2 Regional overview

This chapter provides the biophysical context for the Corangamite region as a synopsis of the physical and environmental elements considered relevant to the origins and distribution of salinity. Sources of the data are identified and their genesis explained where the data sets have been generated specifically for this research. The review of previous work assists in clarifying the research questions addressed in this thesis.

2.1 Physiography and drainage

The physiography of the Corangamite region is categorised into regions according to its geography and landform (Figure 2.1). The northern portion is generally referred to as the Central Highlands or Midlands (Hills 1940) and comprises the southern slopes of the Great Dividing Range which forms the watershed between the South East Coast Division and the Murray Darling Division of the Australian Drainage Divisions (GA 1997). The central portion comprises the Western District Plains or Victorian Volcanic Plains which are low undulating plains with numerous lakes and wetlands. The southern portion comprises the Coastal Plain or Heytesbury region in the west, the mountainous Otway Ranges and foothills in the south, and the undulating Barrabool Hills and Bellarine Peninsula in the east.

The highest elevations in the Corangamite region are in the north, with the volcanic cones of Mt Buninyong (745 m), Mt Warrenheip (741 m), and Tipperary Hill (743 m) rising above the axis of the drainage divide along the northern eastern boundary (740 m maximum). In general, the landscapes of the northern highlands are characterised by undulating low hills dissected by a dendritic drainage pattern that forms the upper catchments of the Moorabool River, Leigh River, and Woady Yaloak River drainage systems. The primary drainage trends parallel to the strike of the bedrock strata and the secondary drainage is controlled by geological boundaries (i.e. lithological boundaries) and rock structures (i.e. faults, joints). The Otway Ranges in the south rise to 686 m (Mt Cowley) and have developed more rugged topography comprising ridges and spurs separated by deeply dissected steep valleys. The drainage is strongly controlled by the geological structure. Drainage on the south and eastern slopes forms short but deeply incised rivers which drain to the Southern Ocean, and the northern and western slopes drain to the Barwon River and Gellibrand River systems.

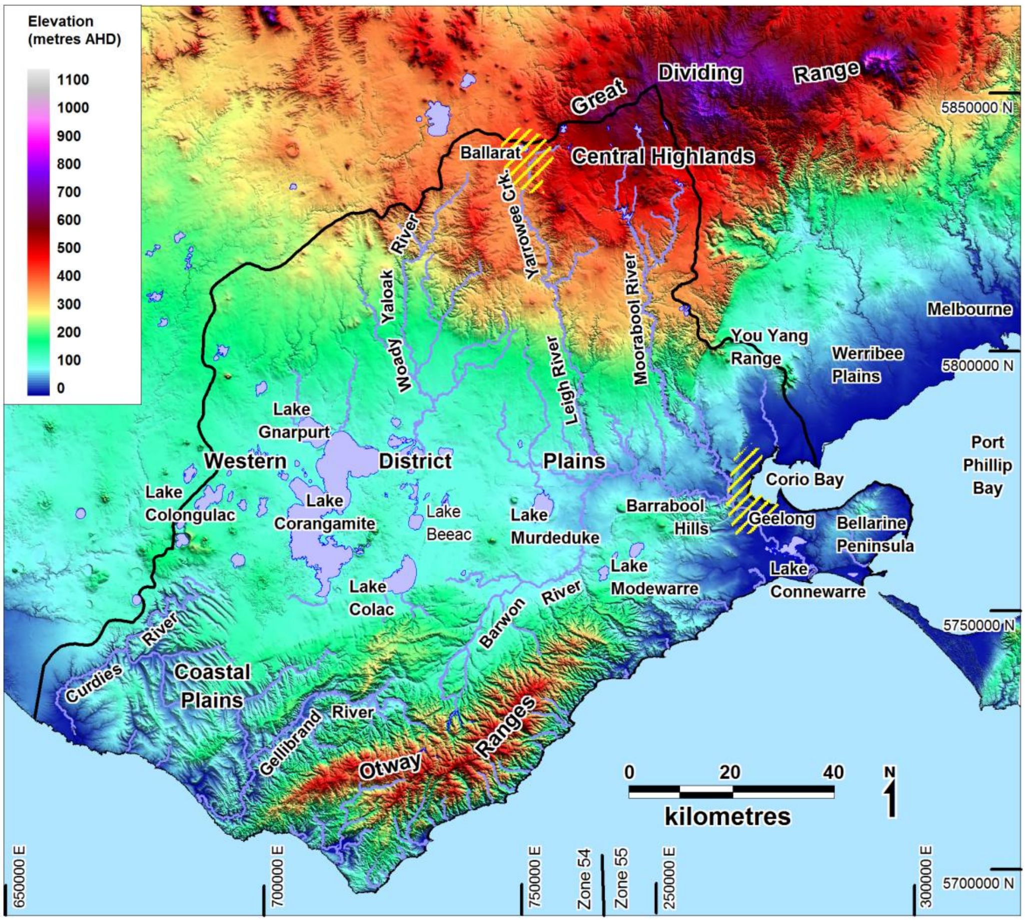


Figure 2.1 Physiography of the Corangamite region

Four Drainage Basins lie within the Corangamite region (GA 1997), *viz:* Barwon River (Basin 33), which includes the Barwon and Leigh rivers; Lake Corangamite (Basin 34) which includes the Woady Yaloak River system; and Otway Coast (Basin 35) which includes the Curdies and Gellibrand rivers; and almost all of the Moorabool River (Basin 32), apart from the Little River catchment in the far east (Figure 2.2).

