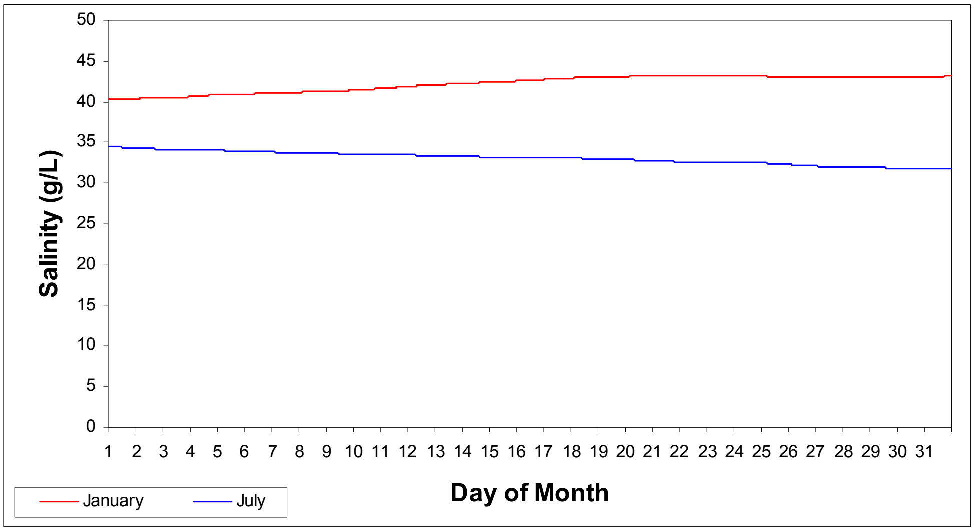
1. Barker Knoll 1976



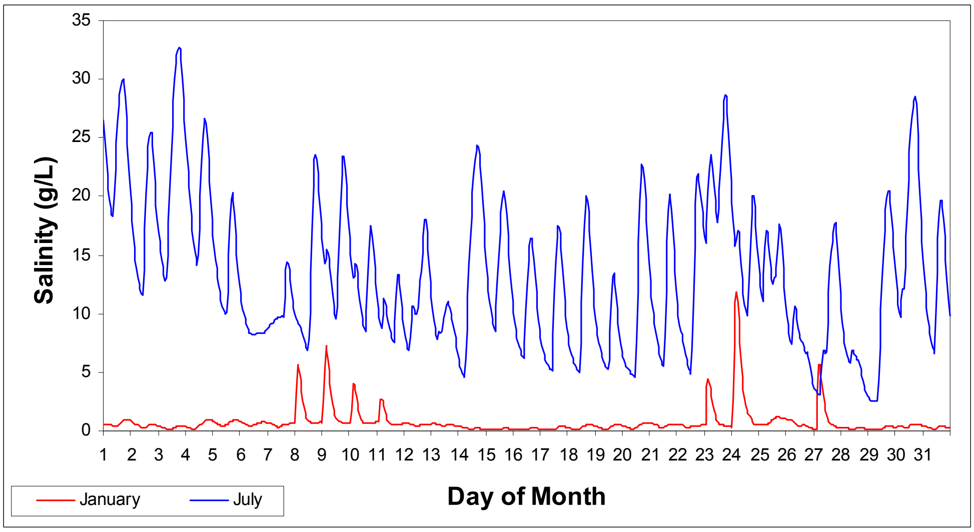
2. Noonameena 1976



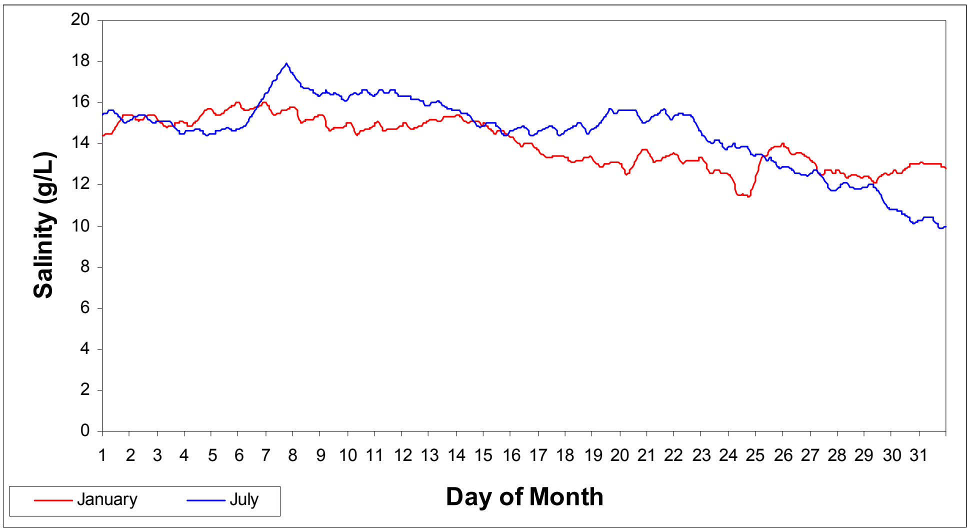
3. Salt Creek 1976



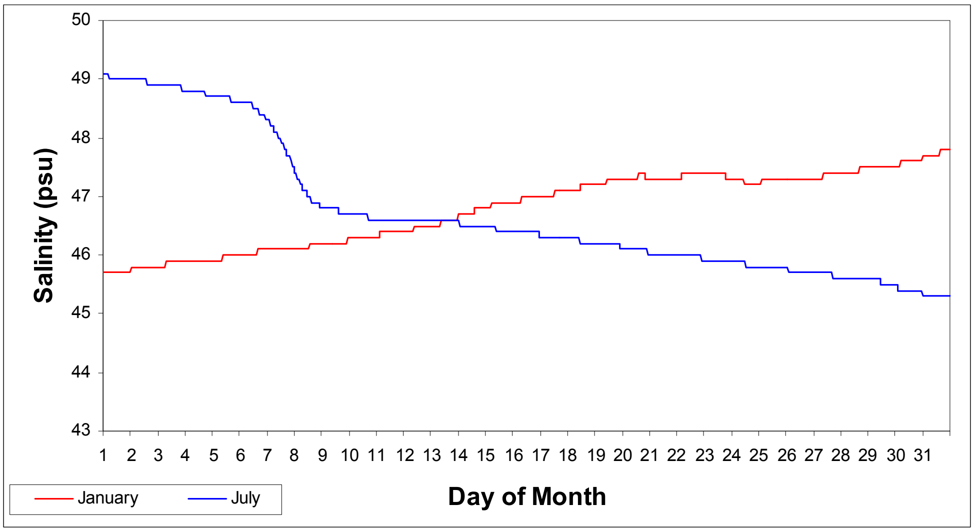
4. Barker Knoll 1993



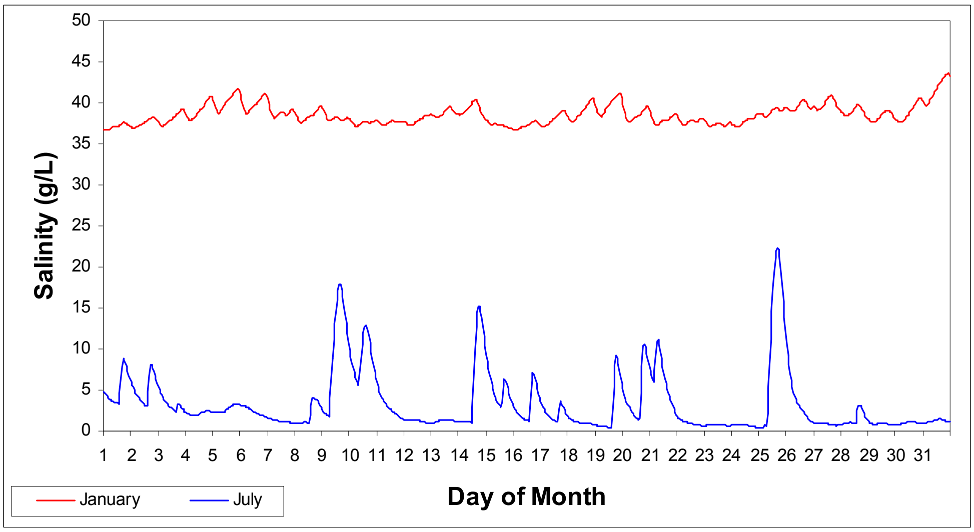
5. Noonameena 1993



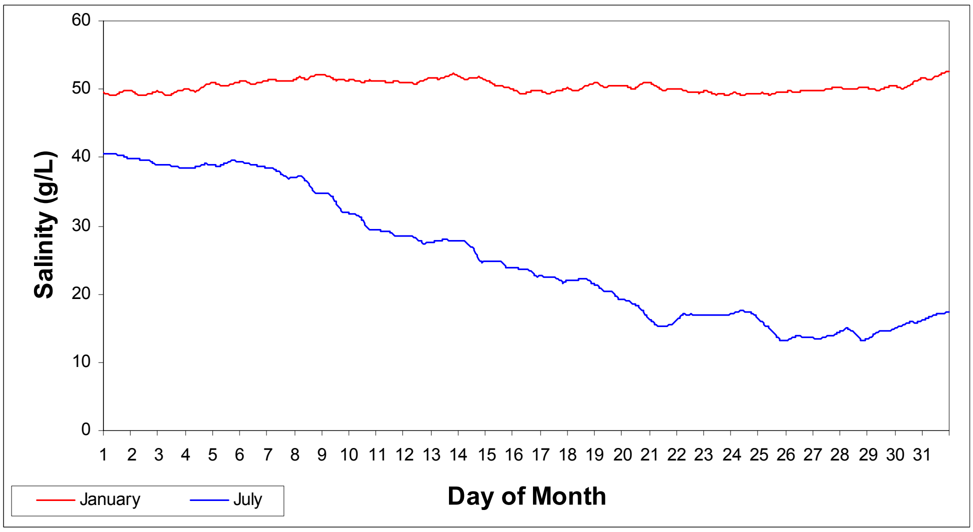
6. Salt Creek 1993



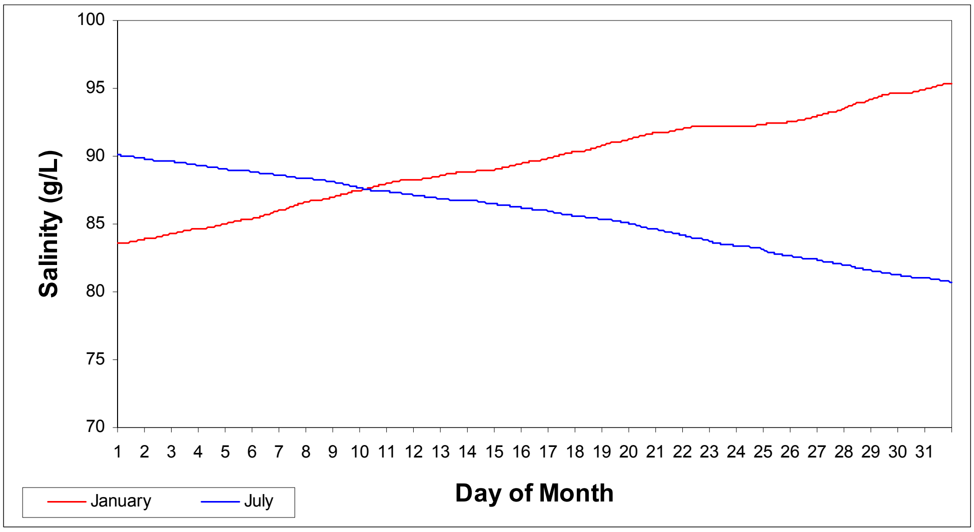
7. Barker Knoll 1988



