Shoreline geomorphology and fringing vegetation of the Gippsland Lakes

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1. The Gippsland Lakes and its catchment – an introduction

The Gippsland Lakes consists of four large, shallow coastal lakes (Lake Wellington – 148 km^2; Lake Victoria – 78 km^2; Lake King – 97 km^2; and Lake Reeve – 52 km^2), fed by five major rivers: the Latrobe-Macalister-Thomson system, flowing into the western side of Lake Wellington; the Avon-Perry system flowing into the northern side of Lake Wellington; and the Mitchell, Nicholson and Tambo Rivers, all eastern rivers flowing into Lake King. Associated with the rivers and the shoreline of the four lagoons is a complex mosaic of fresh, brackish, and hyper-saline wetlands; the largest of these are the brackish-water Lake Coleman (~20 km^2), Dowd Morass (~15 km^2) and Macleod Morass (~5 km^2), and the ephemeral and often hyper-saline Lake Reeve wetlands. Of the remaining wetlands, only Sale Common (~2 km^2) remains naturally fresh.

The combined surface area of the connected lakes and associated closed lagoons is 365 km^2 (Gippsland Coastal Board 2001). If the Gippsland Lakes is defined as extending from the western end of Lake Reeve to Red Bluff east of Lake Bunga, the catchment area contributing runoff to this system extends across ~20,300 km^2 of eastern Victoria (Figure 1), or ~10% of the total land area of the State.

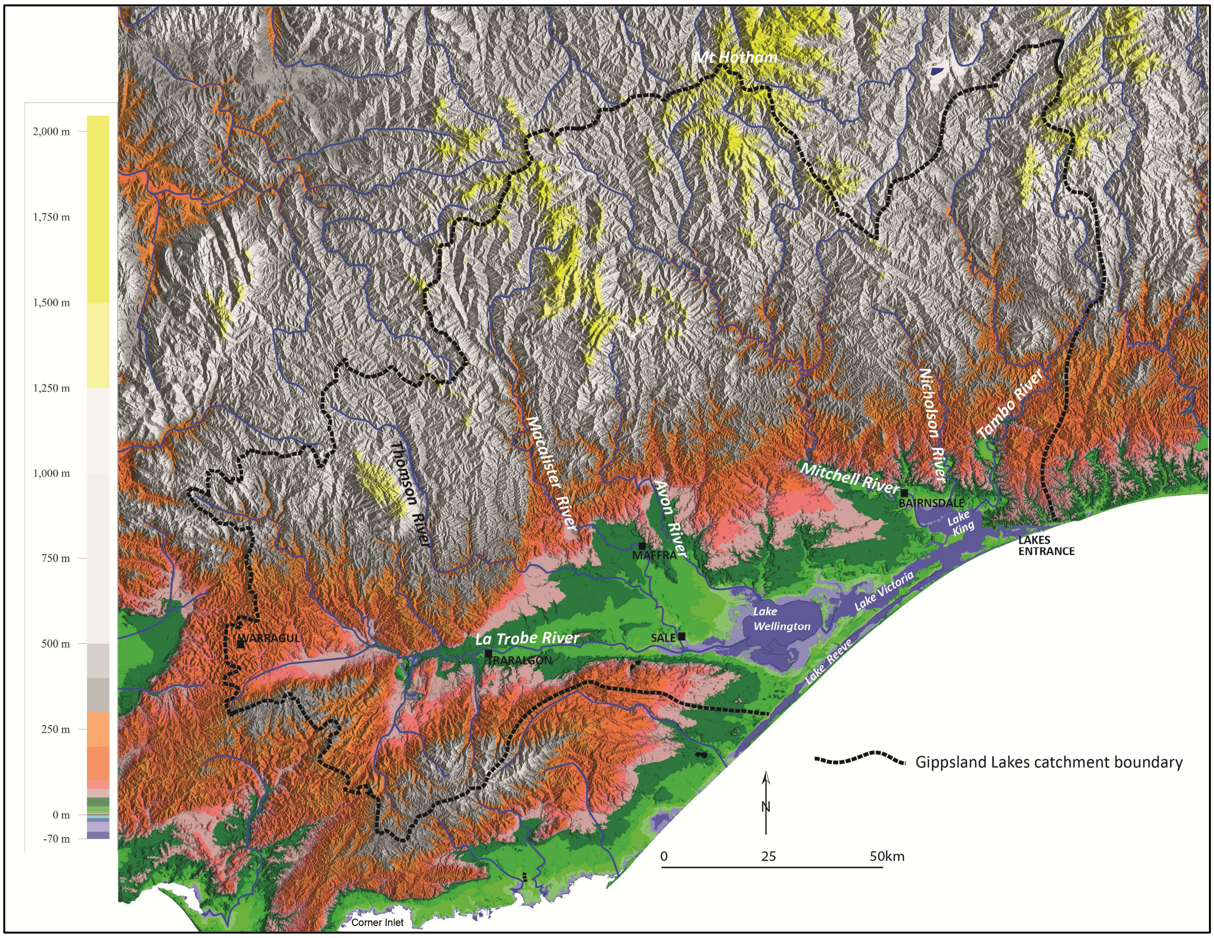


Figure 1: Digital elevation model (DEM) of Gippsland Lakes Catchment. Source: DEM from Department of Environment and Primary Industries, Victoria.

The Gippsland Lakes is a multi-component system with a wide range of marine, coastal, terrestrial, fluvial, and biological components and processes. Although the focus of the present study is the shorelines of the enclosed and semi-enclosed and linked lake basins that form the main body of the Gippsland Lakes, an understanding of the range of factors that contribute to the form and functioning of the lakes and its shorelines is needed to fully appreciate the geomorphological role played by fringing vegetation. Moreover, the past development of the lakes system and ongoing and future changes in the ecology and geomorphology of the lake shorelines are closely related to the evolution and dynamics of the Ninety Mile Beach and backing coastal sand barriers. Both the relict (inland) and active outermost (seaward) barriers determine the broad character of the system. They are very sensitive to changes in climate and sea-level on a short-term to long-term time scale.

The broad character of the Gippsland Lakes and bordering lowland is determined by the topographical and geological character of the catchment, past and present climate, marine processes and changing sea-levels, the geomorphology and hydrology of inflowing rivers and the dynamics of contributing groundwater systems. Also relevant to understanding the present physical and associated biological systems that form the Gippsland Lakes are the direct, indirect, deliberate and inadvertent impacts of human activities.

1.1 Catchment geomorphology

Descriptions of the landforms and geomorphological evolution of parts of the Gippsland Lakes catchment are included in several papers in McAndrew & Marsden (1971) and in the 1:250,000 geological report of VandenBerg & O'Shea (1981). Rosengren (1984) mapped the geomorphology and assessed geoscience sites across the entire catchment. The Victorian Geomorphology Review Group (http://vro.depi.vic.gov.au/dpi/vro/) has prepared maps showing the geomorphology of Victoria at various scales including all the Gippsland Lakes catchment. Land system studies (geology, landforms, vegetation and soils) of the entire catchment include Nicholson (1978) and Aldrick *et al.* (1988). Also of relevance to the Gippsland Lakes are studies of the form and evolution of the upland areas of south-eastern Australia. The timing and causes of uplift and the development of the modern mountain and drainage systems determine the source and rate of transfer of sediment to the Gippsland Basin. A wide range of views has been proposed – ranging from the uplands as remnants of ancient higher mountains to being geologically young with several phases of uplift occurring over the Cainozoic, (Andrews 1933; Wellman 1979, 1987; Lambeck & Stephenson 1986; Galloway 1987; Ollier 1987; Holdgate *et al.* 2008; VandenBerg 2010). A number of studies of the catchment have concentrated on the dynamics of fluvial systems and the nature and causes of river channel changes (Erskine *et al.* 1990) and implications of changes in sediment supply and soil erosion on the Gippsland Lakes (Rutherfurd 1994; Wilkinson *et al.* 2005; Robinson & Sargant 2010).

The Gippsland Lakes catchment displays a wide array of topography and slope morphology. The major streams that flow into the Gippsland Lakes originate in some of the highest terrain in south-eastern Australia, including areas that experience several months of snow cover. The catchment boundary between the headwaters of the Tambo River and Thomson River forms part of the Great Divide in Victoria. The highest elevation in all the catchment is Mount Hotham (1862 m) at the headwaters of the Dargo River, a major tributary of the Mitchell River. Mount Bogong (1986 m) is north of the Divide and not part of the Gippsland Lakes catchment. Much of the northern catchment is over 1200 m elevation with extensive areas of tableland and elevated plains flanked by escarpments. Most of the upland terrain is a dense network of steep gradient streams and bordering valley slopes separated by narrow ridges. Locally deep weathering of rocks of varying resistance, slope movements (in part occasioned by periglacial freeze-thaw), and energetic fluvial action in response to tectonic uplift has combined to define the lithological and structural control of many landforms of the upland catchment. Long deeply incised valleys with gorge sectors and narrow floodplains are characteristic of all the major rivers and extend across the break-of-slope at the southern Palaeozoic boundary across the plains of Neogene sediments that border the Gippsland Lakes.

Between 100 and 150 m above sea-level is an abrupt boundary where the elevated terrain descends to the plains and stepped terraces bordering the La Trobe River and the East Sale Plain and Munro Plain north of the Gippsland Lakes (Figure 2). This boundary defines the southern limit of Palaeozoic rock outcropping across Gippsland (Figure 3).

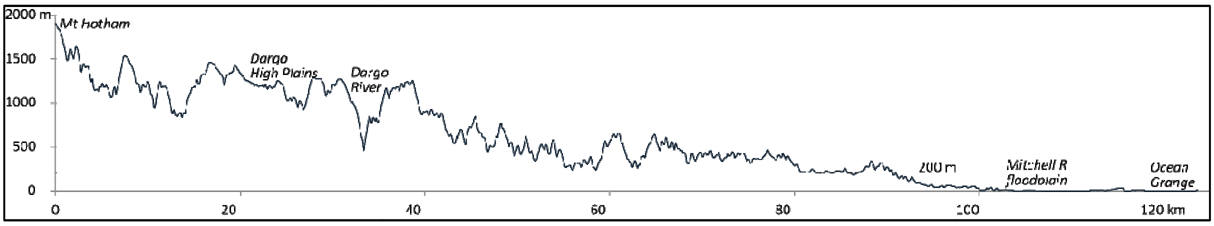


Figure 2: Profile drawn from DEM, Mount Hotham to Ocean Grange, showing elevation, tablelands, ridge & valley terrain and lowland plains. Source: DEM from Department of Environment and Primary Industries, Victoria.

1.2 Catchment geology

There is an extensive literature dealing with aspects of the geology of Gippsland including the area of the Gippsland Lakes catchment. Several papers in McAndrew and Marsden (1971) and the comprehensive analysis of VandenBerg *et al.* (2000) and Birch (2003) provide stratigraphic and structural analysis of Palaeozoic basement rocks and reconstructions of the tectonic evolution of Gippsland. These regional analyses incorporate the earlier literature including the pioneering work of Howitt (1875, 1876). The Gippsland Basin has been a focus for detailed studies initially targeting the extent and environments of deposition of onshore brown coal, and since the 1950's the offshore hydrocarbon potential (Hocking 1976). Detailed stratigraphy of the Seaspray Group and reconstruction of ancestral river and barrier systems has been the subject of recent studies e.g. Holdgate *et al.* (2003) and Mitchell *et al.* (2007).

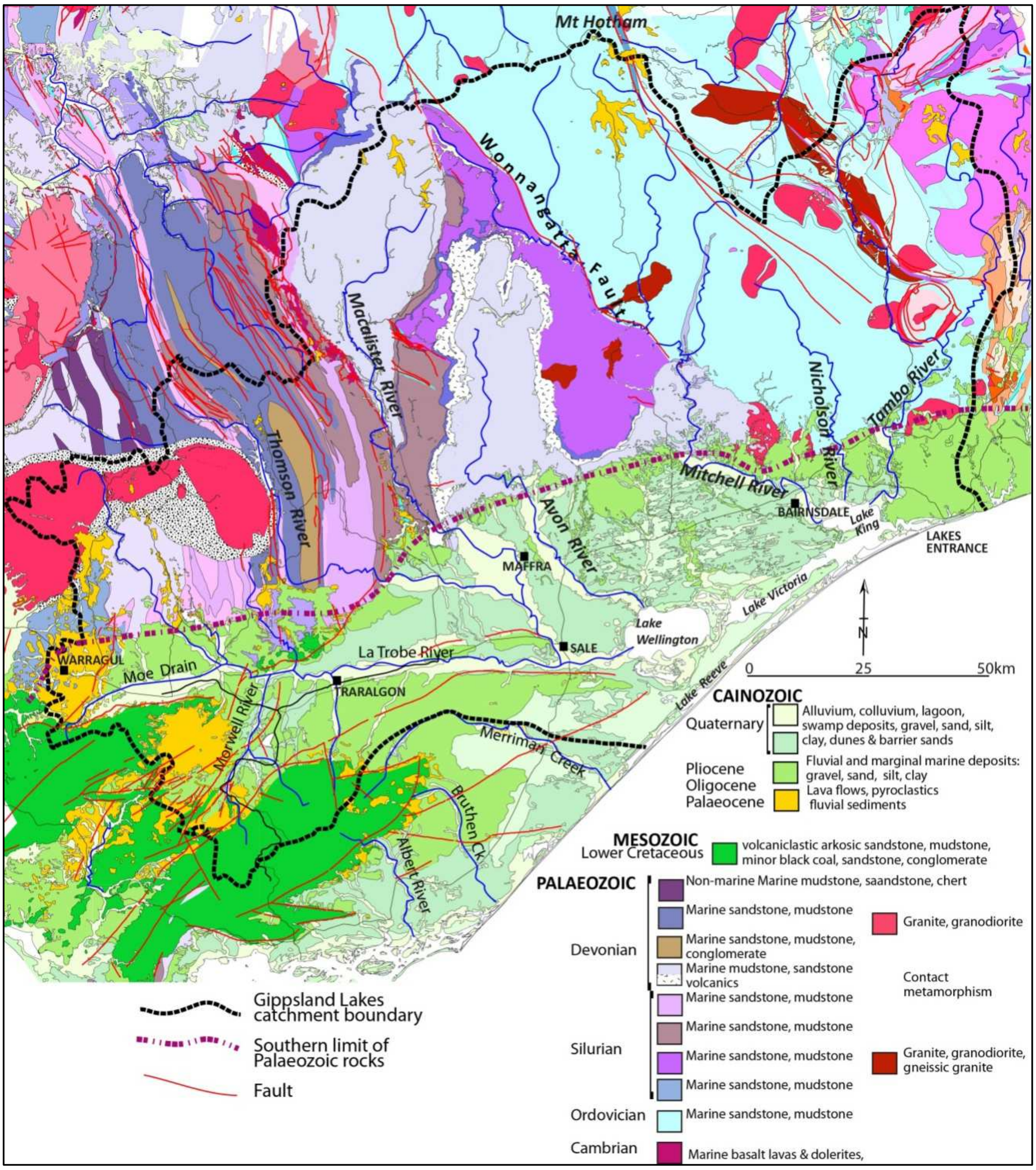


Figure 3: Geology of Gippsland Lakes catchment. Source: 1:500,000 Geology Eastern Victoria, Geoscience Victoria.

Basement geology of the highlands

The elevated areas of the northern catchment are developed on Palaeozoic sediments and metasediments of the Tasman Fold Belt System, intruded by granitic plutons of Silurian to Late Devonian age (Figure 3). The largest area of granitic terrain is the Baw Baw granites in the headwaters of the La Trobe and Thomson Rivers, with moderately sized bodies in the Mitchell, Nicholson and Tambo valleys. The basement geologies are dominated by siliciclastic sediments including thick sandstone and mudstone units. The geological evolution of the catchment is complex and varies from west to east, as several episodes of deformation have resulted in folding, cleavage, jointing and faulting in the sedimentary and volcanic beds. The oldest rocks are fault-slices of Cambrian volcaniclastic and other sediments in a narrow belt in the upper Macalister River north of Licola. The Palaeozoic basement of marine sandstone-rich beds is divided by the Wonnangatta Fault defining the boundary between Ordovician rocks to the east and Silurian to the west (Figure 3). The Palaeozoic rocks occur in well-defined belts with N-S to NNW-SSE orientation determined by a series of sub-parallel faults and fold axes. Unconformably overlying the older marine sediments are a series of non-marine sedimentary and volcanic rocks of Upper Devonian age. These accumulated in structural basins that coincide with the present Avon River and Caledonia-Macalister River catchments. The sediments are dominantly sands and conglomerates with locally thick distinctively red beds mudstone and shale. The NNW-SSE trend of the bedrock is intersected by north-northeast and east-northeast-trending faults that show distinctive lineaments on Digital Elevation Models derived from Space Shuttle Radar data.

The youngest hard rock units of the northern catchment are basalts of Paleocene to Oligocene age occurring as ridge-cappings and upland plains. The basalts have unknown sources but their age (25–405 million years) and the stratigraphy of underlying sediments indicate they were erupted onto a surface of moderate relief and elevations much lower than their present altitude. Their present position in the landscape suggests that uplift of several hundred metres at least has occurred since their emplacement.

The Gippsland Basin

The western and southern catchment of the Gippsland Lakes is developed on Mesozoic and Cainozoic sedimentary rocks of the Gippsland Basin, one of the largest sedimentary basins of southern Australia. The basin originated in the early stages of rifting of eastern Gondwana in the initial breakup and separation of Australia and Antarctica in the Late Cretaceous 70 million years ago. The basin overlies Palaeozoic metasedimentary rocks of the Eastern Uplands and these define its northern margin. The Gippsland Basin is now a series of sediment-filled, tectonic depressions and includes uplifted fault blocks of the Strzelecki Ranges, the down-faulted La Trobe Valley and plains east and south, and extends for several hundred kilometres offshore as the Bass Strait continental shelf (Figure 4).