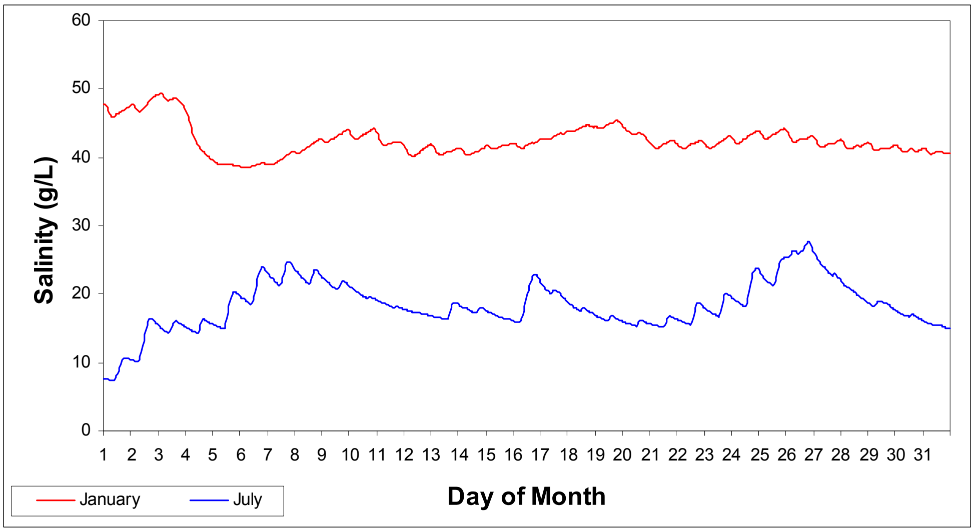
8. Noonameena 1988



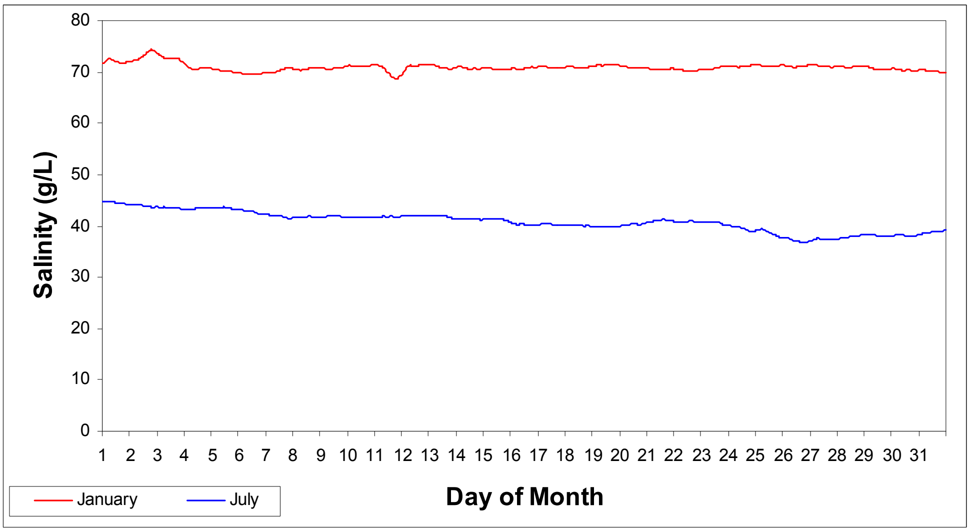
9. Salt Creek 1988



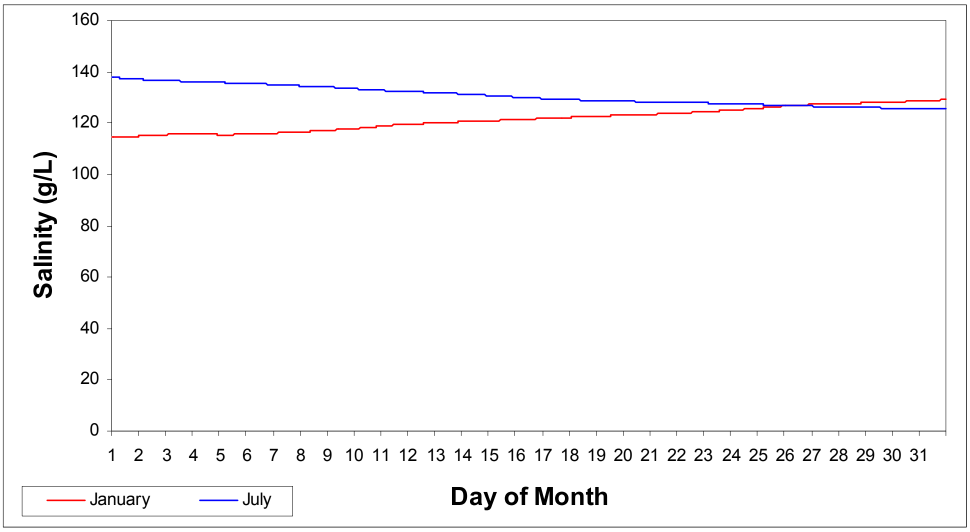
10. Barker Knoll 2005



11. Noonameena 2005

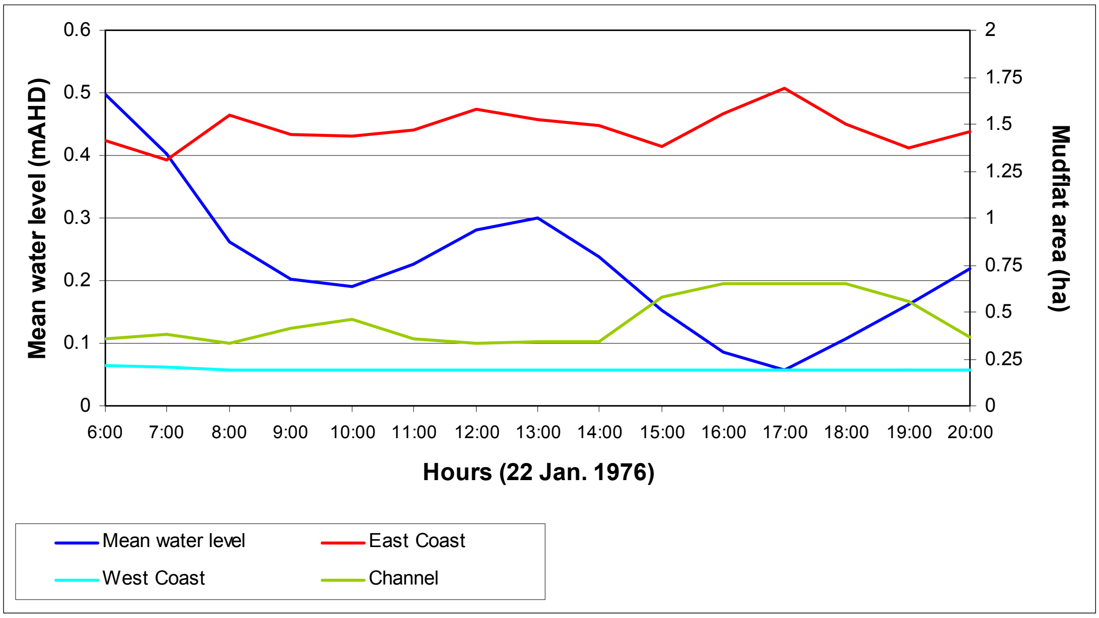


12. Salt Creek 2005

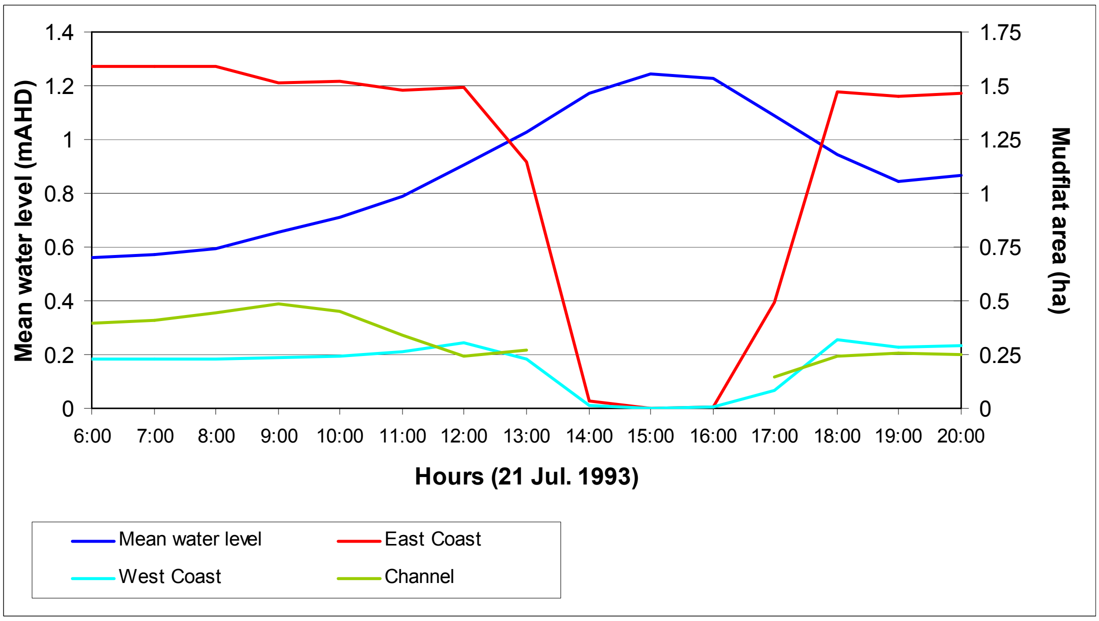


Appendix 6.5: Mudflat availability on the day with maximum and minimum mean water level for January and July of wet and dry years at Barker Knoll, Noonameena and Salt Creek.

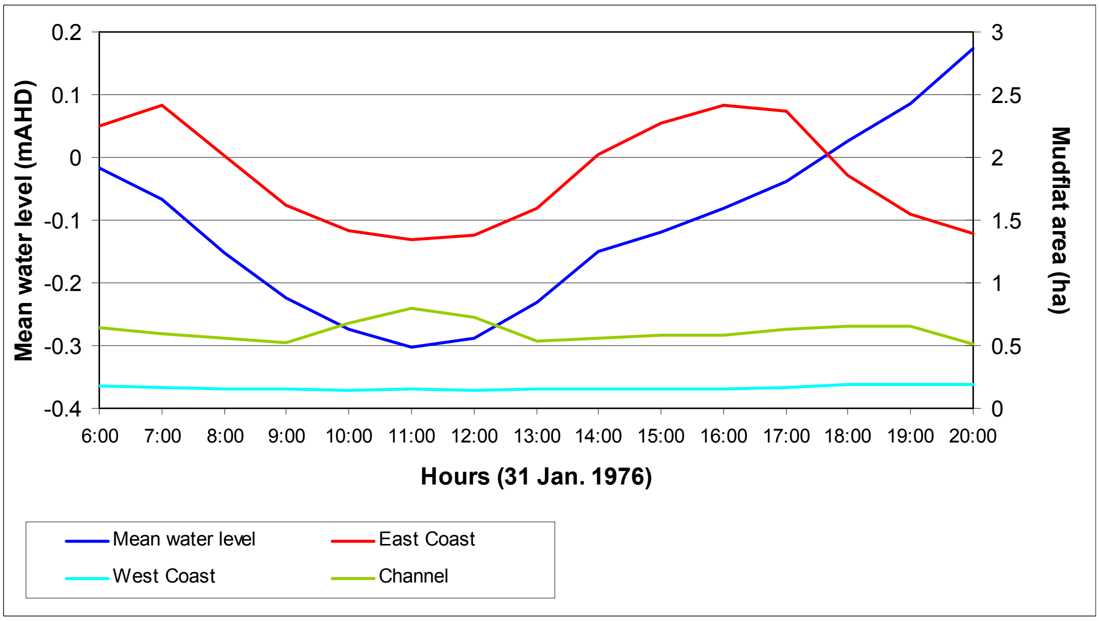
1. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached maximum level at Barker Knoll (22 January 1976).



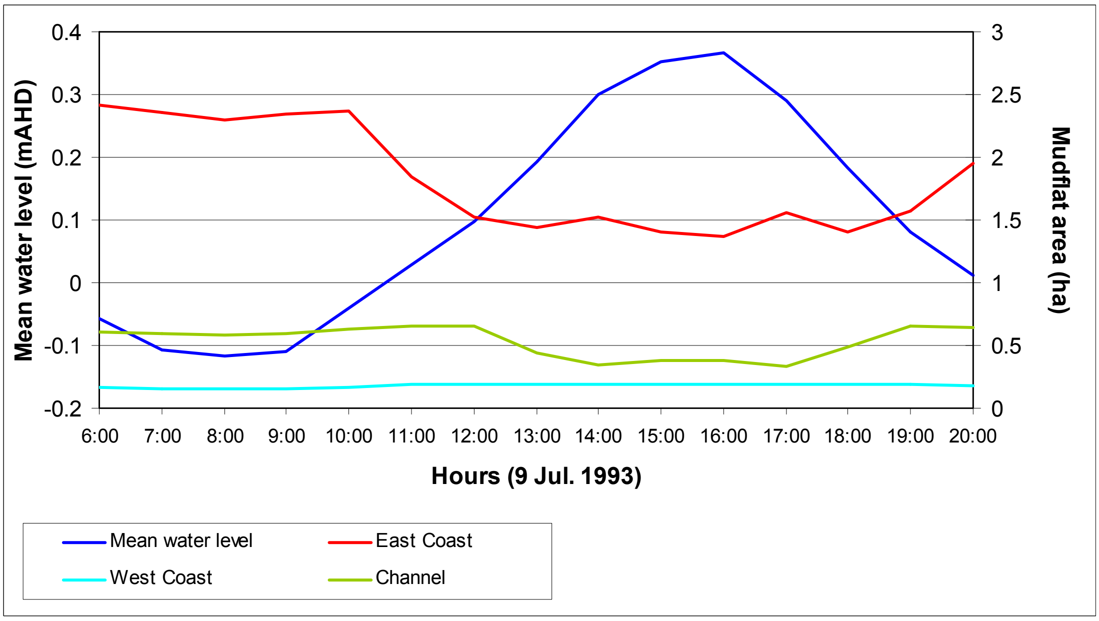
2. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached maximum level at Barker Knoll (21 July 1993).



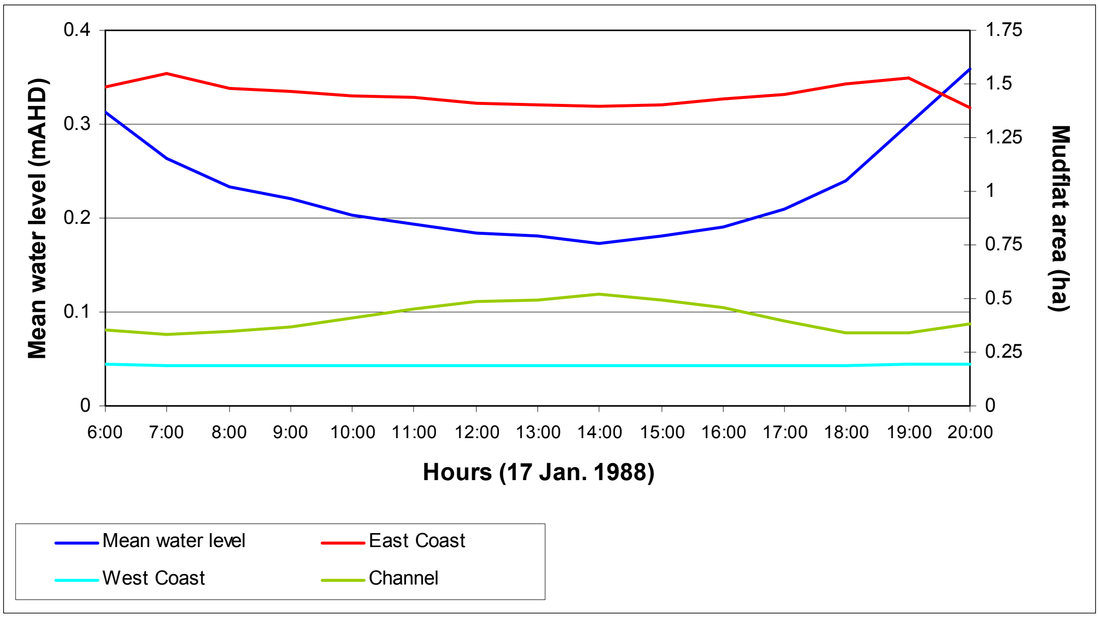
3. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached minimum level at Barker Knoll (31 January 1976).