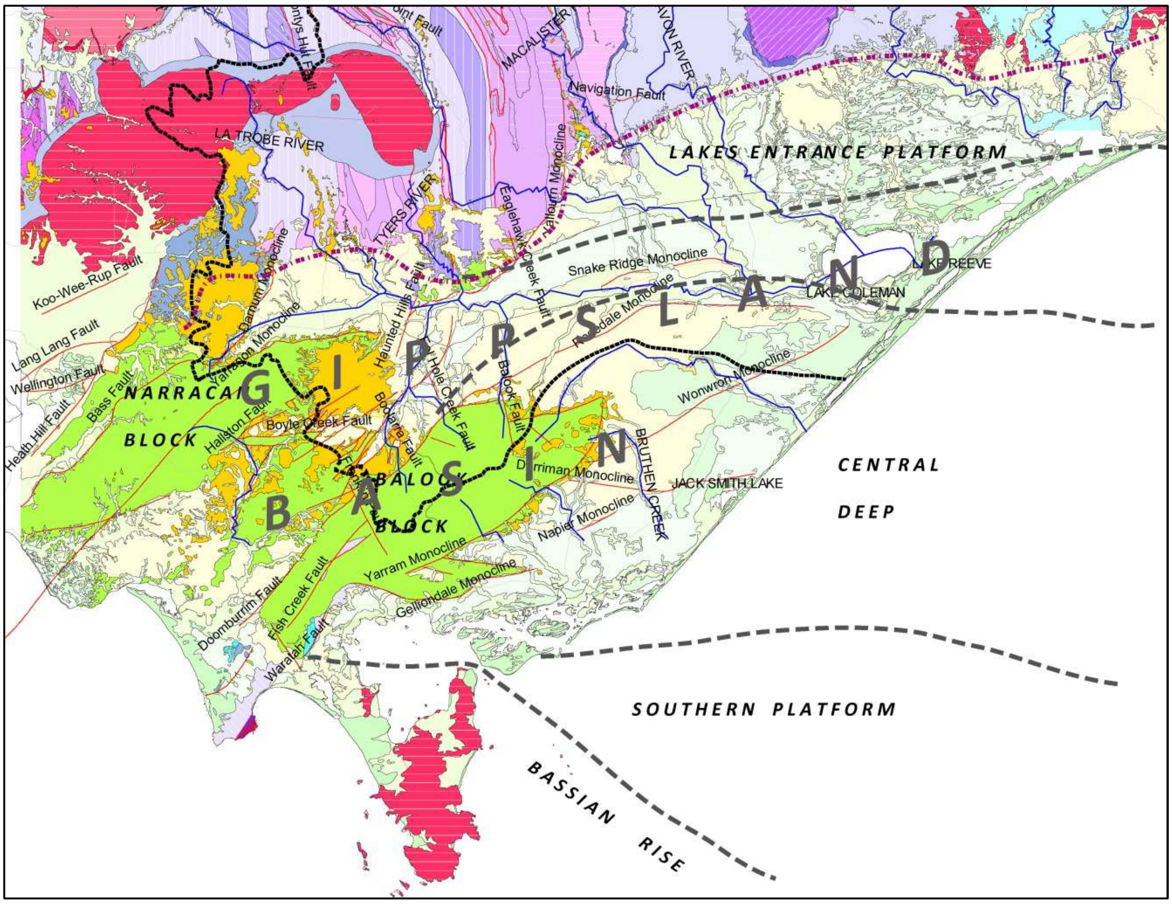


Figure 4: Onshore and offshore Gippsland Basin. Source: Rosengren (2009).

There are five broad geological time-rock units represented in the Gippsland Basin:

(i) *Early Cretaceous: Strzelecki Group*: 140 million years ago (Ma) to 98 Ma ago.
Sedimentary rocks formed by rapid deposition of weathered volcanic fragments in river channels, floodplains and lakes now outcropping as the Strzelecki Ranges. In places they are covered by weathered basaltic lava flows of Paleocene (65 million to 55 million years ago) age. Onshore these form the uplifted and deeply dissected hills of the Narracan Block and Balook Block of the Strzelecki Ranges.

(ii) *Late Cretaceous to Eocene: Latrobe Group:* 98 Ma to 34 Ma.
Siliceous marine and non-marine sediments comprise the main host for the Gippsland Basin hydrocarbon resource. The uppermost units of the Latrobe Group contain the extensive non-marine Traralgon brown coal seams. The Late Cretaceous sediments do not outcrop and the main body of these rocks occurs offshore.

(iii) *Oligocene to Upper Pliocene: Seaspray Group:* 34 Ma to 3.6 Ma.
The Seaspray Group includes several formations of predominantly marine carbonate-rich rocks (limestone and marl) alternating with calcareous muds and sands of estuarine, barrier and fluvial origin and including ferruginous gravel beds. Onshore the Seaspray Group include the Morwell and Yallourn brown coal seams while offshore they form the sealant for the oil and gas reservoirs. The upper (youngest) members of the Seaspray Group outcrop at Red Bluff, in lake shore and former sea cliffs in the Bairnsdale–Lakes Entrance region, and along the lower Tambo, Nicholson and Mitchell River valleys and underlie the trench that contains the modern Gippsland Lakes. The Gippsland Basin rocks were uplifted and folded towards the end of the Miocene or Early Pliocene with axial trends aligned west-east and have undergone extensive reverse faulting.

(iv) *Pliocene to Upper Pleistocene: Haunted Hills Formation:* 3.6 Ma to 0.5 Ma.
Overlying the Seaspray Group in the Gippsland Basin is a widespread deposit of quartzose sand, clay and gravel, often iron-cemented, referred to as the Haunted Hills Formation (formerly Haunted Hills Gravel). These are the most extensive surficial materials across the Gippsland Plains from Westernport Bay to Mallacoota and have a marked angular unconformity with the eroded surface of the underlying Seaspray Group (and equivalent) beds (Figure 5). Up to 90 metre thickness of Haunted Hills Formation sediment, ranging from ligneous clays to coarse gravel occurs in boreholes around the Gippsland Lakes.

The Haunted Hills Formation was derived from the denudation triggered by tectonic compression, uplift and development of highland relief coinciding with climate change in eastern Victoria in the early Pliocene. They represent a period of rapid and sustained terrestrial sedimentation and formed a virtually continuous apron of coalescing alluvial fans and floodplains along the lower slopes of the Eastern Uplands. They were built in part by ancestral streams of the modern Gippsland river systems and traces of these can be determined by magnetic signatures well out into Bass Strait. These deposits were a significant source of sand for beach and barrier building during the marine transgressions of the Pleistocene. The accumulation decreased and apparently ceased by Middle Pleistocene as the bulk of the more readily denuded material had been transferred from the Eastern Uplands to the lower slopes.

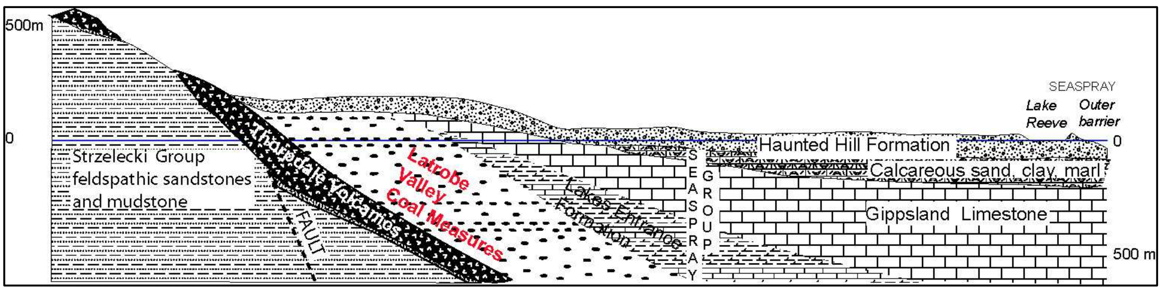


Figure 5: Generalised stratigraphy of the Gippsland Basin along the La Trobe Valley to Seaspray. Source: Rosengren (2009).

The Haunted Hills Formation underlies and forms the margins of the central and western trenches of the modern Gippsland Lakes basins, but there are few exposures to now provide a source of sand for lake beaches.

(v) *Middle Pleistocene to Holocene:* 0.5 Ma to present.
These are the surficial lithic and organic materials developed over a wide range of climatic and process regimes as *in situ* and transported regolith across the entire catchment and adjacent coastline. They include alluvial and colluvial fans and other mass movement material, fluvial channel and terrace deposits, aeolian sands, coastal barrier and beach sands and lake and swamp sediments. They occur in three broad environments: (a) as alluvial fans and elevated terraces of the plains north and west of the Gippsland Lakes; (b) as alluvium and alluvial terraces in incised valleys; (c) as coastal barriers and associated swale deposits in and seaward of the Gippsland Lakes.

The basement rocks of the Eastern Uplands are the source of clastic sediment that has been transferred to the Gippsland Plains by fluvial and mass movement processes. During lower sea-levels over the last 4 million years the streams flowing into the Gippsland Basin extended across the exposed floor of Bass Strait as fans and floodplains. Part of the sediment deposited at that time, and previously as White Hills Formation, has been reworked shoreward as it was submerged during rising sea-level and nourished the growth of coastal barrier formations

2. Geomorphology of the Gippsland Lakes

Geomorphological studies of the lake shores and floor of the Gippsland Lakes can be grouped into three types: (a) system-wide studies assessing the evolution and dynamics of the lake basins, (b) local studies of geographical area(s) of the lakes, and (c) thematic studies relating to specific components and/or processes of part or all of the lake system. The first comprehensive studies of the form and evolution of the Gippsland Lakes were those of Bird (1965) and Jenkin (1968). They advanced different interpretations of the age of the barrier sequences and the development of some shoreline features, e.g. the Mitchell River delta (Bird 1970; Bird & Rosengren 1971). Other studies of the age of sand bodies (mainly modern and stranded barriers) with implications for the evolution of the entire system were made by Ward (1977), Thom (1984) and Bryant & Price (1997).

The most extensive, continuous and on-going studies of the geomorphology and changes of the Gippsland Lakes are those of ECF Bird. His studies of the lakes commenced in 1957 and resulted in many papers including the evolution of the system (Bird 1965, 1966, 1978) and details of shoreline changes (Bird 1961a, b, 1962a, b, 1966, 1970, 1980, 1983, 1993, 2010; Bird & Rosengren 1971; Bird & Lennon 1973, 1989). The Bird (1961a) paper was the first publication to link recession of the shoreline of the lakes with die-back of the fringing reeds due to increased salinity after the opening of the artificial entrance. Bird was also a partner in the study of Sjerp *et al.(* 2002) which examined the complete shorelines of the Gippsland Lakes and quantified changes over the historical period based on documents and a wide-ranging time set of aerial photographs.

Sedimentation rates in the Gippsland Lakes and the contribution of inflowing rivers have been the focus of several studies (Davis *et al.* 1977; Cecil 1982; Reid 1989; Erskine *et al.* 1990; Rutherfurd 1994; Reinfelds *et al.* 1995; Grayson *et al.* 1998, 2001; Grayson & Argent 2002; Cottingham *et al.* 2006; Hancock & Pietsch 2006; Hancock *et al.* 2007; Rustomji & Piestch 2007; Robinson & Sargant 2010; Kabir *et al.* 2011; Smith *et al.* 2011). This topic is addressed in detail and with specific reference to shoreline dynamics in Section 4.6.

2.1 Origins

Central to the origins of the modern Gippsland Lakes is the rise in eustatic sea levels that took place over the past ~11,000 years (Timms 2012). The most recent analysis of sea-level rises in that of Sloss *et al.* (2007), which shows that sea levels in south-eastern Australia rose rapidly over the period ~11,000 to ~8,000 years BP, reached a high-point ~6,000 years BP, and fell slightly and/or remained relatively constant until the increase to rates of ~3 mm year^{-1} that has observed over recent decades[1] (Figure 6). Rahmstorf (2010, Shepard *et al.* (2012) and Gehrels & Woodworth (2013) have addressed the topic of recent sea-level rise.

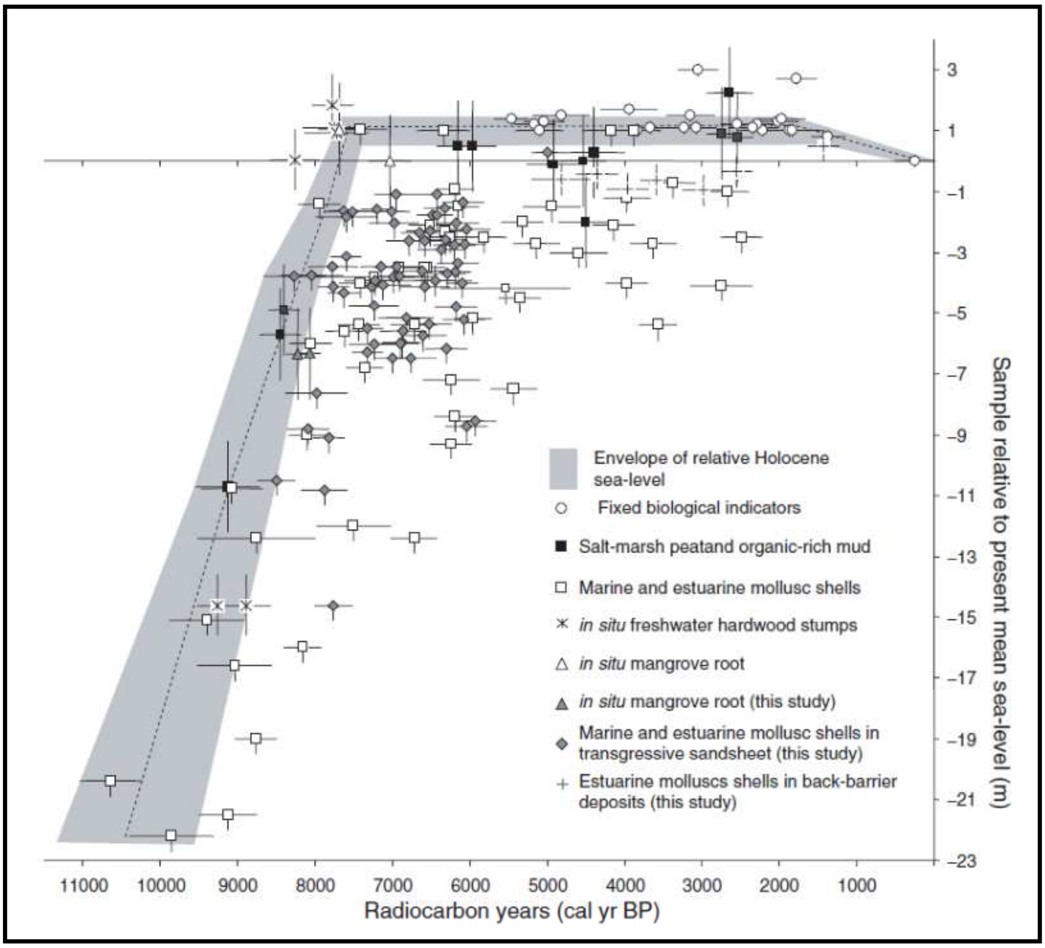


Figure 6: Holocene sea-level rise curve for south-eastern Australia. Source: Sloss et al. *(2007, Figure 5).*

[1] http://www.cmar.csiro.au/sealevel/sl_hist_last_15.html Viewed 29/07/2014

The Gippsland Lakes is a series of coastal lagoons that occupy part of a former marine embayment cut at higher sea-levels into the sediments of the Gippsland Basin. The embayment is now enclosed and partly filled by a sequence of coastal sand barriers of Pleistocene to Holocene age. A variety of coastal, lacustrine, paludal and fluvial landforms has developed during episodes of higher and lower sea level and the system comprises one of the largest and complex coastal barrier and lagoon systems on the southeast coast of Australia. The former embayment is cut into a level to gently sloping surface with a basement of Seaspray Group carbonate rocks covered by Haunted Hills Formation sand, clay and gravel (Figure 7). During times of Pleistocene marine transgression higher sea levels, wave action eroded the edge of this submerged plain forming an active cliffed coastline that extended into the major stream valleys as estuaries. At lower sea levels, the cliff was abandoned and streams extended beyond the former shoreline cutting deeper valleys. This abandoned cliff – termed the marginal bluff (Bird 1978) – is a convenient landward boundary to define the Gippsland Lakes as a geomorphological entity.