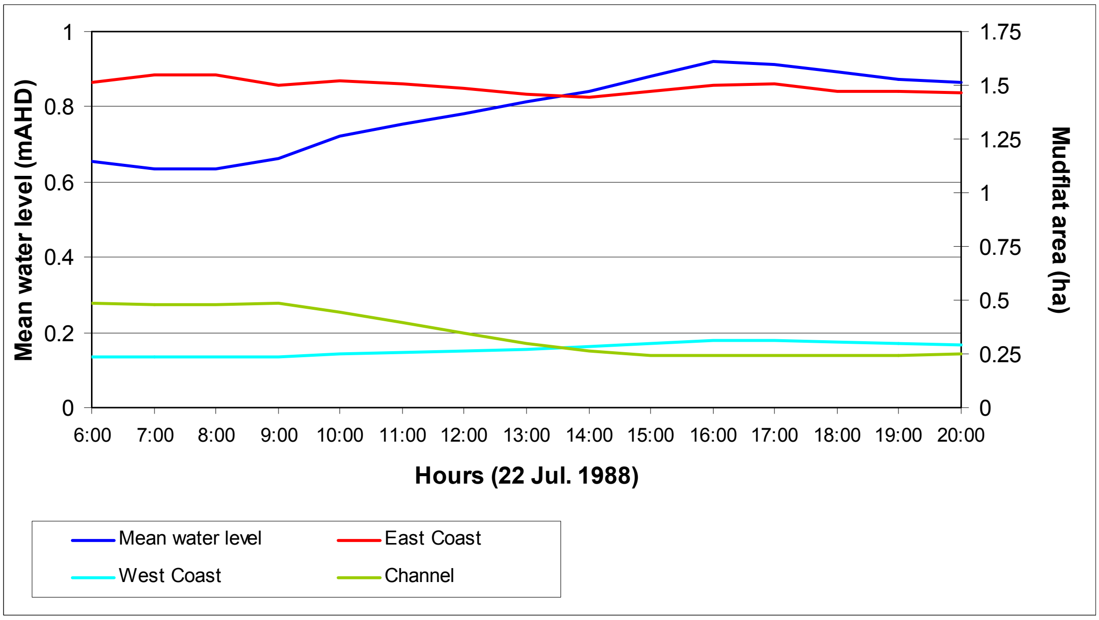
4. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached minimum level at Barker Knoll (9 July 1993).



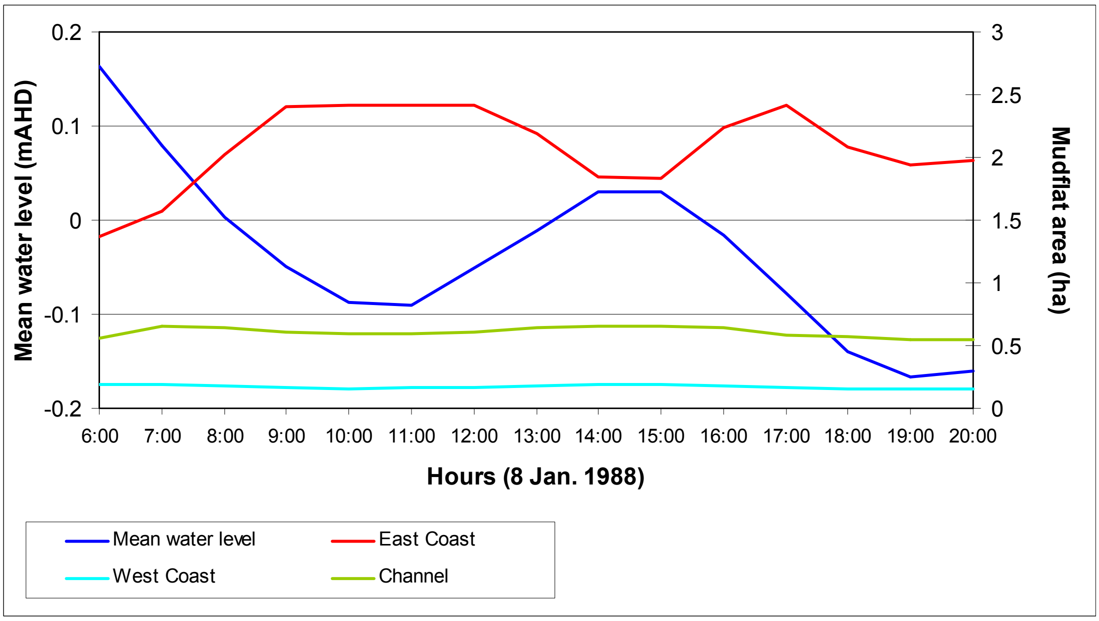
5. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached maximum level at Barker Knoll (17 January 1988).



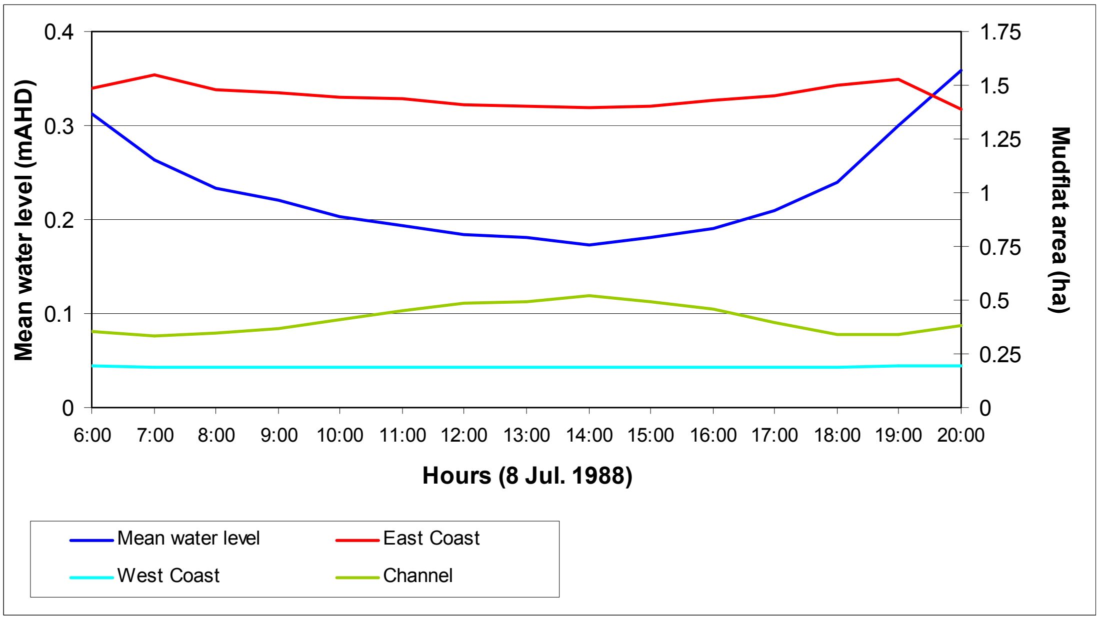
6. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached maximum level at Barker Knoll (22 July 1988).



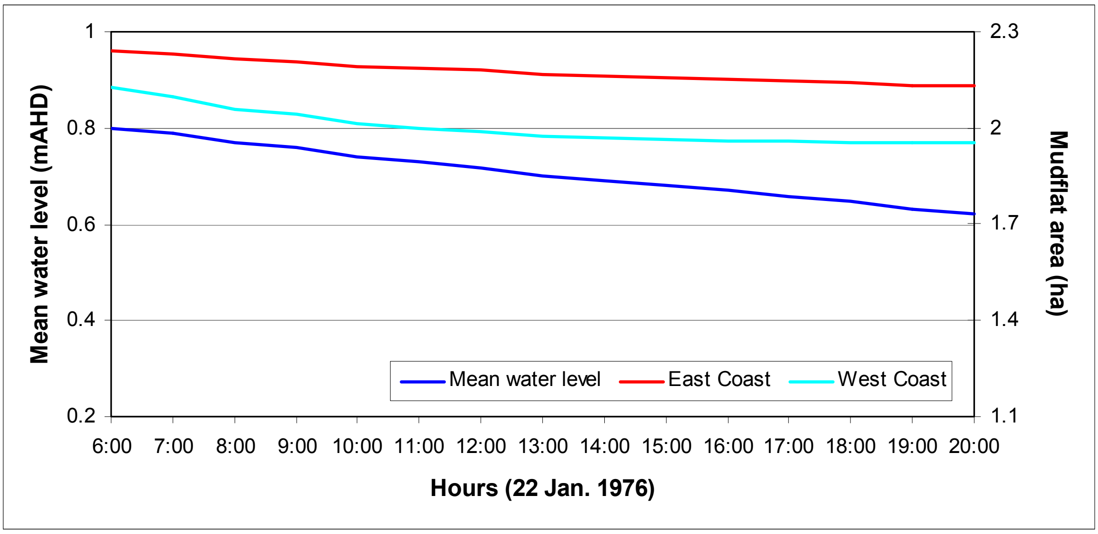
7. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached minimum level at Barker Knoll (8 January 1988).