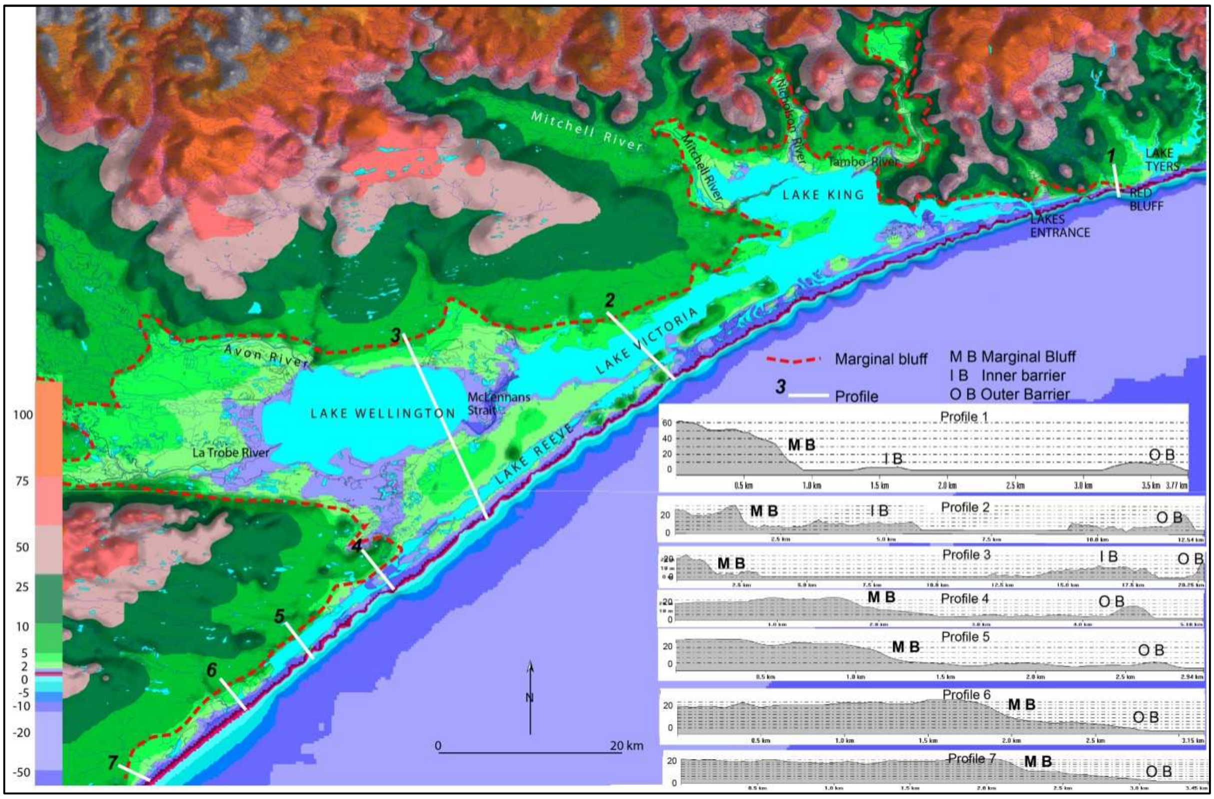


Figure 7: Marginal bluff, lakes and barriers of the Gippsland Lakes. Source: Rosengren (2009).

This sequence of submergence and emergence happened on multiple occasions over the past 4 million years in response to global glacial and interglacial conditions. Features formed at low sea were submerged, reshaped or removed during the transgressions. Magnetic imagery of the lakes region reveals numerous traces interpreted by Holdgate *et al.* (2003) as buried low sea-level river channels and remnants of multiple barrier systems dating back to Late Miocene (Figure 8).

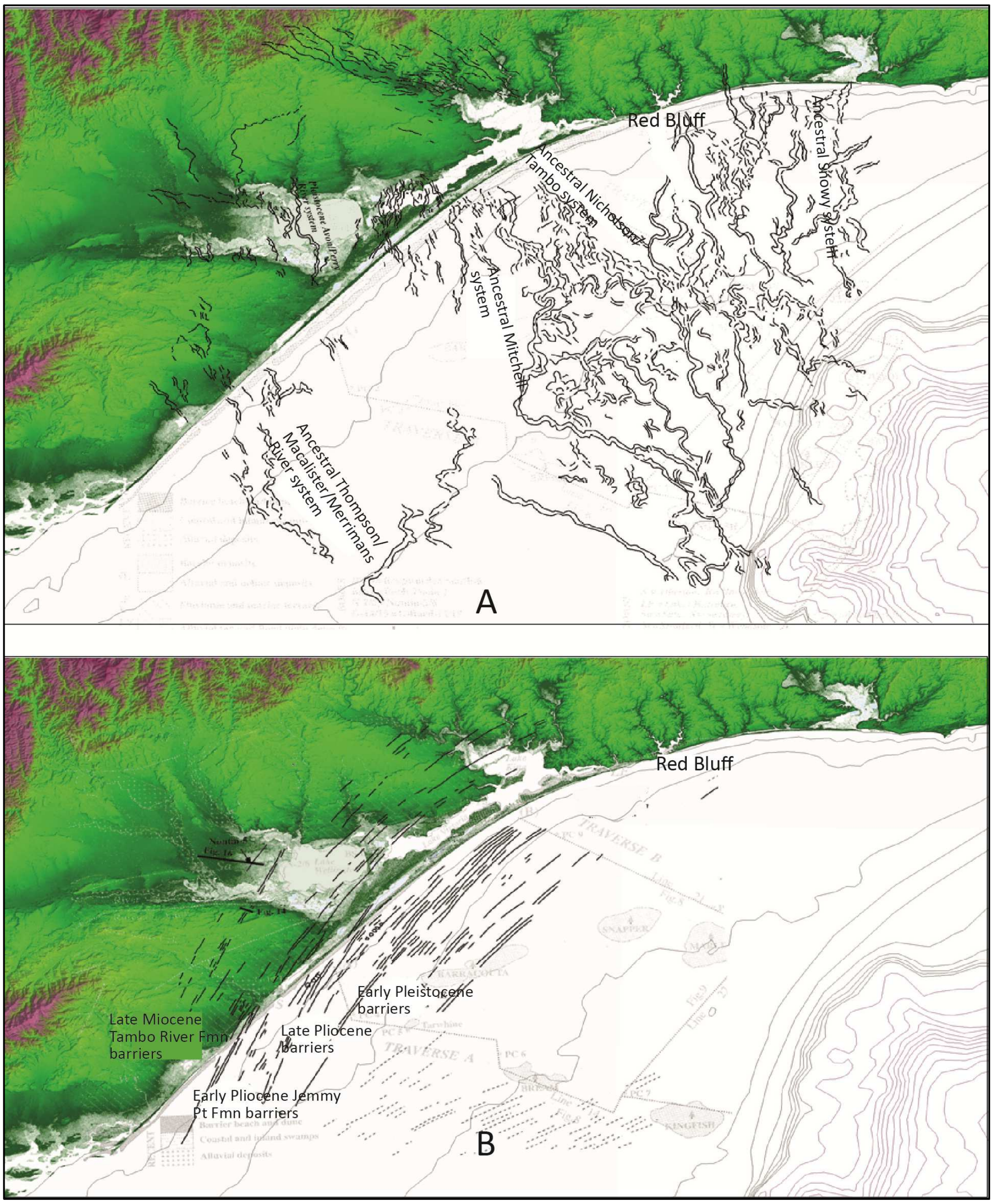


Figure 8: Ancestral stream traces and palaeo-barriers interpreted from magnetic imagery. Source: Holdgate et al. *(2003).*

The palaeo-river systems are interpreted as low sea level extensions of the modern rivers; however the magnetic traces of the former coastal barriers have an orientation about 15^0 more northerly than the trend of the modern Ninety Mile Beach. There is no surface expression either onshore or offshore of these features.

The marginal bluff, modified where incised by the rivers defines the landward extent of the modern Gippsland Lakes systems - the seaward margin is defined by the Ninety Mile Beach. The detailed configuration of the system is determined both by features inherited from past episodes of higher and lower sea-levels and those developed during the Holocene marine transgression. Three broad groups of land-forming processes are recognized: i) the development of the marginal bluff; ii) the growth and modification of coastal sand barriers; and iii) the input of the five major river systems. These processes have resulted in six fundamental groups of landforms that comprise the key components of the Gippsland Lakes. The principal characteristics of these are summarized below and details of other important components given in later sections:

(i) A marginal bluff (a former marine cliff) marking the limit of Pleistocene high sea level submergence of the Gippsland Basin. This submergence created the embayment that the lakes now occupy.

(ii) The plains and low plateau bordering the embayment. Surface features on these plains include palaeo-fluvial features (channels and levee banks) and broad, multiple terraces separated by low escarpments and with linear and arcuate sand and ridges that may be traces of pre-Pleistocene marine transgressions.

(iii) The open water bodies and shorelines of the main lakes and a variety of wetlands only slightly elevated above the lake shore level.

(iv) Elongate sand and gravel ridges that are active and relict coastal barriers initiated by ocean wave action and modified by wind action and vegetation growth. These have a complex topography of ridges and depressions, many with small lakes or wetlands.

(v) The main river valleys and associated channels, floodplains and deltas that extend into the lakes.

(vi) The Ninety Mile Beach and the nearshore wave and current environment created by swell waves in Bass Strait.

Superimposed onto these fundamental landforms are secondary features and processes that have been directly attributed to European settlement of the region. The most obvious of these include:

(i) Opening and maintenance of the artificial entrance at Lakes Entrance since 1889 has created a permanent tidal entrance allowing regular incursions of seawater into the lake system. This has altered the salinity regime of the eastern parts of the lake systems from fresh or intermittently brackish to one of continuous higher salinity, with subsequent impacts on the ecology and geomorphology of many of the lake shorelines. It has also interrupted the longshore movement of sand on the Ninety Mile Beach and created ebb and flood tide deltas that require maintenance dredging. It has triggered increased sedimentation and segmentation of the formerly open waterway of Cunninghame Arm.

(ii) Alterations to flow regime of rivers by dams, irrigation diversions, channel clearing and levee bank construction. This has reduced the mean fresh water inflow and changed the shape of the annual and flood hydrographs. There has been local increase in sediment load in the rivers as a result of land clearing and river bank destabilization.

(iii) An increase in physical pressures on the water and land surfaces by buildings, roads, harbour and marina construction, boat traffic and shoreline engineering works has altered the geometry of some landforms and changed the physical and ecological processes of the surface, lake and groundwater systems.

2.2 Sand barriers

The four elongate lagoons of the Gippsland Lakes (Lakes Wellington, Victoria, King and Reeve) form the outermost (seaward) water bodies of the system, separated from the sea by narrow sand barriers – Cunninghame Arm, the closed and partly filled channel to the natural entrance to the lakes is 5 km long, Bunga Arm east of Ocean Grange is 13 km long, and Lake Reeve southwest of Ocean Grange extends for 55 km long from Ocean Grange to Seaspray.

Several groups of coastal barriers occur in the Gippsland Lakes, with differing morphology and history. Terminology and interpretation of barrier history varies between authors but there are at least three groups of elongate, more-or-less parallel sand ridges (some with a locally significant gravel component) initiated and broadly configured by wave action that developed at different stages of sea level during the Pleistocene and Holocene. At least three stages of barrier formation can be recognised in the Gippsland Lakes region, each with a distinctive morphological and sedimentary style. Bird (1965 and subsequent papers: see Figure 9) grouped and named the barriers as:

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

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

(iii) *Outer barrier*. The outer barrier extends continuously from the sand islands of eastern Corner Inlet to Red Bluff east of Lakes Entrance. It is the youngest of the coastal barriers and the morphology and present dynamics are highly variable. This outer barrier complex extends for 135 kilometres between Red Bluff near Lake Tyers and Shoal Inlet nine kilometres southwest of Reeves Beach. It is one of the longest, continuous beaches in Australia and is almost straight for most of its length with only a gentle concave curve between Loch Sport and Red Bluff. It is interrupted only by the artificially maintained cut at Lakes Entrance and intermittent openings of Bunga Arm and Merrimans Creek. The barrier is a mass of unconsolidated sand, shaped either as a single, narrow ridge or a broad, compound feature with multiple ridge crests and intervening swales. Based on width and number of ridges and the backbarrier morphology, the outer barrier is comprised of seven distinctive sectors. At Letts Beach (Golden Beach) there are 13 well-defined closely spaced ridges up to 10 m high. More commonly there are only two to four ridges, the inner ridge rising to 15 m high in places. At Seaspray and The Honeysuckles and for some kilometres to the southwest the outer barrier is now only a single low and narrow single foredune ridge (to eight metres high) with an irregular crest punctured by dune blowouts.

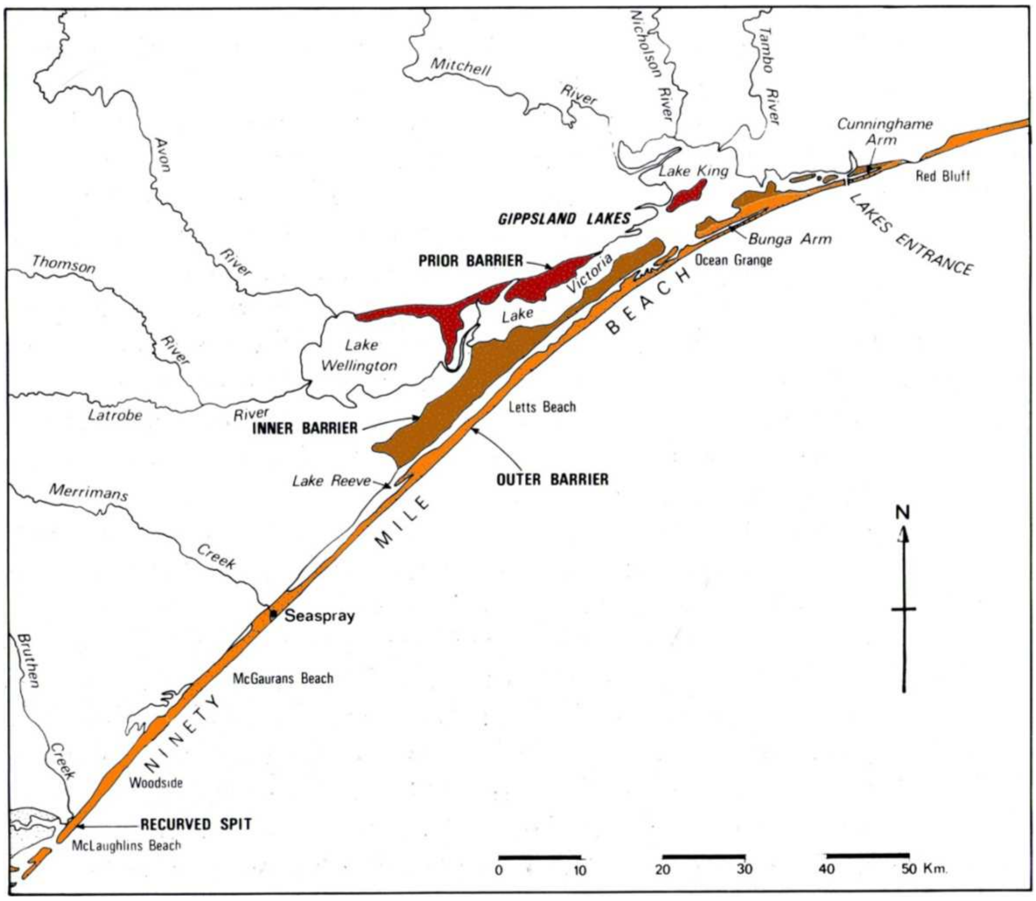


Figure 9: Barriers of the Gippsland Lakes, as per the terminology of Bird (1965).

2.3 Shoreline types

The shorelines of Lakes Wellington, Victoria and King extend for ~60 km, ~100 km and ~160 km, respectively. In a comprehensive review of shoreline conditions using extensive field inspection and aerial photographic interpretation, Sjerp *et al.* (2002) recognised eight categories of shorelines (foreshores) in the Gippsland Lakes (excluding the Ninety Mile Beach ocean shoreline). These incorporated several values including elevation and slope of the backshore (above mean lake level), surface materials, type and rates of shoreline change (accretion/erosion), ownership (farmland), and shorelines altered by human action. The Sjerp *et* *al.* (2002) study also detailed changes over historical time-scales, using earlier studies by Bird (1983) and detailed aerial photographic comparisons. To put that study into context, the sections below briefly describe the shoreline types based on mode of origin rather than on present dynamics and recent (historical) change (Figure 10).

Figure 10: Several shoreline types – outer barrier, inner barrier, placed sand, and hard engineered coast at Lakes Entrance. Photograph by Neville Rosengren, October 2010.

Outer barrier shoreline

By their mode of origin as wave- and wind-built ridges, coastal barriers are sandy and in places contain coarse sediment including gravel and broken shell. For example, the inner edge of the outer barrier forms parts of the shoreline of Lake Reeve, Lake Victoria (at Ocean Grange), Bunga Arm and Cunninghame Arm. Those sections of the Gippsland Lakes that developed adjacent to the shoreline of modern or older barriers, originally had sandy shorelines but the the inner (landward or backbarrier) morphology of the barriers are variable. This edge is developed by a number of processes, not all occurring uniformly, including dune blowouts and barrier overwash. Overwash occurs when waves surge over a backshore dune or barrier and send a spray of water, flotsam and sediment into the lagoon or depression behind the ridge. In an extreme event overwash of a barrier may result in a long-term tidal entrance developing. The most complex backbarrier section occurs between Loch Sport and Ocean Grange where a distinctive pattern of sub-parallel, curving channels (former tidal entrances) on either side of Rotomah Island extend from the rear of the barrier into Lake Reeve and Lake Victoria. The site is an example of washover channels developing a long-lived tidal inlet, with a delta island and channel complex forming between the Boole Poole Peninsula and Rotomah Island. The curvature of the forms is a result of alongshore drift deflecting the ebb and flood tidal currents towards the east and northeast therefore defining the orientation of the channels and tidal depositional banks.

A number of sandy lobate features extend from the inner edge of the barrier ridge into Bunga Arm (Figure 11). These originate either as storm washover fans, dune blowout splays or cuspate shoreline segmentation spits and many are probably of compound origin. Within the Gippsland Lakes system, they develop almost exclusively on the barrier shore of Bunga Arm with poor development on the Rotomah Island shoreline. Although similar in some respects to the tidal delta islands and banks at Ocean Grange, these originate from short-lived breaches of the outer barrier and have not had time to develop as tidal deltas.