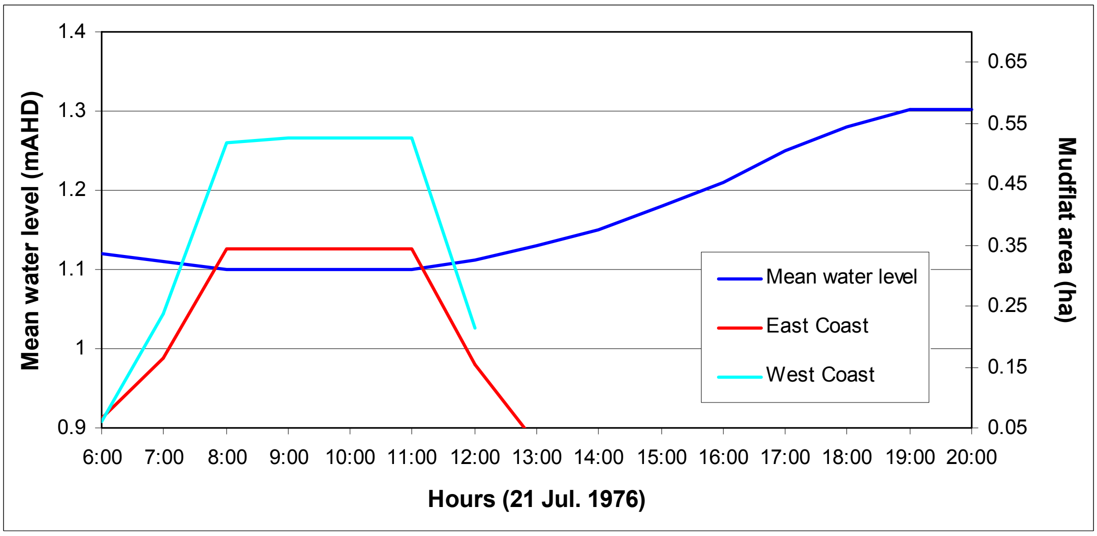
8. Mudflat availability on the eastern and western shores and the channel for the day the mean water level reached minimum level at Barker Knoll (8 July 1988).



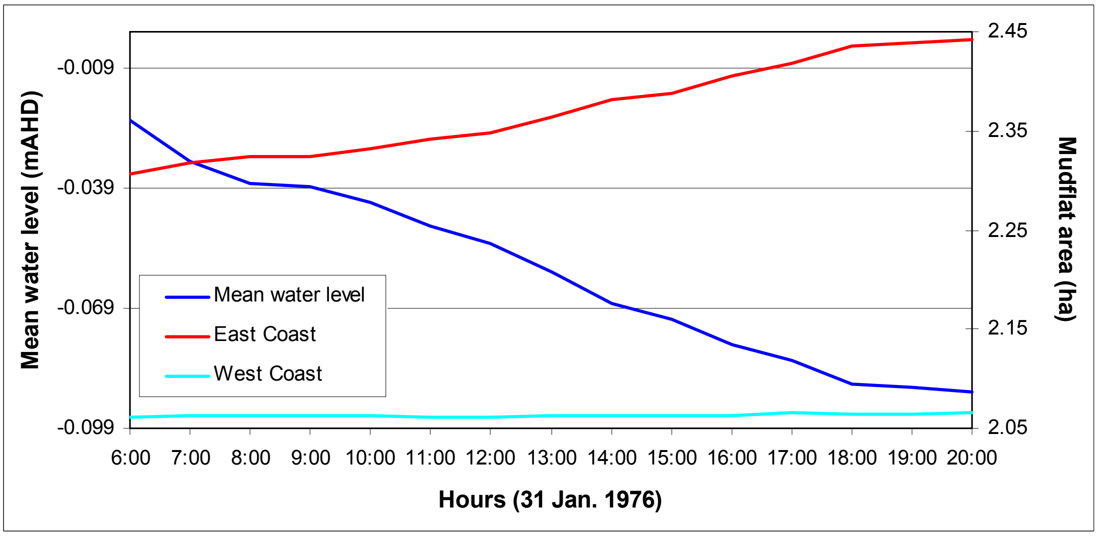
9. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Noonameena (22 January 1976).



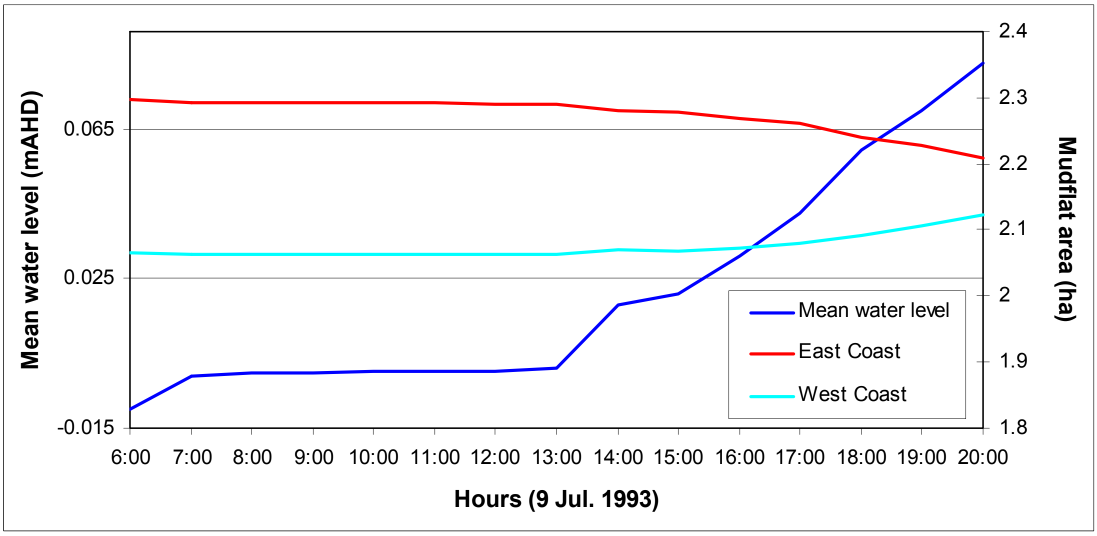
10. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Noonameena (21 July 1976).



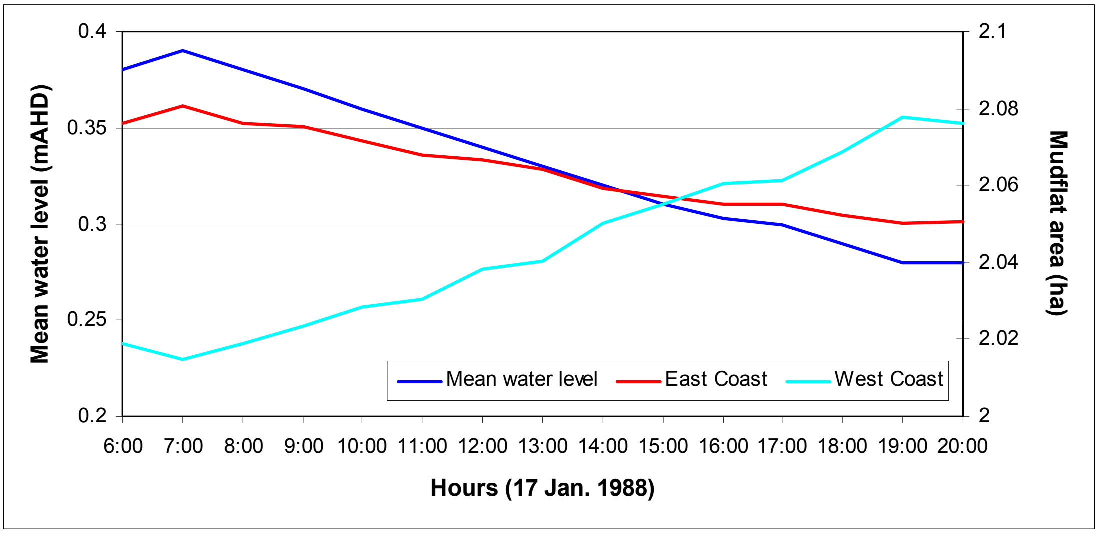
11. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Noonameena (31 January 1976).



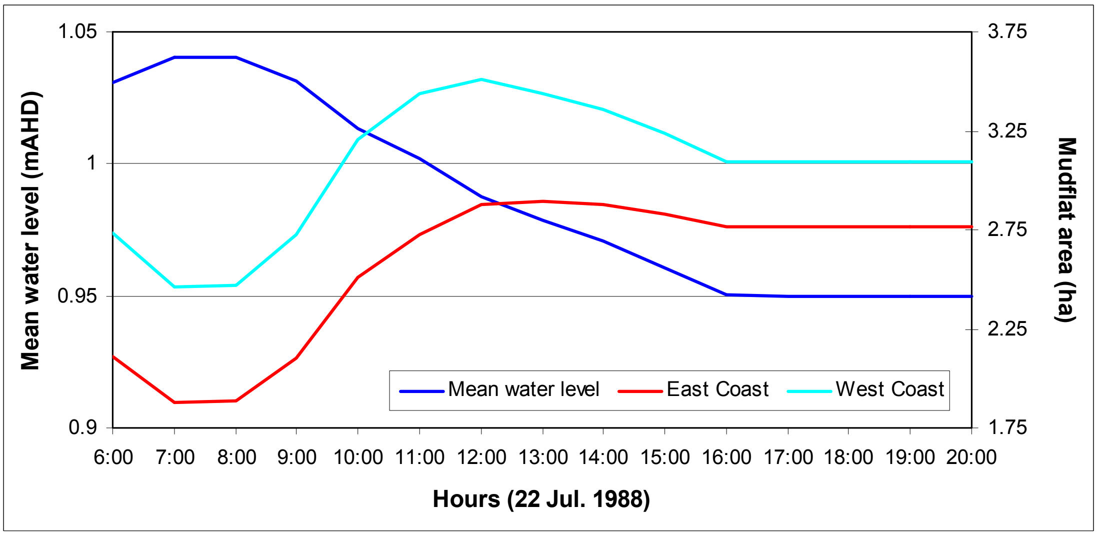
12. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Noonameena (9 July 1993).