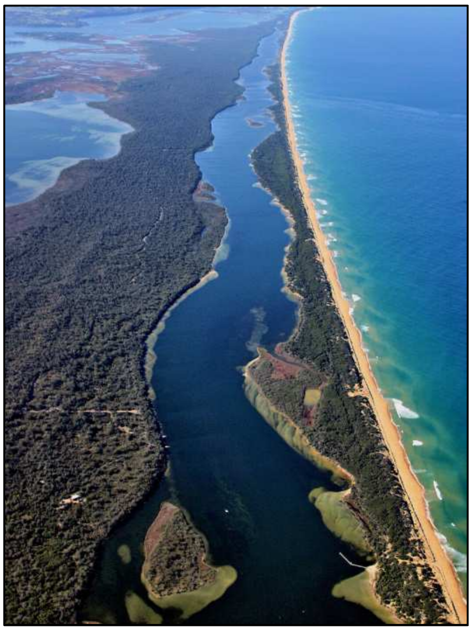


Figure 11: Former tidal inlet channels and delta islands west of Rotomah Island (left) and barrier adjacent to Bunga Arm (right). Photographs by Neville Rosengren, August 2009.

Older barrier and other sandy shorelines

Shorelines formed on older barriers are more variable as they include a wider range of materials e.g. gravels at Banksia Peninsula, and have had a longer period of isolation from marine action. These are typically sandy shorelines, as is Eastern Beach and Point Plover adjacent to the western entrance to McLennan Strait. The southern shore of Lake Victoria is developed on barriers of variable age which have been modified by weathering, and have deeper soils with diverse vegetation communities than the younger barriers. There are also transgressive dune blowouts that have swales below present lake level (Figure 12). The shores also have features suggestive of slightly higher water-levels with relict spits and sandy foreshore terraces now above normal lake levels.

Figure 12: Older transgressive dunes with swales below lake-level Sperm Whale Head. Photograph by Neville Rosengren August, 2009.

Alluvial and delta shorelines

The protruding deltas of the Latrobe, Avon-Perry, Mitchell and Tambo rivers are major geomorphic features of the Gippsland Lakes and are sensitive to environmental changes that alter sediment load, river flow and salinity of the lakes they discharge to. Considerable recession of the Mitchell and Tambo river deltas has been observed since the earliest surveys and there is concern that change of similar magnitude may occur at the mouth of the Latrobe and Avon-Perry systems (Figure 13).

Figure 13. Protruding reed-fringed delta of the Avon-Perry Rivers. Photograph by Neville Rosengren, August 2009.

Much of the lowland shores fringing the lakes - northern Lake King, northern Lake Wellington and the river deltas are of poorly consolidated silty alluvium with only local accumulations of sand, gravel or other relatively resistant substrates. These shorelines, such as southern shore of Lake Wellington have a fringe of aquatic vegetation that has generally become narrower and more intricate in outline since the lakes have become more saline (Figure 14). When exposed to wave action after loss of fringing vegetation, the fine materials disperse rather than developing a beach unless there is an alongshore or onshore transport of sand from another source.

Figure 14: Intricate re-entrant shorelines with variable vegetation fringe, eastern McLennan Strait. Photograph by Neville Rosengren, August 2009.

High shorelines

Two groups of high shorelines with steep slopes and/or active cliffs occur:

(i) where the marginal bluff is reached by the present lake water level such as the cliffs and bluffs of Seaspray Group sediments along the northern shore of Reeves Channel;

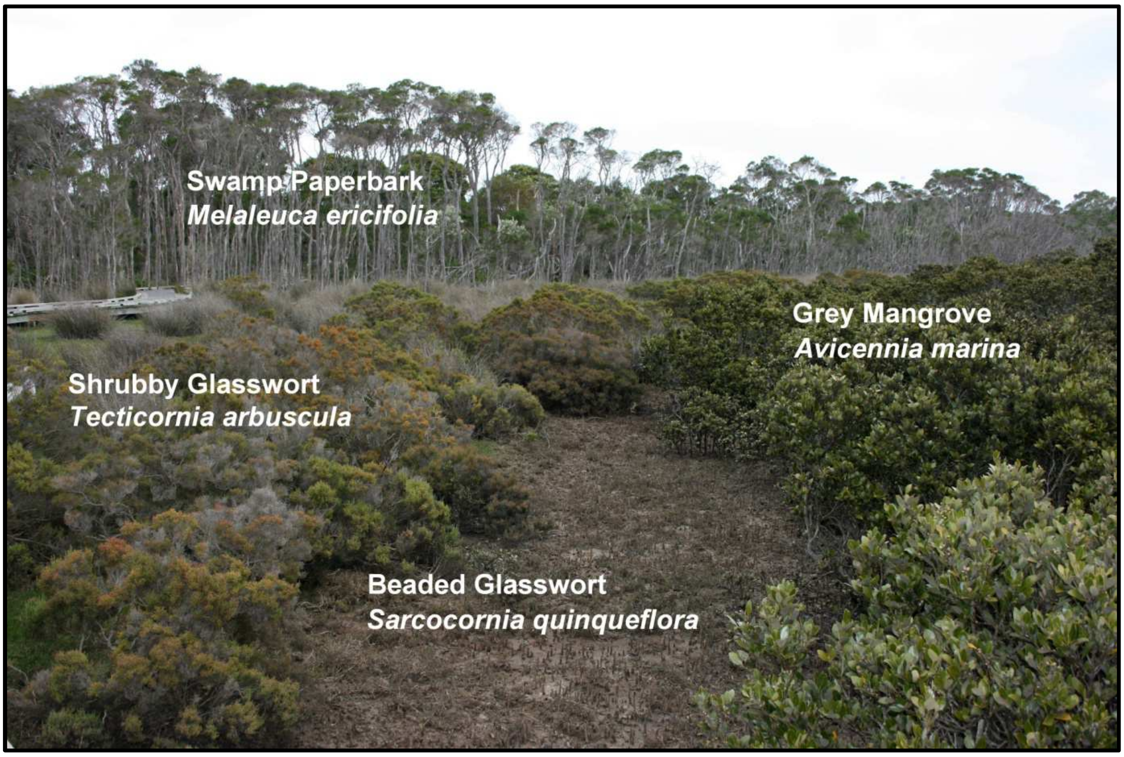
(ii) where high sand ridges of the barriers or transgressive dune ridges are exposed to wave action.

3. Fringing water-dependent vegetation of the Gippsland Lakes

Water-dependent[2] vegetation along the coast of eastern Victoria typically shows a strong zonation with elevation and with distance from the sea (Figure 15). The most seaward zone is typically a mono-specific stand of the Grey Mangrove *Avicennia marina* var. *australasica* (Duke

[2] All vegetation, of course, requires water to some degree or other, but some more so than others. Botanists commonly identify mangroves, saltmarsh and other wetlands, and seagrasses as 'water-dependent vegetation'. Other vegetation types are described simply as 'terrestrial', even if the differentiation is often blurred in swampy areas.

2006), and to landward are typically relatively clearly defined zones of coastal saltmarsh, Sea Rush *Juncus kraussii*, and Swamp Paperbark *Melaleuca ericifolia*.



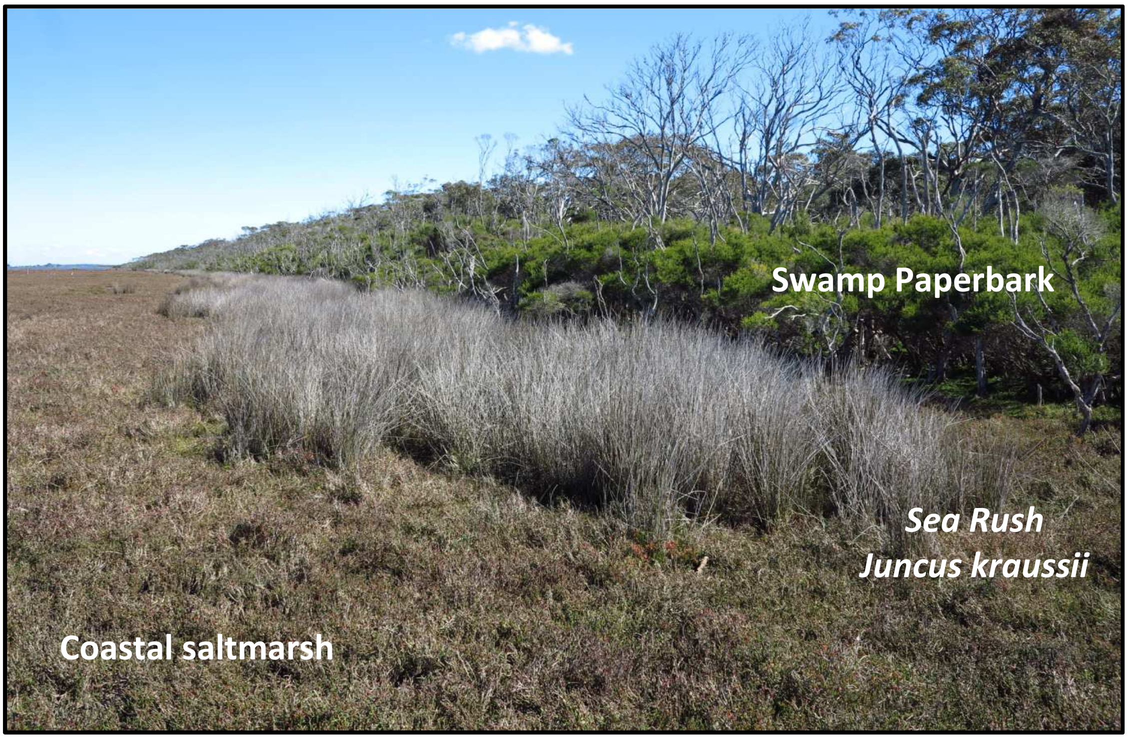


Figure 15: Two images showing the typical zonation of fringing vegetation along low-energy coasts of eastern Victoria. Source: upper image: taken from Boon et al. *(2014), based on a photograph by Chris Harty; lower image of Trapper Point, Sperm Whale Head, photograph by Paul Boon, September 2014.*

3.1 Mangroves

Woodroffe & Davies (2009, page 66) defined mangroves as 'trees, shrubs, or palms, exceeding 0.5 m in height that occur in the upper intertidal zone'. Duke (2006, page 12) adopted a similar definition with regard vegetation structure but was more prescriptive about tidal position: he indicated that mangroves normally grew '… above mean sea level in the intertidal zone of marine coastal environments and estuarine margins.' Australia has the fourth-highest species diversity of mangrove taxa of any country, after the Philippines, Indonesia and Papua New Guinea (Duke 2006).

Only one taxon of mangrove, *Avicennia marina* subsp. *australasica*, occurs in Victoria. It has a discontinuous distribution, from the Barwon River in the west (38°17' S, 144°30'E) to McLoughlins Beach in the east (~38°40' S, 146°52' E) of the State. Mangroves are particularly well developed around Western Port (including on French Island) and in the Corner Inlet-Nooramunga area of South Gippsland. The most southerly occurrence of mangroves in Australia (and indeed the highest latitude occurrence of mangroves anywhere in the world) is in Victoria, in Corner Inlet, where *Avicennia marina* occurs to a latitude of 38° 45'S (Duke 2006). In general, *Avicennia marina* occurs along the Victorian coast as a dense, monospecific shrubland, with individuals growing as shrubs or small trees from 0.3 to 4 m tall. Their densities, however, can vary from individual plants growing sparsely on the shoreline to dense, near-continuous belts of vegetation. There is little or no angiosperm understory, except in the better-drained zones or in landward areas where mangroves become more scattered, and where *Sarcocornia quinqueflora* and *Triglochin striata* may occur as a sparse ground layer. Nevertheless, much of the sediment may be covered by brown algae, including *Hormosira banksii*. Algal mats of *Bostrychia* and *Catanella* species are usually associated with pneumatophores and lower tree stems.

There is a small stand of mangroves at the distal end of Cunninghame Arm in the most eastern part of the Gippsland Lakes (Figure 16). An isolated specimen occurs also near Bullock Island, and it is possible that other specimens occur elsewhere in the most saline parts of the Lakes. The origins of these mangroves is a topic of debate. According to Harty (2011), the specimens in Cunninghame Arm were planted, probably in the late 1980s or early 1990s. No evidence was provided for the assertion. The potential for mangrove propagules to spread (either from the west, from Corner Inlet-Norramunga; or from the north, from southern New South Wales), however, suggests their establishment in the Lakes may be a natural phenomenon, occurring in response to the creation of a new and vacant niche in the intertidal zone as a result of chronic salinization. Clarke & Allaway (1993) and Clarke & Myerscough (1993) showed that the establishment of *Avicennia marina* was limited within existing mangrove stands only by the amount of propagules, but in mangrove-free areas by light, salinity, and sediment suitability. As an expansion of mangroves has been reported for many parts of south-eastern Australia (Saintilan & Williams 1999; Rogers *et al.* 2005; Saintilan *et al.* 2009), it is perhaps not surprising that they are found now also in the Gippsland Lakes. The limiting factor may be dispersal from existing mangroves, and the sole report on the topic (Clarke 1993) suggest a limited capacity for *Avicennia marina* propagules to move more than ~ 10 km from their parent tree.

Figure 16: Small stand of mangroves Avicennia marina *at the distal end of Cunninghame Arm. Photograph by Paul Boon, September 2014.*

3.2 Coastal saltmarsh

Behind the mangrove zone of the Victorian coast, at least in the more sheltered areas, typically occurs a floristical and structurally diverse band of coastal saltmarsh. Carr (2012) identified over 130 taxa of indigenous vascular plants in Victorian estuaries (including saltmarsh), as well as 118 exotic taxa. A wide range of life forms are represented in the Victorian saltmarsh flora, including non-succulent annuals, perennial rhizomatous, stoloniferous, tufted or tussock-forming herbs, large shrubs, and emergent aquatics. Succulent shrubs include *Tecticornia* spp.; large tussocky monocots (e.g. *Austrostipa stipoides* and *Gahnia filum*), low rhizomatous grasses (e.g. *Distichlis distichophylla* and *Sporobolus virginicus*), succulent herbs (e.g. *Sarcocornia* spp., *Hemichroa pentandra* and *Disphyma clavellatum*), and prostrate shrubs (e.g. *Frankenia pauciflora*) are other common structural types[3].

[3] Note that the taxonomy of an important group of chenopods in Australian saltmarsh – the genera *Halosarcia*, *Pachycornia*, *Sclerostegia*, *Tecticornia*, and *Tegicornia* – was revised by Shepherd & Wilson (2007). These genera are now placed in an expanded circumscription of *Tecticornia*.)

Until recently, coastal saltmarsh was ascribed to the Ecological Vegetation Class EVC 9 Coastal Saltmarsh Aggregate. Vegetation is classified and described in Victoria in terms of Ecological Vegetation Classes, or EVCs (Department of Natural Resources and Environment 2002; Department of Sustainability and Environment 2012). Ecological Vegetation Classes are defined as one or a number of floristic and structural types that appear to be associated with a recognizable environmental niche and which can be characterized by their adaptive responses to ecological processes that operate at the landscape scale. The EVC approach to vegetation classification therefore uses floristic and structural criteria, combined with ecological information on niches and distributions. In this typology, mangroves are classified as EVC 140 Mangrove Shrubland (Department of Sustainability and Environment, 2012), a tightly defined classification unit that requires no revision because there is a characteristic floristic composition (dominated by *Avicennia marina*), a consistent structure (a shrubland), and a well-defined environmental niche (the intertidal zone).

Coastal saltmarsh is currently classified as a single Ecological Vegetation Class, EVC 9 Coastal Saltmarsh Aggregate. As it stands, EVC 9 describes coastal saltmarsh as a variously low shrubby or herbaceous (to grassy or sedgy) type of vegetation that occurs on salinized coastal soils in or adjacent to tidally influenced wetlands, and includes a number of types with different structures and floristics. Collectively, these include shrubby dicots such as *Tecticornia* [previously *Sclerostegia*; see taxonomic note above] *arbuscula*, grasses such as *Austrostipa stipoides*, and dicot herbs such as *Sarcocornia quinqueflora* (Department of Sustainability and Environment 2012). Other common types of coastal vegetation dominated by species with various degrees of salt-tolerance, for example *Juncus kraussii*, *Phragmites australis*, and *Melaleuca ericifolia*, are sometimes included in inventories of saltmarsh taxa (e.g. Sainty *et al.* 2012) but are covered by other, mostly well-defined EVCs in the Victorian typology (e.g. *Juncus kraussii* in EVC 10 Estuarine Wetland; *Phragmites australis* in EVC 952 Estuarine Reedbed; *Melaleuca ericifolia* in EVC 953 Estuarine Scrub): see Boon (2012).

The problem with the existing EVC 9 Coastal Saltmarsh Aggregate is that the floristic and structural complexity of coastal saltmarsh in Victoria has been recognized in many reports (e.g. Bridgewater 1975, 1982; Opie *et al.* 1984; Vanderzee 1992; see Adam *et al.* 1988 for an analogous case in New South Wales) but this complexity is not acknowledged in the current classification unit. Indeed, the fact that the unit is termed an 'Aggregate' of varying structure and floristics suggests that finer distinctions are required to better describe the taxonomic and structural diversity of the vegetation and the number of environmental niches encompassed by the term 'coastal saltmarsh'.

The classification typology has been recently revised by Boon *et al.* (2014) and the seven new EVCs erected better reflect the floristic and structural diversity of coastal saltmarsh in Victoria. These new EVCs has received preliminary acceptance in the latest version of vegetation descriptions for the Index of Wetland Condition (Department of Sustainability & Environment 2012).

Coastal saltmarsh is well developed along the Gippsland Lakes. Figure 17 shows the extensive saltmarsh in Lake Reeve. At the time the photograph was taken, Lake Reeve was filled with shallow ponds of saline water.

Figure 17: Coastal saltmarsh (arrowed) of Lake Reeve, as seen from the sand dunes near Seaspray. Photograph by Paul Boon, 2008.

A State-wide survey of 2008−2011 mapped some types (mangroves, coastal saltmarsh, *Juncus kraussii*-dominated wetlands) of water-dependent vegetation of the Victorian coast, including all of the Gippsland Lakes and the downstream sections of its inflowing rivers, at a scale of 1:10,000, using the proposed revised classification typology for coastal saltmarsh described above (Boon *et al.* 2011, 2014). Figure 18 shows, as examples of the mapping now available, wetland mapping for two sections of the Gippsland Lakes: the southern shore of Lake Wellington; and Lake Victoria, around Paynesville and Sperm Whale Head.

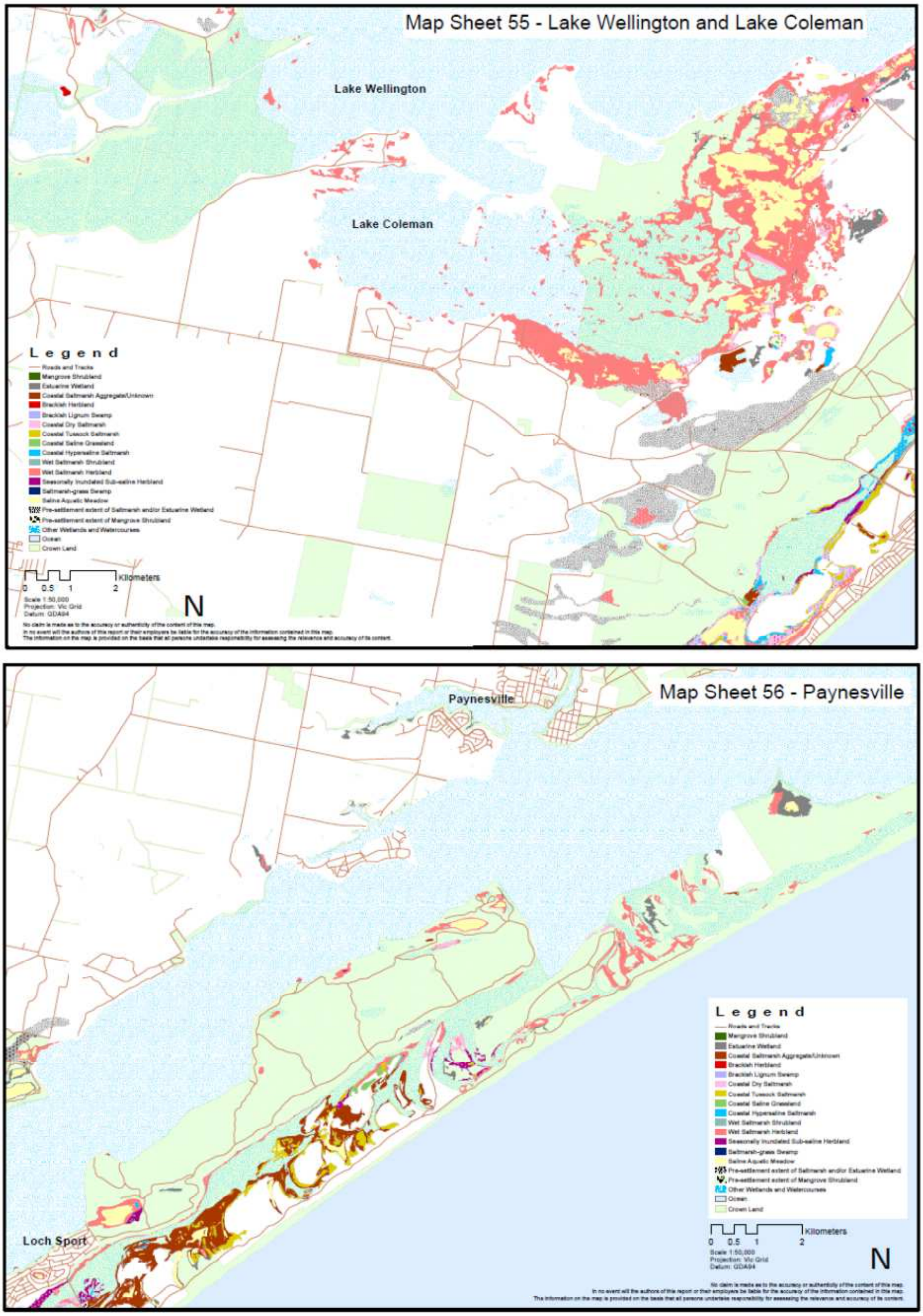


Figure 18: Examples of recent mapping of saltmarsh and other coastal wetlands of the Gippsland Lakes. Source: Boon et al. *(2011).*

3.3 Other emergent woody vegetation

A band of woody emergent vegetation frequently occurs at higher levels, behind the saltmarsh zone (Figure 15). In eastern Victoria, this woody emergent, water-dependent vegetation is typically dominated by paperbarks, in the genus *Melaleuca* (Turner *et al.* 2004). The dominant coastal paperbark species of the Gippsland Lakes is Swamp Paperbark, *Melaleuca ericifolia*. The life history attributes of *M. ericifolia* in relation to wetting and drying cycles and salinity regimes are reasonably well understood (Bird 1962b; Boon 2012; Boon *et al.* 2008; Gibson *et. al.* 1987; Hamilton-Brown *et al.* 2009; Ladiges *et al.* 1981; Morris *et al.* 2008; Robinson *et al.* 2006, 2008, 2012; Salter *et al.* 2007, 2010b, c; Raulings *et al.* 2007, 2010, 2011). As with many wetland taxa of the Gippsland Lakes (Hatton *et al.* 2008), this species can tolerate moderate-to-high levels of salinity and can maintain growth, usually via clonal mechanisms, under chronically waterlogged conditions, sometimes for decades. Even so, many of the paperbark-dominated wetlands of the Gippsland Lakes are in poor ecological condition because of the combination of high salinity and prolonged inundation (Figure 19).

Figure 19: Swamp Scrub (Swamp Paperbark) vegetation in Dowd Morass. Photograph by Paul Boon, July 2010.

3.4 Other emergent non-woody vegetation

Although saltmarsh dominates many of the more elevated intertidal habitats along Australia's south-eastern coastline, a wide range of other non-woody vegetation also occurs along less saline parts of the coast. Adam *et al.* (1985), for example, identified a variety of tall reedbeds, short grasslands and sedgelands, non-saltmarsh sedgelands, wet meadows, semi-aquatic and aquatic herbfields and open freshwater swamps in their inventory of New South Wales coastal wetlands. In Victoria, there are at least 10 Ecological Vegetation Classes (EVCs), in addition to seagrass beds, mangrove woodlands and paperbark-dominated systems, recognized by the Department of Sustainability and Environment (2012) within coastal wetlands and floodplains of eastern Victoria (Table 1).

Moreover, in estuarine systems, coastal saltmarsh is often juxtaposed with a complex suite of other non-woody wetland types and variously inundated by saline and fresh water over highly variable spatial and temporal scales (Keith *et al.* 2007). Even nominally freshwater wetlands in estuaries may be influenced by seawater during periods of extremely high tides or after storm surges. A second context where coastal saltmarsh can be difficult to distinguish from other estuarine wetlands is where freshwater flows emerge at the coast in estuaries or from groundwater seepage. These transitional mosaics are often characterized by dense stands of perennial monocots, including *Juncus kraussii* and *Phragmites australis* in the seaward reaches, and *Bolboschoenus caldwellii* and *Schoenoplectus pungens* in areas further from the influence of seawater (Adam 1994; Sinclair & Sutter 2008). Under these conditions, halophytic and glycophytic species are often intermixed to form complex patterns and mosaics that reflect the interplay of site elevation, saline and freshwater inundation, and groundwater flows (see Clarke & Hannon 1967, 1969, 1970 for the classic analysis, using saltmarshes in the Sydney region of New South Wales).

The dominant type of non-woody emergent vegetation in the Gippsland Lakes is beds of the Common Reed, *Phragmites australis*. These commonly form dense bands behind and within Swamp Paperbark woodlands, commonly close to the water's edge (Figure 20). Reeds and other perennial, emergent rhizomatous taxa also occur around the Gippsland Lakes, including a range of sedges, spike-rushes, and rushes.

Table 1: Types of water-dependent vegetation found along the eastern Victorian coast. Note that not all of these EVCs are found around the Gippsland Lakes. Source: Department of Sustainability & Environment (2012)

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

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

Figure 20: Fringe of Common Reed (Phragmites australis) in Dowd Morass, between the landward Swamp Paperbark woodland and permanent standing water. Photograph by Paul Boon, July 2010.

3.5 Fringing vegetation and freshwater subsides

The vegetation types that fringe the coast and, in particular, forms verges to estuaries are necessarily salt-tolerant to various degrees. They must possess some degree of salt tolerance since they are subject to periodic (mangroves) or episodic (coastal saltmarsh) inundation with seawater and even if elevated sufficiently to be beyond even the highest astronomic tide, are subject to salt spray and to rare inundation with saline water from exceptionally high storm surges. Because of these factors, freshwater inputs play a critical role in structuring the vegetation, fauna and ecological interactions of coastal wetlands and other types of fringing water-dependent vegetation (Boorman 2009).

Fringing vegetation receives inputs of freshwater directly via rainfall, indirectly as runoff from the adjacent hinterland, and as groundwater flows; in the case of coastal floodplains, inundation can occur also when flood-swollen rivers overtop their banks. As a result, the relative ratio of inundation with tidally forced saline water and with freshwater of diverse sources is thought to be a factor controlling many aspects of the ecology of coastal wetlands (Clarke & Hannon 1967, 1969, 1970; Adam 1990, 2002; Boorman 2009). In the upper parts of saltmarshes, for example, swards of salt-tolerant grasses (e.g. *Distichlis* and *Sporobolus* spp.) often occur where freshwater inputs are large enough to significantly dilute soil salinities (Specht & Specht 1999). As salinities further decrease with lesser tidal influence, less salt-tolerant plant taxa such as *Juncus kraussii* often come to dominate; under fully freshwater conditions, a range of mostly salt-sensitive emergent macrophytes, including *Carex* spp., become the visually dominant taxa. Woody taxa are also affected by the interplay of marine and fresh waters. The germination and establishment of the Swamp Paperbark *Melaleuca ericifolia*, for example, progressively declines as salinity increases (Robinson *et al.* 2006, 2008; Salter *et al.* 2007b, c), and even temperate mangroves, long thought to be the model marine woody plant, germinate best in water less salty than straight seawater (Morrisey *et al.* 2010). Similar negative responses to higher salinities have been observed for Common Reed *Phragmites australis* as well (e.g. Bart & Hartman 2003; Greenwood & MacFarlane 2006).

Many non-perennial estuarine plants also require periods of reduced salinity for their seeds to germinate, and seasonal relief of high salinities can prompt annual taxa to divert resources to reproductive structures and set seed (Ungar 1962, 1978). Ponds of stagnant rainwater, for example, are a critical factor for the occurrence of many submerged plant taxa in coastal saltmarshes of western and northern Europe (Beeftink 1977). Similarly, many intertidal wetlands along the south-east Australian coast possess large, shallow depressions that rapidly fill with rainwater after storms and are soon colonized by submerged angiosperm taxa such as *Lepilaena* spp., which rapidly form extensive shallow aquatic meadows. Even small depressions constitute an important component of the environmental heterogeneity of coastal wetlands and are often valuable foraging sites for shorebirds, as well as breeding sites for insects such as mosquitoes and midges.

The influence of groundwater exchange on coastal vegetation is less well understood than that of seawater or surface inputs of freshwater, and is likely to vary among different types of coastal wetlands (Crowe & Shikaze 2004). Groundwater intrusions can affect (mostly to decrease) soil salinities and lower the position of the freshwater-brackish water interface in coastal saltmarsh and other estuarine wetlands (Werner & Lockington 2006; Carter *et al.* 2008). Groundwater can also affect nutrient dynamics, especially through the supply of critical plant nutrients to otherwise nutrient-limited coastal ecosystems (Krest *et al.* 2000). There is increasing evidence that groundwater exports from coastal wetlands can have impacts on receiving waters as well: the specific case of acidic and metal-laden waters seeping from hydrologically modified coastal wetlands that overly acid sulfate soils is discussed later. An example of linkages among groundwaters, estuaries and coastal wetlands is provided by Ahern *et al.* (2006), who correlated the occurrence of cyanobacterial blooms with the efflux of groundwater from paperbark-dominated wetlands in coastal southern Queensland. They concluded that discharges of acidic groundwater increased the availability of nutrients to phytoplankton, thus initiating and prolonging algal blooms in the adjacent estuary.

4. The changing environment of the Gippsland Lakes

4.1 Early descriptions

First visits to the Gippsland Lakes by Europeans were apparently by pastoralists from the Monaro region of New South Wales in 1838 seeking drought relief (Ducker *et al.* 1977). In 1839−40 Angus McMillan followed the Tambo River to its mouth and gave names to Lake

Victoria and the Nicholson and Mitchell Rivers and continued across the Macalister to the La Trobe (Favenc 1908). The early records clearly indicate the lakes to be of potable water and with extensive fringing and aquatic vegetation. According to Ducker *et al.* (1977), the first eyewitness accounts of the Lakes and surroundings was made by WA Brodribb, a member of a group of stockmen who in 1841 crossed the LaTrobe River and Avon River and followed the Avon "…along broad marshes covered with reeds…to a broad sheet of water extending right and left as far as the eye could see". Brodribb's party named this Lake Wellington and recorded the waters to be "…fresh at least drinkable by man and beast."

In 1855, Ferdinand von Mueller visited Gippsland, including the northern shore of Lake King, and appended a plant list from the Gippsland Lakes to his annual report (von Mueller, 1855). Acheson (1861, cited in Robinson 1995) recorded that "…the La Trobe flows into Lake Wellington which is fresh at all times". Rawlinson (1863) in his "Report on the Entrance to the Gipps Land Lakes [*sic*] Lakes" comments on the "...remarkable deltas and great extent of low land swamp and morasses which form the river valley bottoms…" of the Latrobe and Mitchell (rivers). He noted the processes that caused the filling of the La Trobe valley "…deposition of mud and accumulation of vegetable matter are still in operation, extending the river deltas, and silting up the lakes, as evidenced by the deposits of fine mud and dense vegetation in the shallow water around their edges, and the shoals in the centre, and…sand drift blown over in gales of wind".

By comparison, Lennon (1975) quotes an account of the expedition led by Commissioner Tyers by boat launched at Glengarry (La Trobe River) in December 1844 that traversed the entire system and found the Lakes to be "…all of salt water and with a rise and fall of two or three feet" and the entrance "…nearly choked up by sand banks rendering it unsafe for vessels even of the smallest kind".

Cadastral, topographic and geological maps of Victoria in the mid to late 1800's show the broad configuration of the lakes (Dixon 1845, Owen 1863, Department of Lands & Survey 1866, Brough Smythe 1872) (Figures 21 & 22).

Figure 21: Extracts from Dixon (1845) maps (left) and Owen (1863) maps (right).

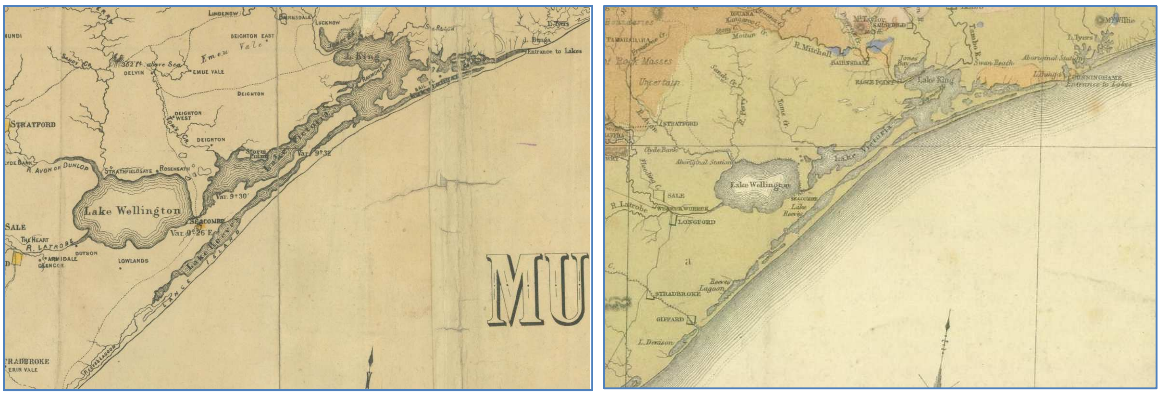


Figure 22: Extracts from Department of Lands & Survey (1866) (left) and Brough Smythe (1872) geological maps (right).

The State Library of Victoria digital map collection has three 'Feature Maps' dated 1849 of Lake Wellington, Lake King and Lake Victoria. They show remarkable detail of the shoreline and adjacent topography and identify main vegetation types (Figure 23). The publisher is not indicated but the map legend states "Feature information supplied by Lands Department".