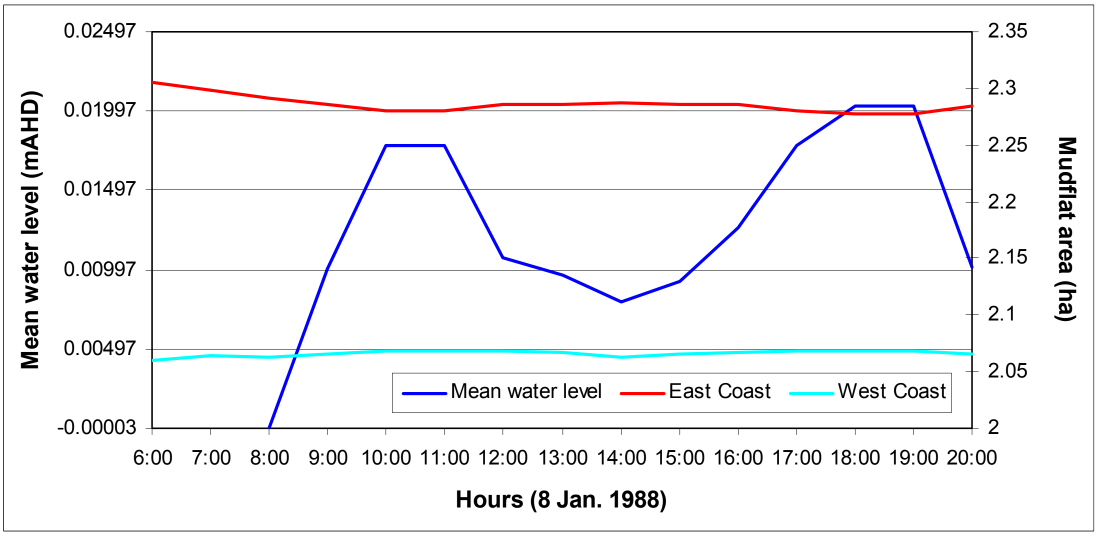
13. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Noonameena (17 January 1988).



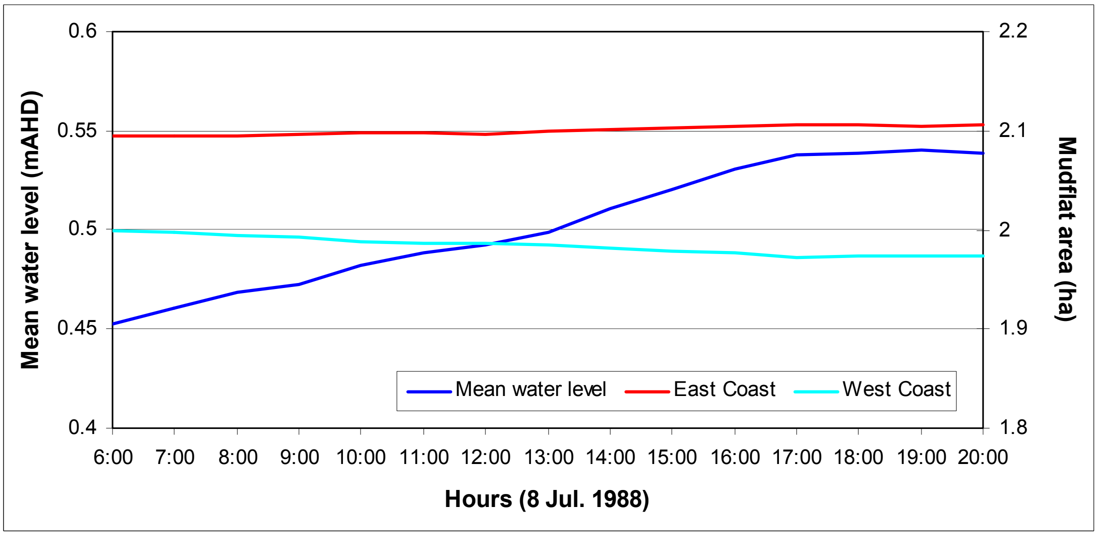
14. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Noonameena (22 July 1988).



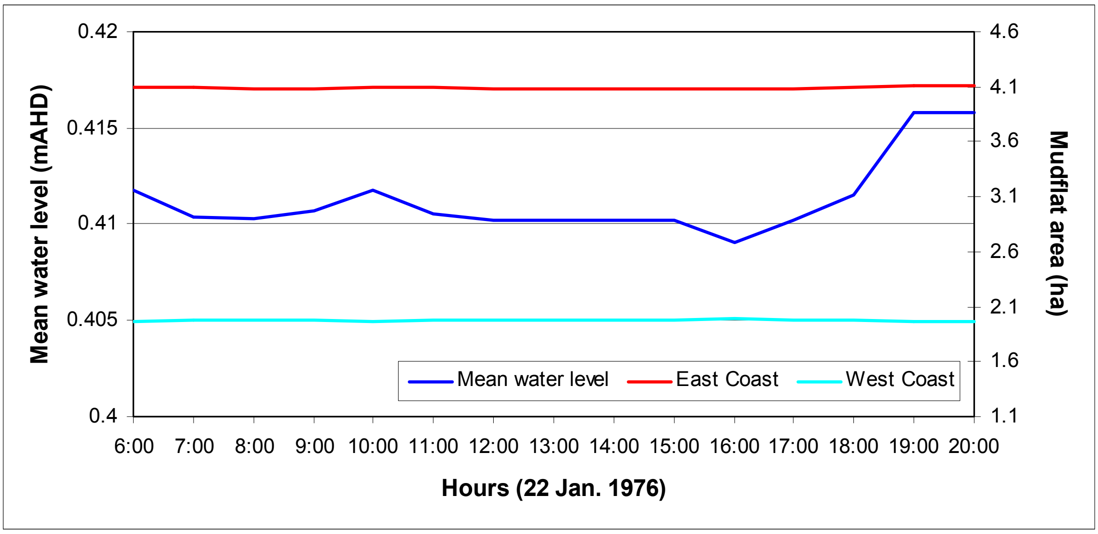
15. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Noonameena (8 January 1988).



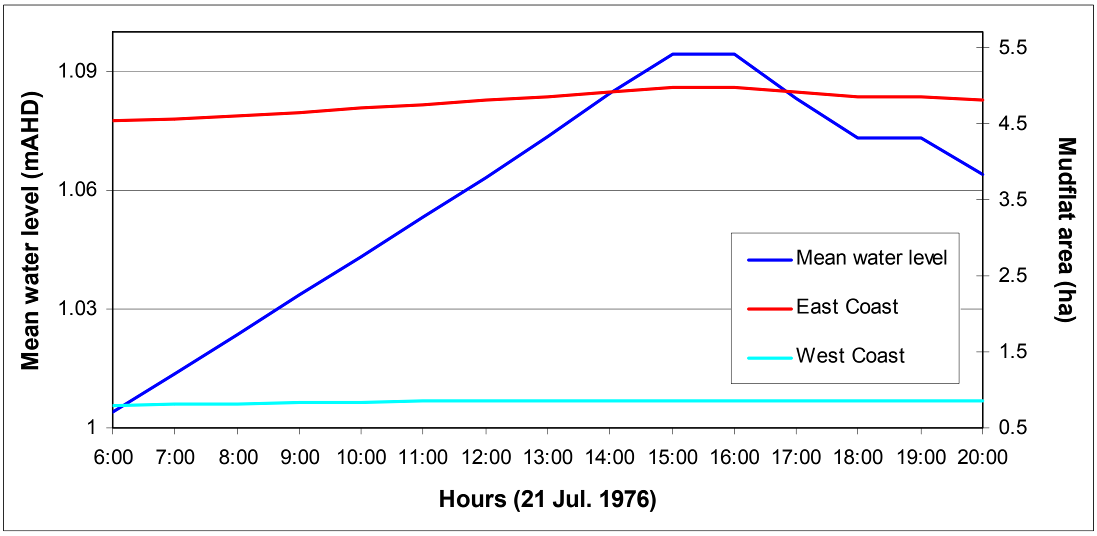
16. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Noonameena (8 July 1988).



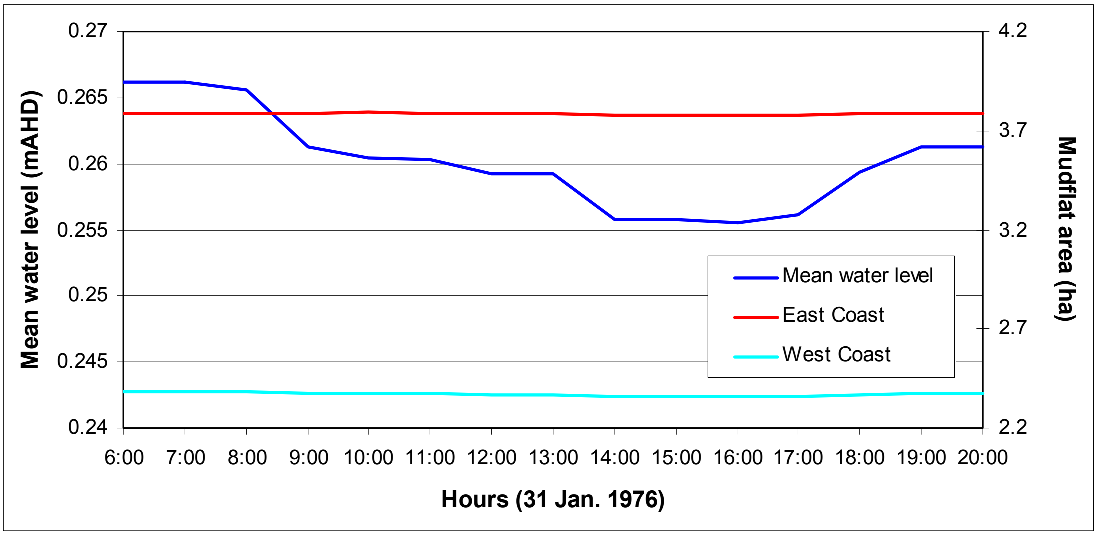
17. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Salt Creek (22 January 1976).