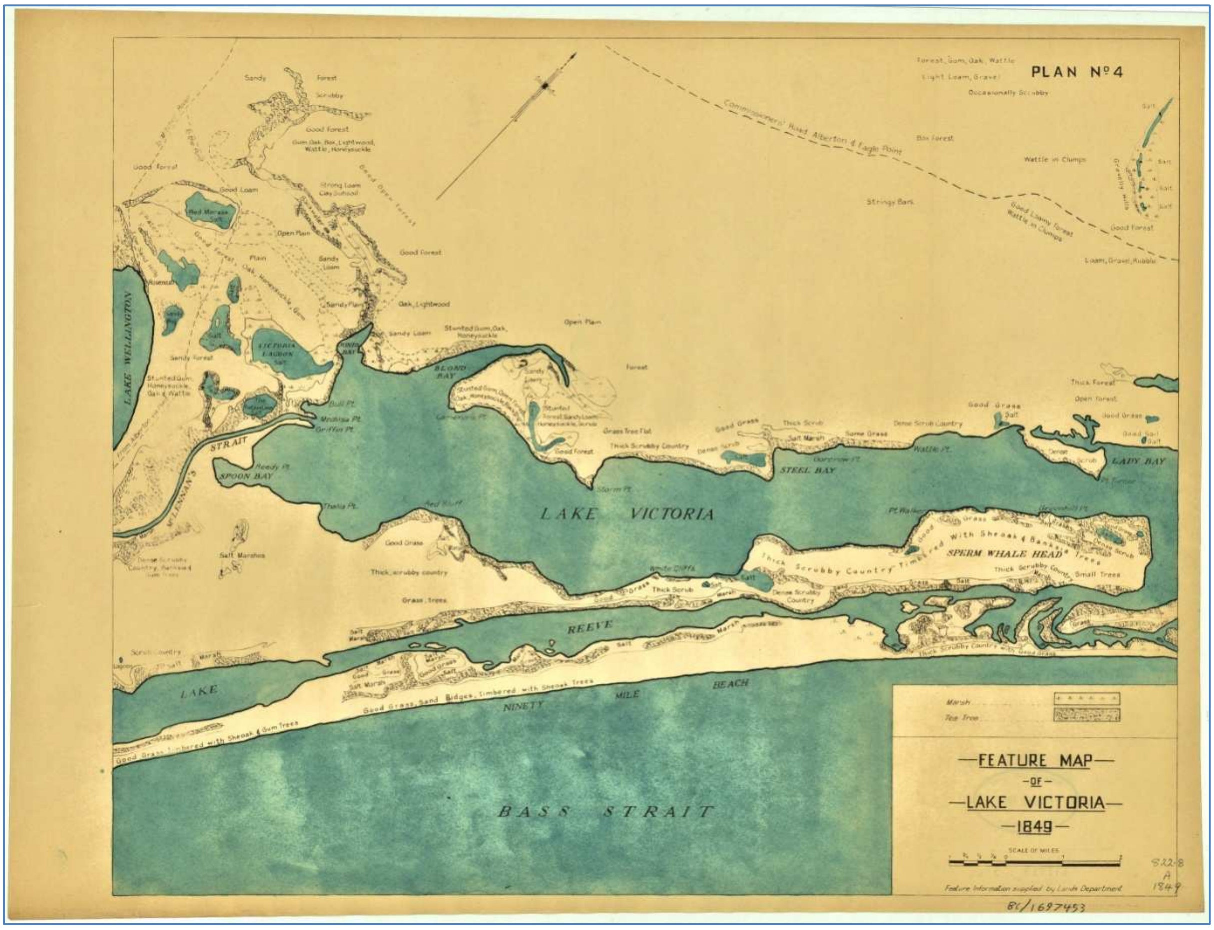


Figure 23: Feature map of Lake Victoria.

4.2 The changing entrance to the lakes

Until the opening of the artificial entrance in June 1889, studies of the morphology of the Gippsland Lakes were focussed on defining the navigability of the lakes and rivers and the position and dynamics of the entrance. The salinity of the lake water prior to 1889 was determined largely by size and length of time an entrance to the sea remained open. John Reeve in 1842 surveyed the coast and determined the location of the then natural entrance and numerous investigations were made in the ensuing years to determine the feasibility of maintaining an entrance for shipping (Bird & Lennon 1973). The intermittent opening shifted from lying almost at the foot of Red Bluff to over five kilometres west (Fryer 1973). During floods, outgoing currents overtopped the sand barrier and the outflowing current apparently kept an opening for several months.

Prior to the construction of the entrance in 1889, impacts on the lake shoreline by vegetation agriculture and jetty construction had been observed (Lennon 1975). After the opening and maintenance of the entrance, regular inflow and outflow of sea water began to influence the hydrological character of the lakes. Evidence was tendered to Parliamentary Committees that a consequence of the opening of the entrance was "…the drainage of the morass land around the Lakes. There are thousands of acres of land now used for grazing that used to be used only be wild fowl", and "...it is considered all over the district that the permanent level of the Lakes has been lowered by a foot and a half since the formation of the Lakes Entrance" (Victorian Legislative Assembly 1900). This reflected a comment made by William Walker an earlier commentator and supporter of a new entrance who in 1866 suggest such an entrance would "…lay dry surrounding swamps for agriculture" (quoted by Bird & Lennon 1973, page 21). The natural entrance towards Red Bluff became sealed over in a few months and Reeves River (the lagoon and channel that connected to the pre-artificial entrance) has now become largely filled with sand washed and blown from the Ninety Mile Beach.

4.3 Form and evolution

Dr JW Gregory, Professor of Geology at Melbourne University, wrote the first comprehensive work on the geography of Victoria (Gregory 1903) and in it devoted 14 pages to the physical character of the Gippsland Lakes. He correctly defined the broad processes that shaped the lakes – a former marine embayment progressively enclosed by the north-east extension of coastal dunes and partial infilling by fluvial sediment. He identified the mechanisms of delta growth at the mouth of the Mitchell River and acknowledged the role of "…water plants and reeds [that] grow on the banks, and help to raise them above water-level. The plants, moreover act as a sieve and catch the mud in any water that may flow across the banks during floods. Thus the bay between the lake shore and the jetty receives only clear water, and is saved from silting up" (Gregory 1903, page 143).

The first comprehensive modern studies of the form and evolution of the Gippsland Lakes were those of Bird (1965) and Jenkin (1968). They advanced differing interpretations of the age of the barrier sequences and the development of some shoreline features e.g. the Mitchell River delta (Bird 1970; Bird and Rosengren 1971). Other studies of the age of sand bodies (mainly modern and stranded barriers) with implications for the evolution of the entire system were made by Ward (1977), Thom (1984) and Bryant & Price (1997).

As noted earlier, the most extensive, continuous and on-going studies of the geomorphology and changes of the Gippsland Lakes are those of ECF Bird. His studies of the lakes commenced in 1957 and resulted in many papers including the evolution of the system (Bird 1965, 1978) and details of shoreline changes (Bird 1961a, 1961b, 1962a, b, 1966, 1970, 1980, 1983, 1993, 2010; Bird & Rosengren 1971; Bird & Lennon 1972, 1989). The Bird (1961a) paper was the first publication to link recession of the shoreline of the lakes with die-back of the fringing reeds due to increased salinity after the opening of the artificial entrance. Bird was also a partner in the Sjerp *et al.* (2002) investigation, which examined the complete shorelines of the Gippsland Lakes and quantified changes over the historical period based on documents and a wide-ranging time set of aerial photographs.

There is a convergence of evidence that the extent of reed-fringed shorelines has been substantially reduced in the last 100 years and this correlates closely with those sectors where recession has been most pronounced. The ecological impact of the creation – and maintenance – of the artificial entrance is outlined in greater detail in the next section.

4.4 Salinity regimes and the permanent connection to the ocean at Lakes Entrance

When the Gippsland region was colonized by Europeans in the 1840–1850s, the Gippsland Lakes were linked with the sea only by a shifting and intermittent outlet through the sand barriers at the easterly part of Lake King (Figure 24). Synan (1989) and Watson (1984) describe this colonization period. Shipping access to the ocean was dangerous and constrained by the often-closed entrance (Rawlinson 1863; Cringle 1866). In response to navigational limitations posed by the intermittent entrance, a permanent (artificial) entrance was cut to Bass Strait in 1889 at Lakes Entrance, ~5 km from the natural entrance (Bird & Lennon 1973, 1989). Sand deposition soon sealed off the old natural outlet and navigation through the artificial entrance has been maintained ever since by dredging (Bird 1966, 1978).

As a consequence of the creation of a permanent entrance to the sea, mean water levels in Lake King and Lake Victoria now correlate closely with the mean water levels in Bass Strait on time scales of ~1 week or longer (Webster *et al.* 2001). Variations in ocean levels in Bass Strait occur in response to long-term changes in atmospheric pressure and the set-up or set-down of storms. The resulting longer term variation in ocean water levels then dominates the observed pattern of variations throughout the two eastern lagoons, and result in fluctuations typically of ±0.2 m about mean sea level. During large ocean surges in Bass Strait the eastern lagoons respond with variations in mean water level of as much as 1 m, and as noted below these can have major implications for the occurrence of saline intrusions into the western parts of the Lakes complex.

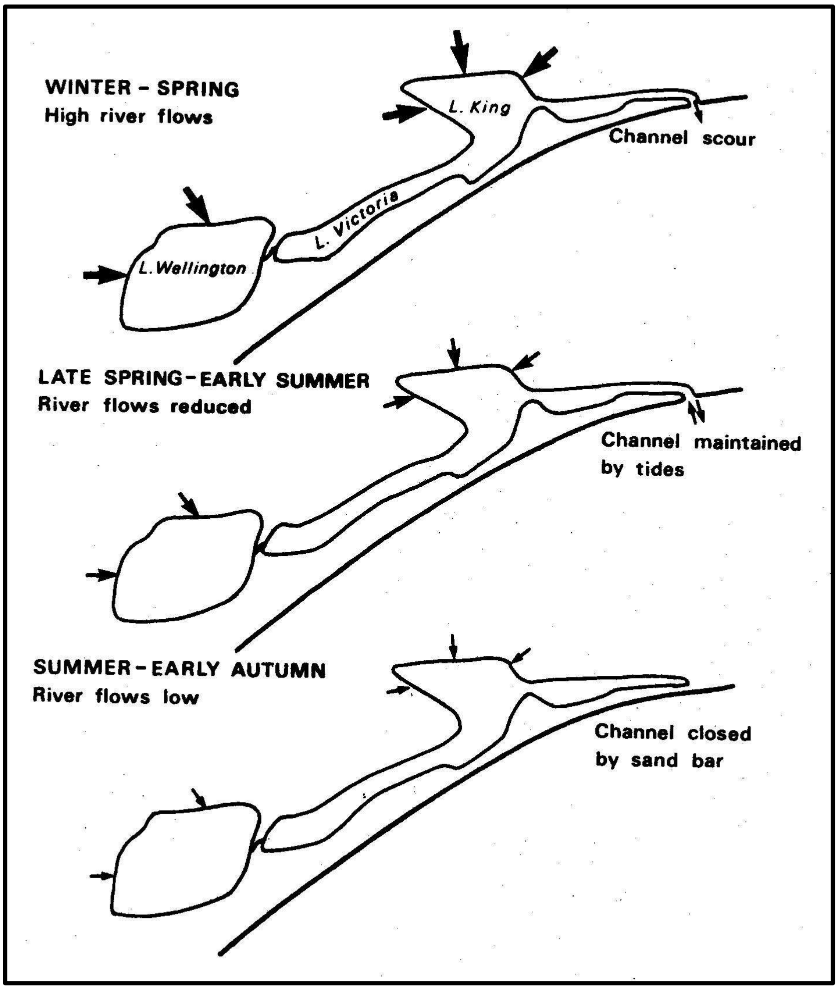


Figure 24: Likely hydrological regimes in the Gippsland Lakes before European colonization and the construction of the permanent opening to the ocean at Lakes Entrance. Source: unknown, possibly ECF Bird.

In contrast to the case with the eastern lagoons, Lake Wellington, the western-most lagoon, is not tidal. Rather, it receives saline influences as brackish water moves through McLennan Strait as a result of variations in water level in the eastern lagoons (Brizga *et al.* 2011; Timms 2012). These can be induced not only by changes in mean ocean levels but also when storms over the eastern catchments result in flooding in the eastern rivers (especially the Mitchell River), which in turn causes saline water to back-up into the western lagoons. Because of the restricted connection to the sea at Lakes Entrance, these large inflows of fresh waters during floods down the eastern rivers cause an increase in water levels in Lakes King and Victoria, and flooding in nearby low lying areas. Lake water level will increase up to 1.8 m and 2.2 m at Lakes Entrance and Lake Wellington respectively in the event of a 1-in-100 year flood (Moroka 2010; see also Timms 2012). Elevated water levels last for several days, until discharge through the entrance return water levels to normal.

The opening of the permanent entrance to the Southern Ocean at Lakes Entrance had two major consequences for hydrological and salinity regimes in the Gippsland Lakes. The first, and immediate, consequence was to modify the range of fluctuating water levels in the lakes; pre-1889, water levels would increase by ~2 m when the entrance was closed, due to on-going river discharge and precipitation (Bird 1966; see also Webster & Ford n.d.). Such high water would persist until the sand berm was breached and the water escaped to the Southern Ocean. Following the cutting of the permanent entrance, water levels vary over only a slight range, largely driven by fluctuations in mean sea level as described earlier. Water levels do increase in times of flood, when water backs-up through the lagoons, but any minor variations induced by tidal influence extend only a short distance up the lower-most parts of Lake King and Victoria.

The second has been to progressively increase the salinity of the Gippsland Lakes, which previously were relatively fresh, or at most brackish, because of their intermittent linkage with the ocean (Bird 1966; Bird & Rosengren 1974; Timms 2012; Webster & Ford n.d.. The increase in salinity following the creation of the artificial entrance has been more gradual than the near-instantaneous effect on water levels, but salinity-mediated impacts on fringing vegetation were probably evident within the first few decades after 1889 (Bird & Rosengren 1974). With the creation and maintenance of the permanent opening, low-frequency sea-level variations in Bass Strait, combined with tidal forcing and the impacts of storms, affect water levels and salinities across all of the Gippsland Lakes, although the effect decreases with increasing distance from Lakes Entrance (Webster *et al.* 2001; Brizga *et al.* 2011). Over recent decades, salinities in the water column of Lake King have typically ranged from 8–26[4] and those in Lake Wellington, the lagoon most distant from the ocean, typically from <1–10 (EPA Victoria 2013). Salinities in Lake Wellington are the most variable and have ranged since 1976 from <1 following floods to >15 during the 1998 drought and to >20 during the 1982 drought (Grayson 2003). Thus not only has there been a chronic increase in salinity since the end of the 19th century, but the permanent opening allows for episodic intrusions of saline water into the Gippsland Lakes following storm surges or differential discharges down the eastern and western rivers, which can push saline water into other lakes not directly affected by flooding (Parks Victoria 1997).

In contrast to pre-entrance conditions, when ingress of seawater was a temporary phenomenon dependent on intermittent breaches in the barrier dune, the artificial permanency of the current entrance has created a constant boundary condition for the lakes. As a result, variability in salinity is now almost solely the result of variability in freshwater inflows from the main rivers, and periods of low river discharge are thus strongly correlated with periods of high lake salinity, and vice versa.

4.5 River regulation and reductions in freshwater inflows

The rivers that discharge into the Gippsland Lakes have been variously developed to provide potable water for the city of Melbourne (primarily via the Thomson Dam, on the Thomson River), to support irrigated agriculture (e.g. Glenmaggie Dam, on the Macalister River), and to provide cooling water (from the Latrobe River) for thermal electricity generation in the Latrobe Valley industrial area. The critical investigation addressing the impact of river regulation and

[4] In the past salinity was frequently reported in units of g L^{-1}, but the UNESCO Practical Salinity Unit scale of 1978 (PSS78) defines salinity in terms of a conductivity ratio, so it is dimensionless. Open ocean salinity is typically ~35 PSU, but can vary over the range 32–37 PSU. In practical terms the difference between salinity and PSU is unimportant, as the numerical values are almost precisely the same.

flow diversion is Moroka (2010). This review showed that the Latrobe-Macalister-Thomson River system (44% of mean annual inflow) and the Mitchell River (35% of mean annual inflow) were the largest contributors of fresh water to the Gippsland Lakes; the Avon-Perry (8%), Tambo (11%) and Nicholson Rivers (2%) make up the balance.

Moroka (2010) showed also that ~20% of the average annual discharge of rivers that flow into the Gippsland Lakes is extracted for agricultural, industrial and domestic purposes before it reaches the lakes. The western rivers have been the most regulated, and they supply ~96% of the water extracted for human use from the various rivers that discharge into the Gippsland Lakes. In contrast, the eastern rivers rise and flow through relatively steep land, much of which is protected as National Park or as State or Forest Park and are currently subject to little extraction. The eastern rivers are largely unregulated and thus extraction represents a markedly smaller proportion of their flows (although the majority of extraction occurs in summer and autumn, when flows are lowest and the rivers are possibly flow-stressed already).

The Latrobe River system has been most affected by regulation and extraction, and >30% of average annual flows down the Latrobe-Thomson-Macalister system are captured for storage or are extracted (Moroka 2010). Moroka (2010) estimated also that full practical usage of existing water entitlements would reduce riverine discharges to the entire system by a further 8% (of current inflow), which would equate to a total reduction of ~44% from natural inflows for the Latrobe River system. A consequence of regulation and extraction of water from the Latrobe-Thomson-Macalister system, and from the Latrobe River in particular, is that the wetlands fringing these rivers are less likely to be inundated by small to medium-sized floods, even if the passage of very large floods is almost unaffected by regulation.

The Latrobe-Macalister-Thomson system also receives a number of licensed discharges of waste, the major contributions being treated sewage from the townships of Warragul, Moe and Morwell, and industrial wastewater from thermal power stations. Within the Tambo catchment there are former mining areas around Cassillis that have eroded in the past, creating large slugs of sand within the lower reaches of the river near Bruthen and Tambo Upper and erodible agricultural areas, particularly in granitic areas. Both the Avon and Nicholson Rivers drain from vegetated upper catchments into areas that are dominated by cleared agricultural land along their lower reaches. The Mitchell River is currently unregulated.

River discharges to the Gippsland Lakes show a strongly seasonal pattern, with low flows in summer and autumn and higher flows in winter and spring, the later following spring snow-melt and, to a lesser extent, seasonal rainfall patterns. Average flows for a 24-year period to 2001 were 4.38 GL day^{-1} for the western rivers and 3.08 GL day^{-1} for the eastern rivers (Webster *et al.* 2001). Because of the distance between the various rivers, discharge from the western rivers may not always be correlated with discharge from the eastern rivers: such differential flows have implications for saline intrusions in different parts of the Gippsland Lakes, as discussed above.

Although groundwater inflows make a relatively small direct contribution to the water balance of the lakes system, there is strong evidence that discharge from the water table to the various tributary rivers is likely to make a significant indirect contribution to the Gippsland Lakes (Moroka 2010; Unland *et al.* 2013). The water table mainly receives recharge from rainfall and irrigation, with some minor upwards leakage from deeper aquifers such as the Boisdale Aquifer. Groundwater discharge contributes 24−36% of annual average flow in the Avon River during periods of average rainfall. Similar contributions are expected for the other major rivers, particularly the Mitchell, Tambo and Nicholson Rivers.

4.6 Sediment and nutrient loads

Section 2 (page 11) listed the many studies that have been undertaken on sediment and nutrient loads to the Gippsland Lakes. External nutrient inputs to the Gippsland Lakes are dominated by riverine inputs (as opposed to marine sources). Inputs from the Latrobe River dominate the total load (Table 2).

It is likely that nutrient loads have changed substantially in the past ~150 years, as agriculture and urbanisation within the Gippsland Lakes catchment have expanded and become more intensive. Grayson *et al.* (2001) showed that loads of Total Nitrogen and Total Phosphorus to Gippsland Lakes from the western catchments have increased by a factor of 3−5 since European colonization, compared with a factor of <2 for the less developed eastern catchments. Taken together, these values generate Lakes-wise anthropogenic increases in nutrient loading by a factor of 2−3.

On a catchment-wide basis, the majority of the increased nutrient loads arise from dryland grazing and from irrigated agriculture (Cottingham *et al.* 2006). Monitoring of flow and nutrients since 1979 has enabled load estimates to the Gippsland Lakes to be constructed over a three-decadal time span (Cook & Holland 2012), and this analysis shows that annual loads are highly variable and that the principle driver for this variability is river flow; loads of Total Nitrogen and Total Phosphorus entering the Lakes are highly correlated with river flow. As land-use has remained relatively unaltered over this period, there is little or no evidence of increasing loads since the early 1980s.

Table 2: Long-term loads of suspended solids and nutrients for six rivers that discharge into the Gippsland Lakes. Source: Grayson et al. *(2001).*

River	Total estimated load (tonnes $year^{-1}$)		
	Suspended solids	**Total nitrogen**	**Total phosphorus**
Latrobe River	93,670	1,277	132
Thomson River	36,230	346	56
Avon River	35,970	321	32
Mitchell River	26,800	436	47
Nicholson River	6,670	59	7
Tambo River	10,540	218	15

5 Environmental consequences of altered conditions

The creation of the permanent entrance at Lakes Entrance initiated an ecosystem-wide cascade of environmental consequences, starting with the whole of the Gippsland Lakes developing into a permanently estuarine environment (*sensu* Tagliapietra *et al.* 2009). As shown in Figure 24, before the cutting of the artificial entrance, the lagoons and their fringing wetlands would have been relatively fresh because of their intermittent linkage with the ocean and large inputs of freshwater from the seven rivers that discharge into the lakes (Bird 1961a, b, 1962a, b, 1966; Bird & Rosengren 1974; Saunders *et al.* 2008). Oral histories of local families even tell of fishermen not taking drinking water with them whilst netting, as the lakes were fresh enough to provide drinking water merely by placing a bottle over the side of the boat (Ellis & Lee 2002).

That there would be marked ecological consequences caused by making a permanent opening to the ocean was first explicitly acknowledged by Bird in 1966, who predicted that the existing fringes of Common Reed would be replaced by the putatively more salt-tolerant Swamp Paperbark and, ultimately, even the latter would be replaced by coastal saltmarsh (Figure 25).

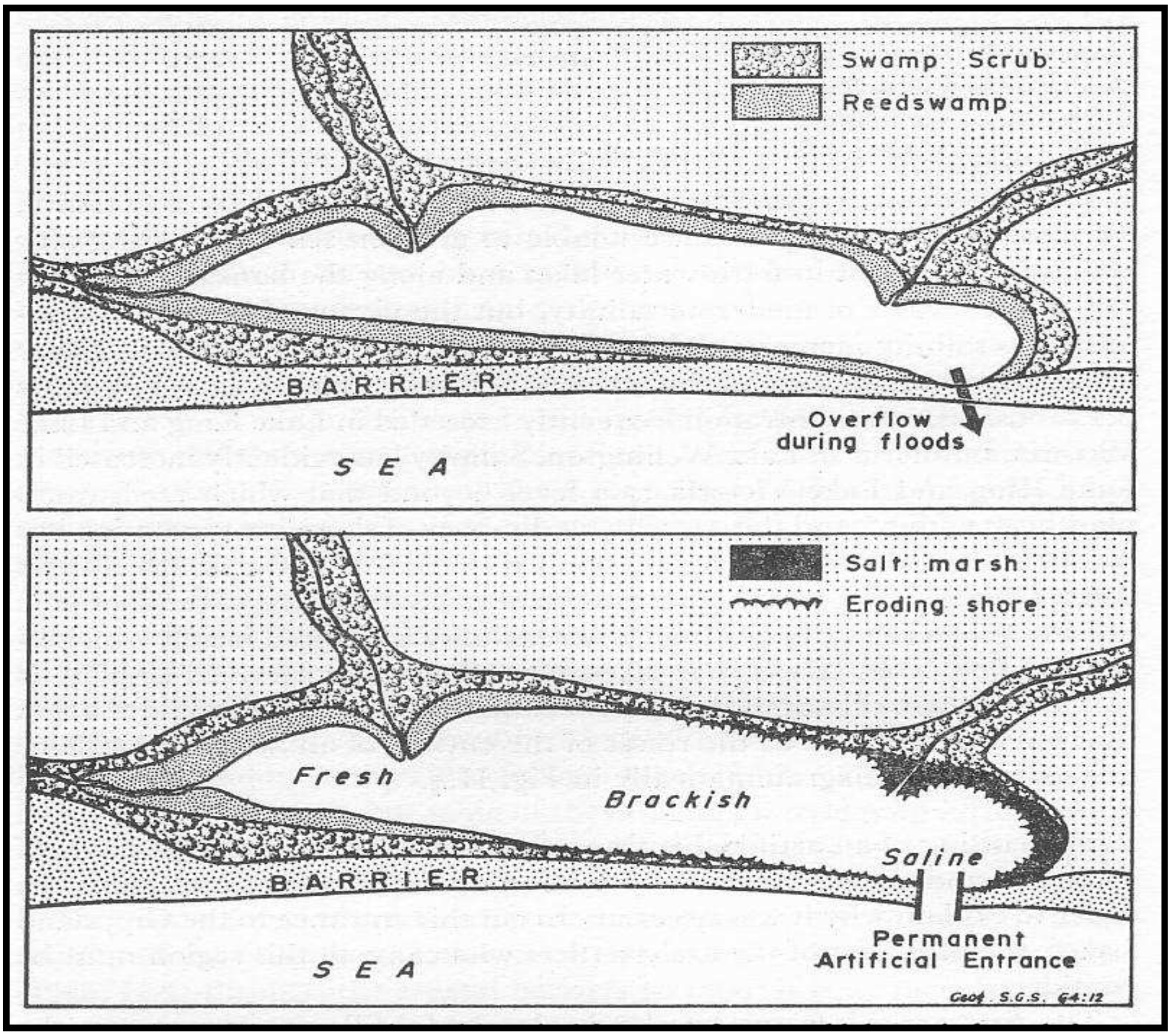


Figure 25: Model of projected change in fringing vegetation of the Gippsland Lakes as outlined by Bird (1966).

There is good empirical evidence to support Bird's predictions. Indeed, the first written record of salinity impacts was by Hart (1921), who noted the salinity-induced cut-back and erosion of shorelines previously densely vegetated by swamp paperbarks. Many of Bird's predictions were confirmed also in the survey of changes in the vegetation communities of Dowd Morass, using post-World War 2 aerial photographs, undertaken by Boon *et al.* (2008). This study showed a progressive loss of Common Reed and their replacement by Swamp Paperbark. As described in the following section, there is also good evidence for an increase in the area of saltmarsh around the Gippsland Lakes, although the spatial and temporal patterns are complex (Sinclair & Boon 2012). The submerged angiosperm *Vallisneria australis* was formerly common in the lakes and fringing wetlands (Aston 1977), including in Lake Wellington (Bird 1978), but is now precluded by high salinities and unstable sediments from these areas (Salter *et al.* 2010a). High salinities also adversely affect the condition, and presumably the productivity, of adult paperbark trees and their ability to recruit sexually (Ladiges *et al.* 1981; Salter *et al.* 2007, 2008, 2010b, c; Robinson *et al.* 2006, 2008, 2012).

The various changes induced by higher salinities on different aspects of the Gippsland Lakes are discussed in turn in the following sections.

5.1 Shoreline erosion and retreat

Shorelines developed on unconsolidated sediment (sand, silt, and clay), organic deposits or other poorly consolidated material such as weakly indurated sandstone or mudstone often respond quickly to changes in the offshore, onshore or terrestrial environmental processes. In the Gippsland Lakes, the known or inferred causes of shoreline change are absolute water level, wave energy and accompanying currents, and changes to fringing vegetation in response to increased salinity following opening of the artificial entrance. Highly vulnerable shorelines such as the Mitchell and Tambo River deltas are clear examples of such changes having taken place in the Gippsland Lakes (Figure 26); Sjerp *et al.* (2002) identified also the Latrobe and Avon River deltas, and parts of McLennan Strait as showing evidence of continuing erosion. Other areas of substantial erosion identified by Sjerp *et al.* (2002) included Poseneath Point, Swell Point, Storm Point, west of the Avon River/Clydebank Morass, Marlay Point, around Loch Sport, Luff Point, Harrington Point, northern Raymond island, Point Fullarton, Tambo Bluff and the northern shores of Jones Bay.

In their assessment of shoreline erosion and retreat, Sjerp *et al.* (2002, page 1) noted the relationship between shoreline dynamics and the loss of fringing vegetation:

> *Ecological conditions within the Gippsland Lakes have changed considerably since the creation of a permanent opening at Lakes Entrance in 1889… Increased water salinity (often in places reaching that of sea water) has resulted in extensive die-back of fringing reedbed vegetation, primarily* Phragmites australis*, around much of the shoreline. From field investigation and comparison of aerial and historic photography, the vast majority of the Gippsland Lakes shoreline continues to change as* Phragmites australis *reedbeds retreat further and erosion persists. Deltas on the Latrobe, Avon, Mitchell and Tambo Rivers and on McLennan Strait all show evidence of continuing erosion.*

Figure 26: Retreating shoreline of the Tambo River delta. Photograph by Neville Rosengren, March 1998.

5.2 Changes in fringing vegetation – loss of predominantly freshwater taxa

Salinity increases following the opening of the permanent entrance would have been more gradual than the near-instantaneous effect on water levels, but salinity-mediated impacts of chronic seawater inputs on salt-intolerant fringing vegetation were probably evident within the first few decades after the entrance was artificially opened (Bird 1966; Bird & Rosengren 1974; see also Wheeler *et al.* 2010).

Figure 27 shows, as an example, the degree to which reed beds have been lost from the western shore of Lake Wellington, around the mouth of the Latrobe River.

Bird (1961b) analysed the factors that may have been responsible for the loss of fringing beds of Common Reed from around the Gippsland Lakes. He concluded that reed regrowth was limited by high salinities, but could not unequivocally dismiss changing land-use practices, especially uncontrolled grazing, as a contributing factor. Interestingly, Roberts (2000) concluded that agriculture was primarily responsible for retractions in the area covered by Common Reed in inland south-eastern Australia.

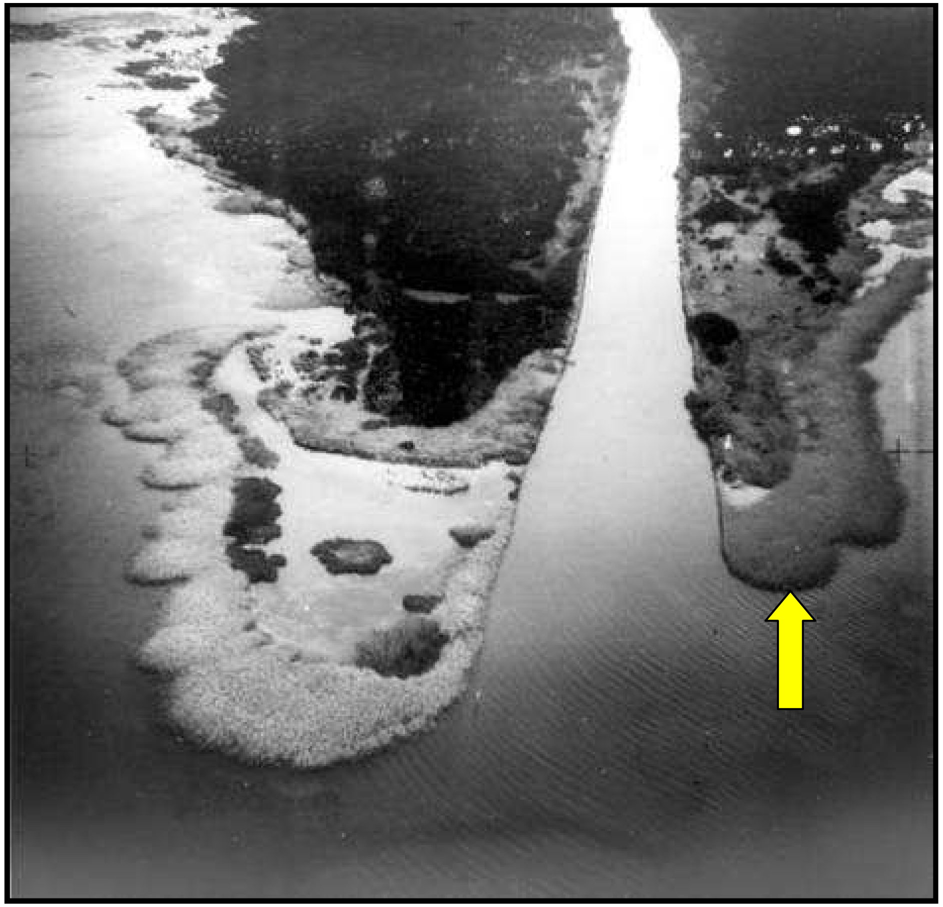


Figure 27: Extent of the fringing sward of Common Reed (Phragmites australis) at the mouth of the Latrobe River, Lake Wellington. The left-hand photograph is an aerial photograph taken in the early 1950s and shows wide and healthy reed beds. The right-hand photographs shows the same part of the Gippsland Lakes in November 2010, and the marked retreat of reed beds from around the western shores of Lake Wellington. The yellow arrows show the two comparable sections of the two photographs. Aerial photograph courtesy of ECF Bird; right-hand photograph by Paul Boon, November 2010.

Clucacs & Ladiges (1980) investigated the loss of *Phragmites australis* from around the Gippsland Lakes and its putative link with increased salinity, and theirs is the most comprehensive study to date. The investigation, based on a BSc(Hons) project, included a field component, where plant performance at a number of sites around the Lakes was compared, and a greenhouse component, in which plants of various providences from different parts of Gippsland were grown under different salinity regimes. For the field survey, plants were collected from Koonwarra (fresh) and Port Albert (saline) in South Gippsland, as well as from two sites in Lake Wellington: Marlay Point and Strathfieldsaye (both brackish). Plants growing at Koonwarra were taller than those from Port Albert, but the shortest of all came from Strathfieldsaye. The conclusion drawn (page 92) was that 'At the sites studied, stand performance is generally correlated with site salinity'… 'Stands growing in areas of high salinity are generally short and sparse; flowering and seed-forming ability are reduced.'

For the greenhouse trials, plants were grown from rhizome cuttings, from shoot cuttings, and from seed. Each of the three different methods had its own limitations. For example, extreme variability in the establishment and subsequent growth of plants derived from rhizome cuttings made it difficult to interpret the results. In the case of experiments with seeds, the time it took for plants to grow to a useful size from seed was a problem. The rhizome-cutting method was finally chosen for the salinity trials, using plant material collected from Koonwarra, Port Albert, and Marlay Point, each grown in salinities of 0, 2, 8 or 16 PSU and in some cases under two water regimes (half waterlogged and fully waterlogged). Poor growth of the rhizomes again limited the usefulness of the investigation, as did complex variations in responses across the various sites and the interaction of salinity and waterlogging regimes in controlling plant performance. The nutrient regime the plants were grown under also influenced their response to salinity, a result that has been observed in many other salinity trials with other plant taxa.