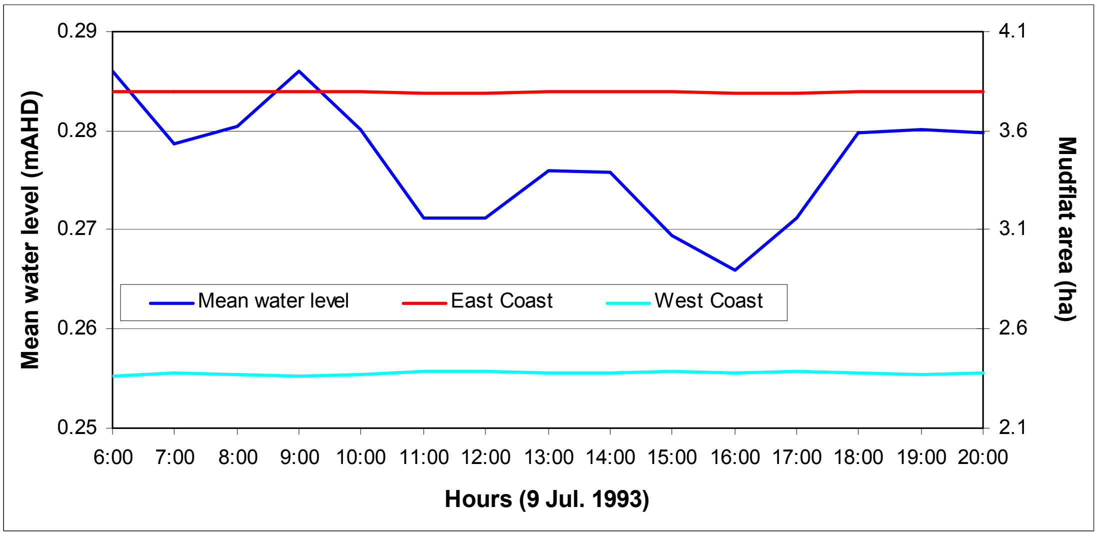
18. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Salt Creek (21 July 1976).



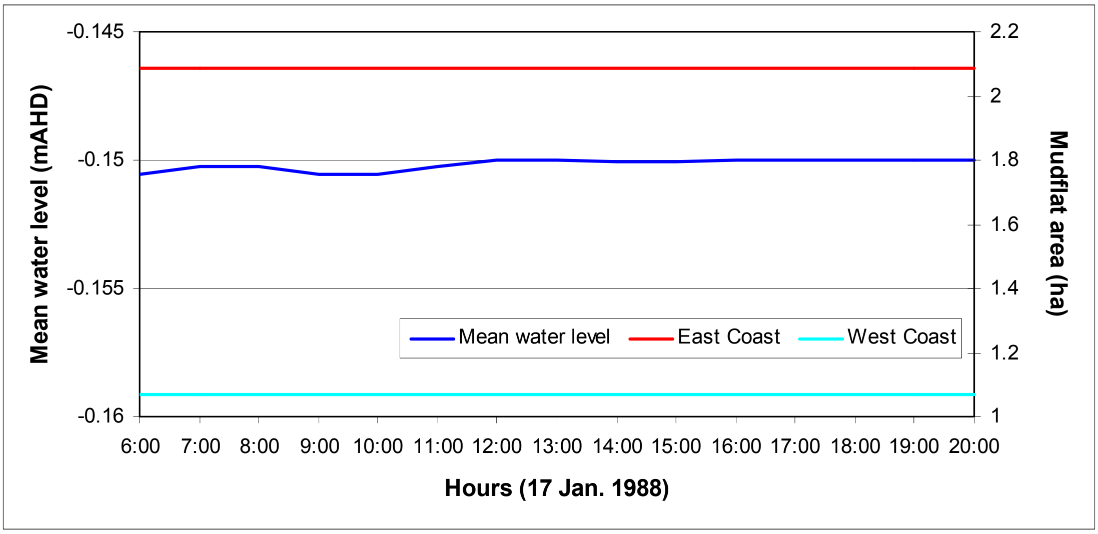
19. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Salt Creek (31 January 1976).



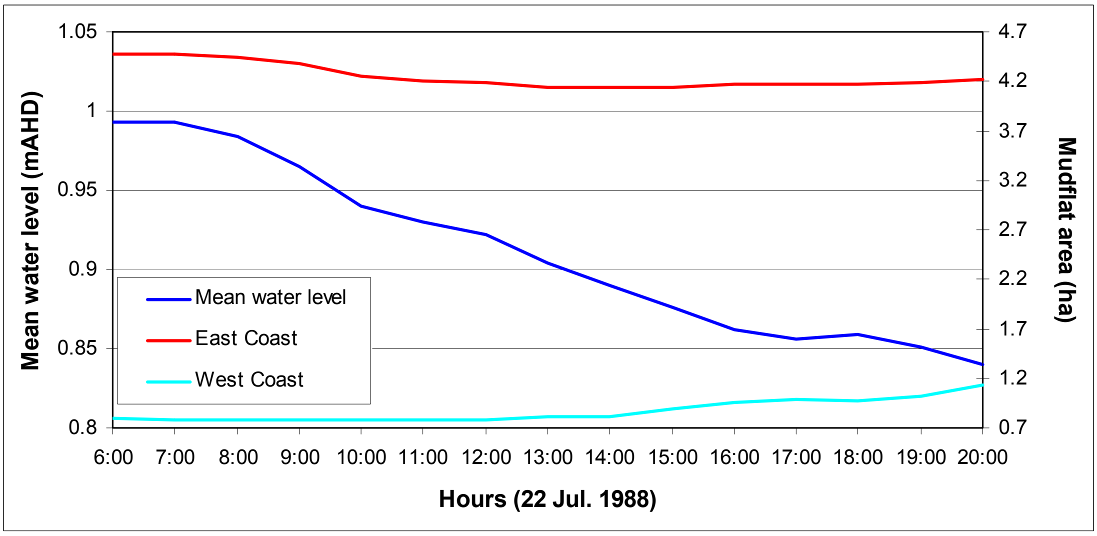
20. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Salt Creek (9 July 1993).



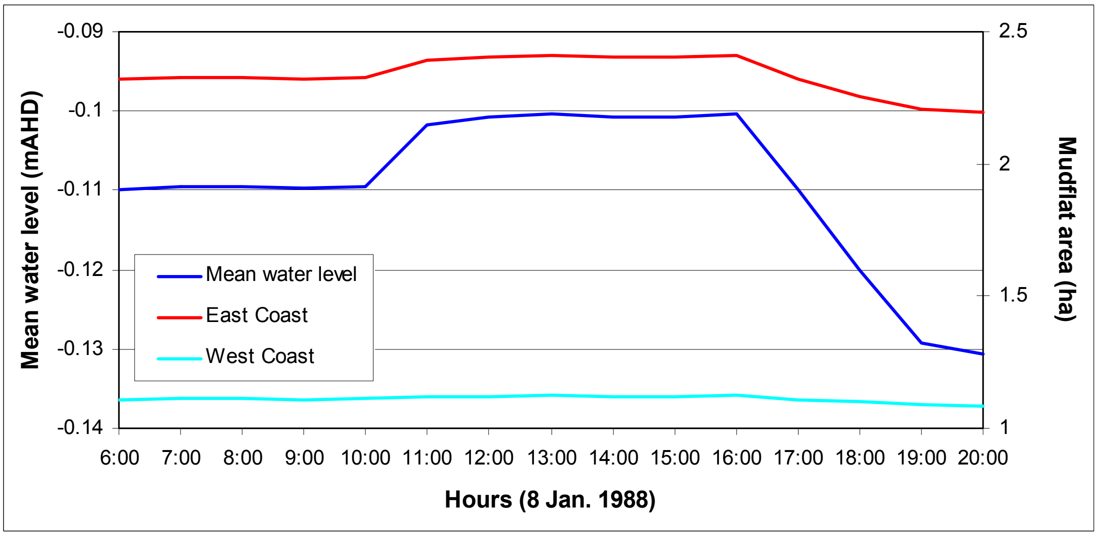
21. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Salt Creek (17 January 1988).



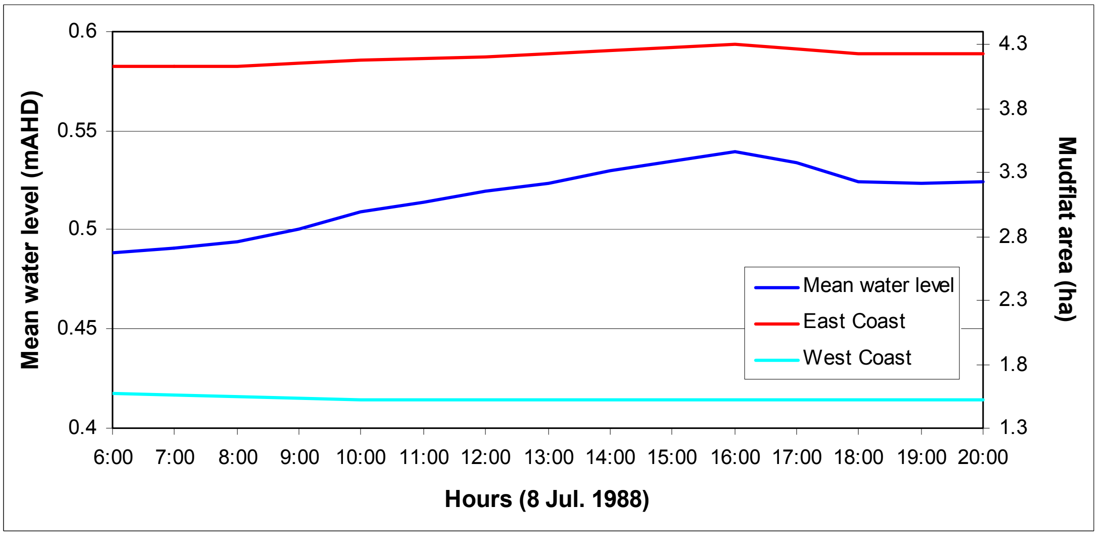
22. Mudflat availability on the eastern and western shores for the day the mean water level reached maximum level at Salt Creek (22 July 1988).