In the case of plant material collected from Port Albert, fully waterlogged specimens grew best in the 0 PSU treatment, and even the 2 PSU treatment decreased plant height by over 50%. In the case of plants taken from Marlay Point, the results depended a great deal upon the water regime, and in half-waterlogged conditions there was little difference in plant height between 0 and 2 PSU, but a very marked decrease in performance at 16 PSU. In fully waterlogged conditions, there was a consistent decrease in plant height with increasing salinity. Plants growing in 16 PSU (which is around half seawater salinity) stopped growing after ~10 weeks, and remained stunted thereafter.

In contrast to the current state, in pre-European times it is likely that many parts of the shoreline of the Gippsland Lakes were fringed with dense, wide and healthy swards of perennial, emergent rhizomatous plants, especially of Common Reed. The situation in other intermittently closed and open coastal lagoons in East Gippsland (e.g. Sydenham Inlet) may provide a model of fringing vegetation in the pre-European Gippsland Lakes (Figure 28).

Figure 28: Swards of Common Reed (Phragmites australis) fringing the shoreline of Sydenham Inlet, East Gippsland. Photograph by Paul Boon, 2008.

Altered hydrological and salinity conditions have also had a marked impacts on the water-column and sediment salinities of the fringing wetlands. The Lake Wellington wetlands are nominally classified as 'permanent deep-water freshwater wetlands' in the State-endorsed system used to classify wetlands in Victoria; 'freshwater' in this typology is indicated by salinities of < 1−3; even so, water-column salinities in one of the largest brackish-water wetlands (Dowd Morass) over the period 2003−2006 (i.e. during the Millennium Drought) have regularly exceeded 15 (Boon *et al.* 2008; Raulings *et al.* 2010, 2011).

Currently only two of the extensive mosaic of fringing wetlands remain fresh: the relatively small Sale Common (~2 km^2), the most upstream of the wetlands included in the Ramsar listing, and the larger Macleod Morass, which is maintained in a fresh condition only because of near-continuous inputs of tertiary-treated sewage from the Bairnsdale Sewage Treatment Plant and the construction of barrage gates at the lower end, which prevent intrusions of saline water from the lower reaches of the Mitchell River. Attempts to rehabilitate now-salinized wetlands around Lake Wellington have been only partly successful (Raulings *et al.* 2007, 2011), in large part because of the risk of further saline intrusions and the activation of potential acid sulfate soils should water levels be dropped to allow flushing flows of fresh waters from the Latrobe River.

5.3 Changes in fringing vegetation – expansion of coastal saltmarsh and other halophytic taxa

Sinclair & Boon (2012) analysed historical records in order to gauge the extent of coastal wetlands before European colonization of Victoria and, using those estimates, to compare them with the present-day inventory of coastal wetlands outlined by Boon *et al.* (2014). They reported that Lake Reeve retained most (~85%) of its pre-European area of coastal marsh, with the exception of one large area claimed for pasture at the western end. The historic record is detailed and shows the vegetation has otherwise changed very little in its extent since the early 19th century. Perhaps the biggest losses have been outside Lake Reeve itself, but included in this sector: early surveyor's maps show extensive patches of 'saltmarsh' between Lake Reeve and Lake Wellington (>750 ha in total; distinguishable from areas labelled 'swamp' and 'tea-tree'). Such areas were clearly not intertidal, but presumably interacted with saline groundwater. Similar patches of 'coastal' marsh lacking tidal connection exist elsewhere (e.g. Lonsdale Lakes). The examples near Lake Reeve have largely been converted to pasture and, in one case, a farm dam.

The case with Lakes Victoria and King are quite different. The model outlined by Bird (1966) was broadly supported by the results of Sinclair & Boon (2012), which showed strong evidence of dieback of the fringing freshwater and brackish-water wetland systems. Nonetheless, the historic record shows clearly that saltmarsh was present and extensive around Lakes Victoria and King in the early 19th century. Saltmarsh or salt lakes apparently occurred naturally right around the lakes: maps show them in Victoria Lagoon and the surrounding depressions, in Jones Bay (Wilkinson 1849), around Loch Sport, Beacon Swamp, Blond Bay, Point Wilson, near Paynesville, on the Mitchell Silt Jetties, on Raymond Island, and on the Boole Boole Peninsula.

As noted in the paper by Sinclair & Boon (2012), two scenarios are shown for the change in coastal marsh area in Lakes Victoria and King. Under Scenario 1, they estimated that there were 4,940 ha of non-mangrove marsh prior to European colonization. About 80% remains today. Under Scenario 2, however, the pre-European estimate fell to 2,510 ha and thus there appears to have been a very substantial increase in the area of saltmarsh (of the order of~1,500 ha) in this part of the Gippsland Lakes. It would thus appear that saltmarsh has expanded in some places around the Gippsland Lakes, remained static in others, and decreased in others. Direct losses of coastal saltmarsh, caused by local land-claims, have in comparison been minor. There is thus some uncertainty as to whether some large expanses of marsh are remnant or adventives.

Like Lakes Victoria and King, Lake Wellington and its fringing wetlands have also been strongly influenced by the opening of the artificial entrance to the ocean at Lakes Entrance (Boon *et al.* 2008, Raulings *et al.* 2010). Bird (1966) suggested that Lake Wellington was once essentially a freshwater lake, and that the saltmarsh on its margins has invaded recently, replacing prior freshwater systems. The historical record partially supports this view. One early map from the 1840s showed Lake Wellington as 'fresh' (Lake Reeve was shown 'Salt'; Lakes Victoria and King are unannotated). In contrast, other early sources of roughly the same time showed very extensive areas of saltmarsh interlaced with 'tea tree' and 'swamp' on the southern margins of Lake Wellington (and Lake Coleman), and in many depressions inland between Lake Wellington and Lake Reeve. In his more-detailed 1965 study used as a basis for the 1966 synthesis, Bird acknowledged the natural (more inland) occurrence of these saltmarsh areas. There is, however, no evidence for an extensive pre-European occurrence of saltmarsh on the western and northern shores of Lake Wellington, which suggests that it has expanded its overall area on this part of the coast.

As for Lakes Victoria and King, Sinclair & Boon (2012) provided two scenarios for Lake Wellington in order to account for several large periods of uncertain history. There was a substantial difference in the areas of pre-European coastal marsh yielded by the two approaches: Scenario 1 gave an estimate of 5,560 ha, whereas Scenario 2 yielded a much lower value of 480 ha. Which of the two scenarios is employed has a major impact on the amount of coastal marsh estimated to be lost (or gained) since the middle of the 19th century.

6. Fringing vegetation and shoreline protection

6.1 The protective role of fringing vegetation

Three recent studies of the global literature ('meta-analyses') have shown convincingly that fringing vegetation, especially if dense and wide, makes coastal shorelines less susceptible to erosion and to damage by storm surges, and potentially even to tsunamis (Prasetya 2006; Gedan *et al.* 2008; Shepard *et al.* 2011). These overviews are consistent with a number of other assessments from elsewhere in the world which show the protective role that fringing vegetation can play. French (1997), for example, showed that coastal wetlands in the United Kingdom provided a critical valuable ecosystem service by protecting land against erosion and that many of those benefits were lost when hard engineering approaches, such as the construction of rock walls, were employed in their place.

Because it is a robust, emergent, perennial, clonal species with a wide hydrological niche (Roberts & Marston 2011; Rogers 2011), Common Reed has been the subject of a number of investigations, world-wide, into the role played by fringing vegetation in protecting shorelines against erosion. Coops *et al.* (1996), for example, showed that in revegetation trials in The Netherlands, *Phragmites australis* not only proved relatively immune to uprooting by waves but also 'influenced the erosive impact of waves by both sediment reinforcement and wave attenuation. A smaller amount of net erosion was measured in the wave-exposed sections covered by vegetation than in the unplanted sections'. Similar results have been reported in other parts of Europe (e.g. Phillips 1987 in England; Caffrey & Beglin 1994 in Ireland; Horppila *et al.* 2012 in Finland) and, in some locations (e.g. the Atlantic coast of France), the loss of fringing reed beds and their associated protection of the shoreline is viewed with alarm (Guillou 2010). Du *et al.* (2011) reported that beds of *Phragmites australis* provided the best protection (of a number of alternative plant communities) against shoreline erosion around Chongming Island, China. In southern Africa, Kotschy & Rogers (2008) reported that the clonal characteristics of *Phragmites mauritianus* helped it survive disturbance in a semi-arid river, and in the Widden brook, a tributary of the Hunter River in New South Wales, Erskine *et al.* (2012, page 102) reported that the 'establishment of stonoliferous and rhizomatous clonal grasses (*Phragmites australis*, *C. dactylon*, *P. distichum*, *P. clandestinum*)[5] is important in inducing sedimentation …'.

6.2 Re-instating fringing vegetation to protect coastal shorelines

Threats to fringing vegetation and coastal wetlands of the Gippsland Lakes

Many reasons have been outlined for the loss and degradation of wetlands in Australia (Finlayson & Rea 1999) and a number of reviews have recently outlined, in general terms, the threats faced by coastal wetlands in particular (Laegdsgaard 2006; Laegdsgaard *et al.* 2009; Thomsen *et al.* 2009; Morrisey *et al.* 2010; Boon 2012; Boon *et al.* 2014). As they have tended to have either a national focus or an emphasis on systems in warm-temperate or sub-tropical parts of the eastern seaboard, these reviews should be viewed as complementing the assessments of threats specific to the Gippsland Lakes in Sections 4 & 5 of this report.

Boon *et al.* (2014) semi-quantitatively assessed threats to Victorian coastal saline wetlands, and Table 3 shows the sections of that review specific to the Gippsland Lakes. The range of threats assessed in that investigation included land-claim ('reclamation'), landfill and spoil deposition, stormwater input, shell-grit mining, salt production, waste-water treatment ponds, vehicular access, stock grazing, access by exotic animals such as deer, goats and pigs, weed infestations, *Spartina* infestation, inappropriate rehabilitation, inappropriate recreational activities, boat-wash effects, over-development of surrounding land, mowing of grassy saltmarsh, and the existence of landward barriers (artificial, land-use related, or topographic). Threats were scored in terms of perceived intensity of impact (high, medium, or low) and its spatial distribution (local or widespread).

The intensity of likely climate-change impacts (e.g. arising from sea-level rise or storm surges) is not scored in Table 3, as it was assumed to be universal along the coast; nevertheless, whether impacts were likely to be local or widespread was assessed. Two recent reviews (Finlayson *et al.* 2013; Saintilan & Rogers 2013) have addressed the issue of climate-change impacts on Australian wetlands and coastal aquatic systems. In the case of the Gippsland Lakes, existing pressures on coastal wetlands and fringing vegetation will be further exacerbated by chronic sea-level rise and increasing storm-surge impacts, and the resultant likelihood of on-going salinization of the site (e.g. see McInnes *et al.* 2005). Sea-level rise and the salinization of formerly freshwater systems is an issue faced by a number of other Ramsar sites in Australia, most obviously Kakadu National Park in the Northern Territory (Finlayson *et al.* 2013).

[5] Full species names of these abbreviated taxa are *Cynodon dactylon* (Bermuda Grass or Couch), *Paspalum distichum* (Knotgrass) and *Pennisetum clandestinum* (Kikuyu)

Table 3: Threats facing coastal saline wetlands (specifically, saltmarshes) of the Gippsland Lakes region. The intensity of impact is colour-coded red (high), orange (medium), or yellow (low); the letters 'l' and 'w' within a cell refer to whether the impact is evident only locally (l) or widely (w). '?' indicates uncertainty as to impacts in that sector. The final three columns are uncoded because the likely intensity of impact from threats associated with sea-level rise was not assessed. Source: extracted from Boon et al. *(2014, Table 5).*

Coastal sector	**Land-claim**	**Landfill and spoil**	**Tidal restriction**	**Stormwater input and**	**Shell-grit mining**	**Salt production**	**Treatment ponds**	**Vehicle access**	**Stock grazing**	**Deer, goats, pigs**	**Weeds**	***Spartina***	**Inappropriate**	**Inappropriate**	**Boat wash**	**Surrounding**	**Mowing**	**Landward barrier**	**Landward barrier (land**	**Landward barrier**
Lake Reeve	l	l	l	.	.	.	.	l	l	l	l	.	.	.	.	l	.	l	w	.
Lakes Victoria & King	l	.	.	.	.	.	.	l	l	l	l	.	.	l	l	.	.	l	w	l?
Lake Wellington	l	.	l	.	.	.	.	l	l	l	l	.	.	.	l	.	.	w	w	l

Revegetation options

As a result of the protective roles played by fringing vegetation against shoreline erosion, it is commonplace for trials to be undertaken in attempts to re-instate vegetation from where it has been lost. Guidelines have been prepared by Frankenberg (1997) for the establishment of *Phragmites australis* beds along inland rivers in south-eastern Australia to provide erosion control, where revegetation efforts have been underway for many decades. In Lakes Alexandrina Albert, on the lower River Murray in South Australia, the tall emergent macrophyte *Schoenoplectus validus* (= *S. tabernaemontani* in Victoria) is currently being planted to provide floristic and habitat diversity and to protect the shorelines against erosion (Nicol *et al.* 2014).

The trial options paper for controlling shoreline erosion in the Gippsland Lakes by Storer (2006) did not include revegetation as a remediation mechanism (despite, in section 4, finding that 'vegetation at all trial sites is in decline due to salinity or erosion'), opting instead for a suite of engineering options. In contrast, the assessment of Sjerp *et al.* (2002) recommended revegetation of both terrestrial and of water-dependent fringing vegetation around the Gippsland Lakes. Terrestrial vegetation, involving the establishment of native species on eroding beaches and foreshores, was recommended as a tool to slow the rate of erosion rather than as a mechanism for halting it completely. Sjerp *et al.* (2002) recognized that, without revegetation of the fringing reedbeds, terrestrial revegetation alone would be only marginally successful. The re-establishment of dense, wide and healthy beds of aquatic macrophytes was recognised as being critical to controlling shoreline erosion and the success of terrestrial revegetation in the near-shore hinterland.

Sjerp *et al.* (2002) recommended that artificial protection against wave action would probably be necessary to facilitate the establishment of fringing vegetation, but no single engineering approach to provide the necessary quiescent conditions could be identified. They recommended too against planting of *Phragmites australis*, on the basis that it was insufficiently salt-tolerant. Mangroves *Avicennia marina*, Sea Rush *Juncus kraussii*, Cumbungi *Typha* spp. and even the exotic Cordgrass *Spartina* and the salt-tolerant *Phragmites karka* (from Asia) were considered as alternatives, but dismissed on various grounds. Today it is unlikely that anyone would seriously consider exotic taxa as the solution to shoreline erosion, given the ubiquitous and near-insoluble problems created by alien plant species in coastal wetlands (Boon *et al.* 2014). Sjerp *et al.* (2002, page 34) concluded that '… no single macrophyte species replicates the role of *Phragmites australis* and the implementation of aquatic revegetation using species indigenous to the Gippsland Lakes is unlikely to prove successful.'

This may be too pessimistic a conclusion. *Phragmites australis* collected from around Lake Wellington is quite salt-tolerant (Morris *et al.* 2008), and it is possible that genotypes with even greater salt tolerance can be found, isolated, and cultured from more saline parts of the Gippsland Lakes or from nearby areas in East Gippsland (e.g. the lower reaches of the Snowy River). Some preliminary analysis has been undertaken of the genetic diversity in *Phragmites australis* around the Gippsland Lakes (Hurry *et al.* 2013; James *et al.* 2013), and the presence of specific genes indicating salt tolerance in this species is the subject of an associated investigation, by Paul Boon and Elizabeth James from the Royal Botanic Gardens, Melbourne. Moreover, revegetation trials undertaken in the salinized Dowd Morass showed convincingly that *Phragmites australis* could establish quickly and successful from self-seeded individuals, if elevated bare ground were provided, free of grazing pressure (Figure 29). Microtopographic relief was critical to the success of these revegetation efforts (Raulings *et al.* 2011; Boon 2011).

Figure 29: Revegetation trials in Dowd Morass. The left-hand photograph shows the construction of elevated earthern banks in 2006 and the planting of Swamp Paperbark (Melaleuca erificolia) seedlings. The right-hand photographs shows the outcome four years later, in July 2010, with the successful take of the paperbark seedlings and, possibly more importantly, the establishment of swards of Common Reed (Phragmites australis) via seed blown in from nearby stands. Photographs by Paul Boon.

7 The next steps

This review has covered the existing literature, both from published sources and from unpublished consultants' reports, on the form and evolution of the Gippsland Lakes, the variety of vegetation that fringes the Lakes' shorelines, and the way both have changed since European colonization of the Gippsland region.

The next step in the first stage of the broader study, *Fringing vegetation and its geomorphological importance for the Gippsland Lakes shoreline*, is to undertake a detailed survey of different parts of the shoreline in order to:

- Describe shoreline geomorphology at a wide range of sites around the Gippsland Lakes
- Characterize the fringing (water-dependent) vegetation at these sites
- Assess the ecological value of this vegetation
- Account, where possible, for any changes in shorelines or in vegetation since European colonization
- Determine any relationship between lake or river-water salinity and shoreline geomorphology and fringing vegetation
- Determine whether a freshwater subsidy is responsible for fringing vegetation occurring along the more saline shorelines, from which it would be otherwise be excluded by high salinity
- Determine whether Common Reed collected from saline sites is more salt-tolerant than plants collected from fresher sites.

The second stage, *Genetic identification of salt-tolerant strains of Phragmites australis (Common Reed) for use in revegetation projects around the Gippsland Lakes*, will determine whether there is a genetic basis to any difference in the salt-tolerance of different strains of Common Reed and the extent to which clones from different sites are genetically related.

The two studies, taken together, will be used to provide more detailed advice on possible revegetation strategies for the shoreline of the Gippsland Lakes and the lower parts of the rivers that flow into it.

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