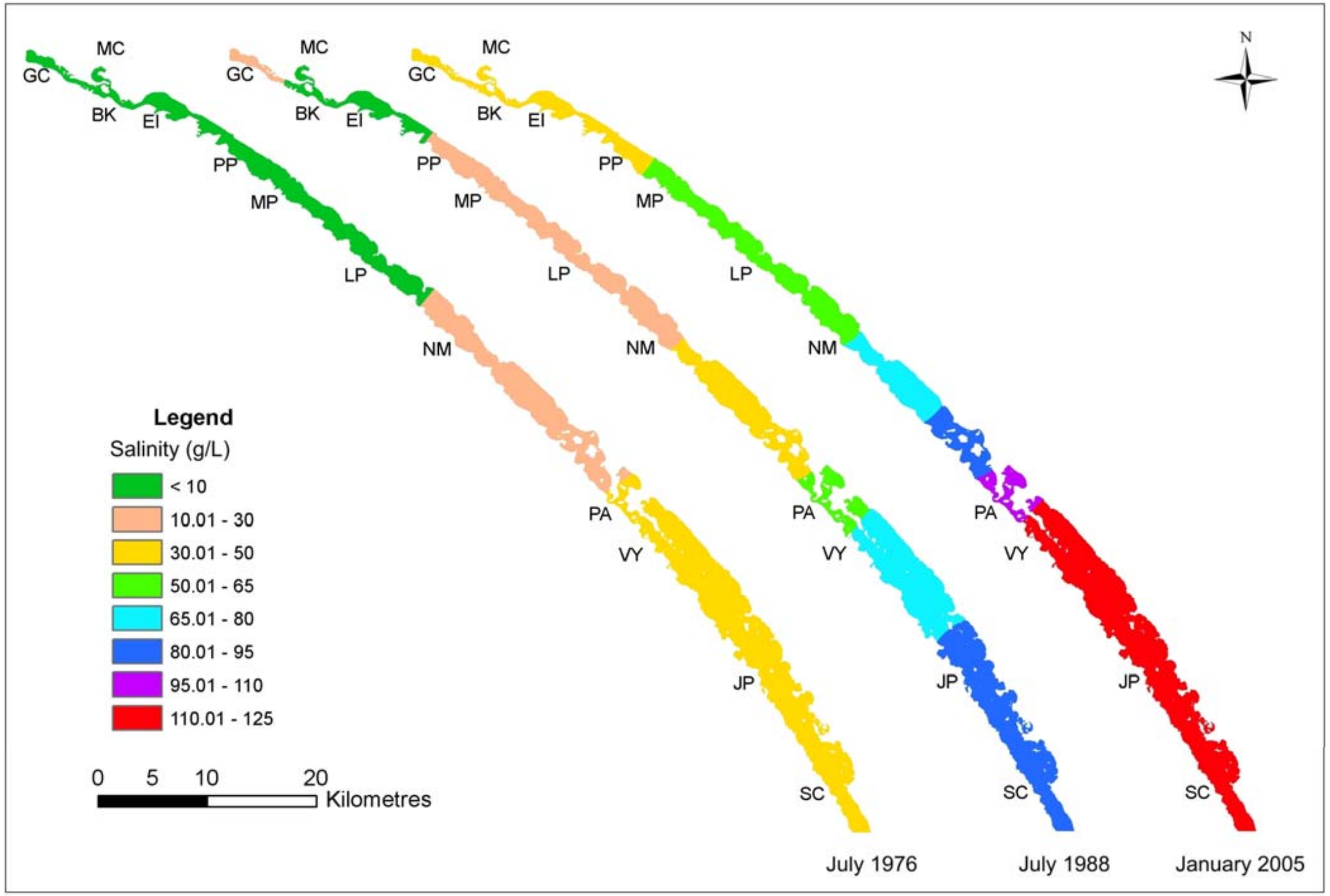


23. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Salt Creek (8 January 1988).



24. Mudflat availability on the eastern and western shores for the day the mean water level reached minimum level at Salt Creek (8 July1988).

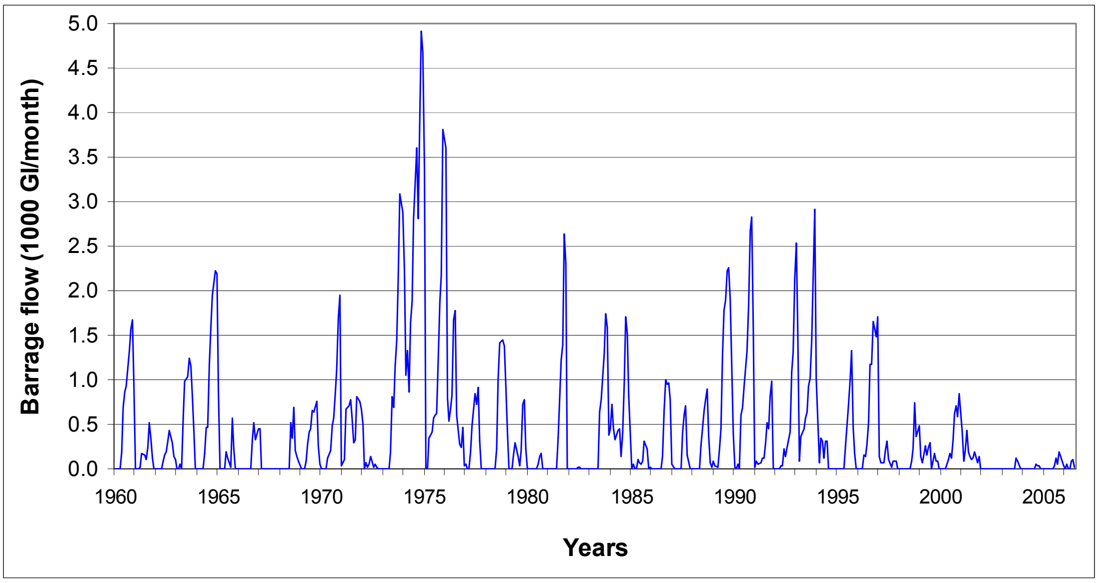




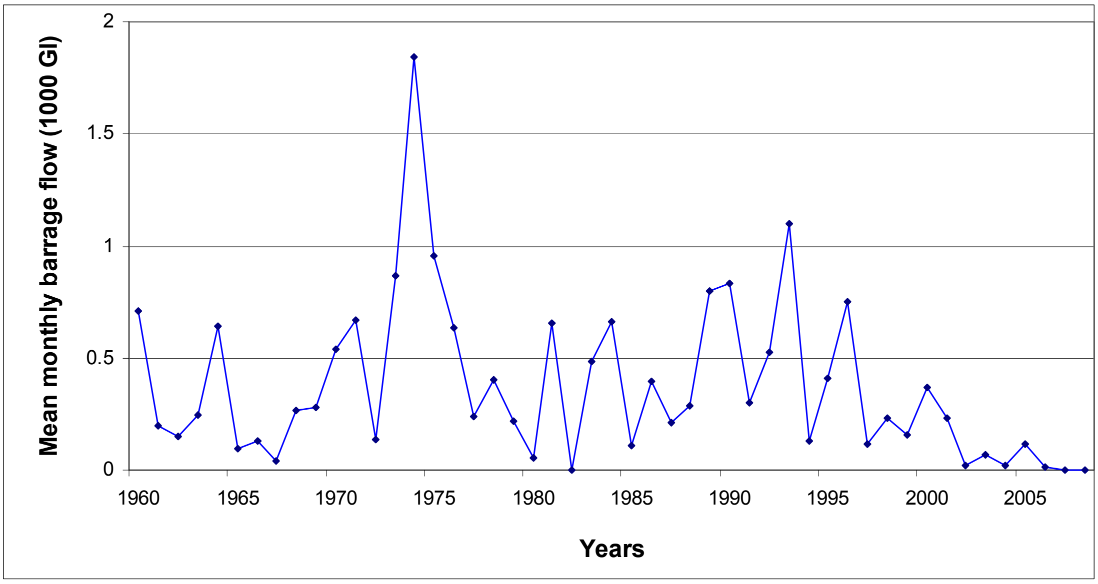
GC = Goolwa Channel
MC = Mundoo Channel
BK = Barker Knoll
EI = Ewe Island
PP = Pelican Point
MP = Mark Point
LP = Long Point
NM = Noonameena
PA = Parnka Point
VY = Villa dei Yumpa
JP = Jack Point
SC = Salt Creek.

Appendix 6.6: Predicted salinities in July 1976, July 1988 and January 2005.

Appendix 6.7: Barrage flow into the Coorong between 1960 and 2008 (Source: Webster, I. T., CSIRO)**.**



Monthly barrage flow into the Coorong between 1960 and 2006



Mean monthly barrage flow into the Coorong between 1960 and 2006