Figure 2.2 Drainage basins of the Corangamite region

Over 1500 lakes and wetlands are a feature of the region, including the internationally significant Lake Corangamite, Lake Gnarpurt, Lake Connewarre, Lake Murdeduke, Lake Colac, Lake Colongulac and Lake Beeac.

2.1.1 Physiography and drainage data sources

2.1.1.1 Terrain data

Due to the unavailability of a regional digital elevation model (DEM) at the commencement of this research, a model (Figure 2.1) was constructed using the 10m contours and spot heights featured on the 113 published 1:25,000 VicMap topographic maps for the Corangamite region. The model was hydrologically enforced and the estimated accuracy for 90 % of the data is ±22.5 m horizontal and ±5 m vertical. The digital processing was completed by Tony Davidson, Geographic Information System (GIS) consultant, Hobart, Tasmania, and the details of the model construction and calibration are appended (Appendix B).

As the research progressed, more accurate DEM data became available through projects initiated by the Corangamite CMA. These data were collected using airborne Light Detection and Ranging (LIDAR) technology, which resulted in vastly improved accuracy and resolution of the DEM. The first of the LIDAR data was collected across the Western District Plains in 2003 and the data supplied as raw x,y,z data files that were processed (by this author) into a numeric surface using 1 m x 1 m grid spacing. A series of subsequent LIDAR surveys were flown in 2007 & 2008, some with very high accuracy (±1m horizontal and ±0.1m vertical). These data were generally supplied as a regularly spaced x,y,z data files (i.e. interpolated x,y,z points) which were converted to GIS grid formats by the author. One difficulty with the higher resolution data is the size of the datasets (approximately 600 Gigabytes total), which limited the manipulation of the data to tiles (either 5 km x 5 km or 2 km x 2 km). The resulting coverage of high resolution DEM is illustrated in Figure 2.3.

More details on the collection and quality assurance of the LIDAR data are appended (Appendix B).

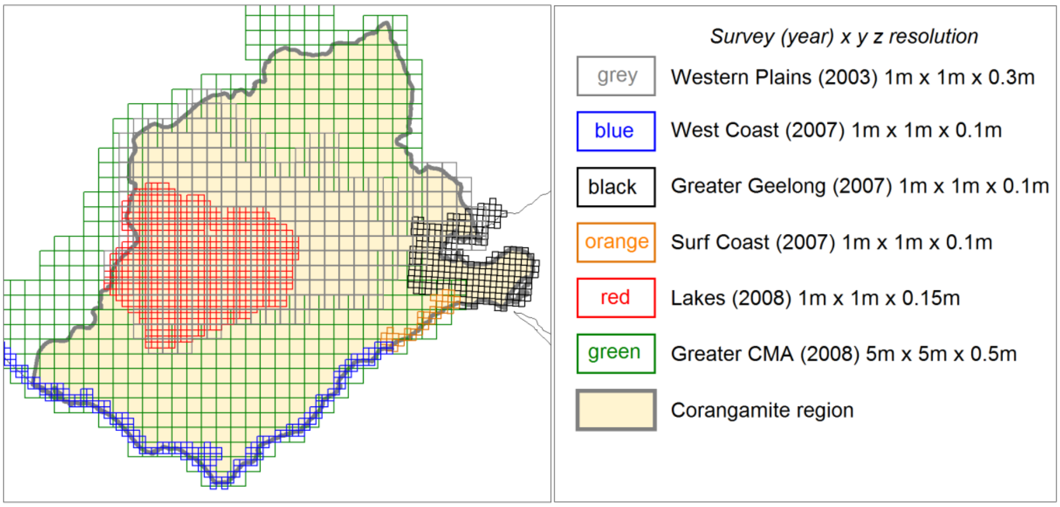


Figure 2.3 LIDAR data available for the Corangamite region

2.1.1.2 Drainage basins, rivers and streams

GIS polygons for Australian Drainage Divisions and Basins were obtained from GeoScience Australia (GA 1997). Rivers, streams, lakes, reservoirs, dams, wetlands, swamps and areas subject to inundation were sourced from the 113 1:25,000 VicMap topographic maps for the Corangamite region and manipulated into separate GIS layers. Some miscellaneous hydrological GIS data (Water Supply Protection Areas, gauging station locations, etc.) were also sourced direct from the Department of Sustainability and Environment (DSE) corporate data library.

2.1.1.3 Stream gauging data

Stream gauging data was obtained from the Victorian Water Resources Data Warehouse (DSE 2009b) by the various consulting companies contracted by DSE to supply the data. The warehouse is the repository for data collected under the Victorian Water Quality Monitoring Network (VWQMN). Use of this data is detailed in Chapter 3.

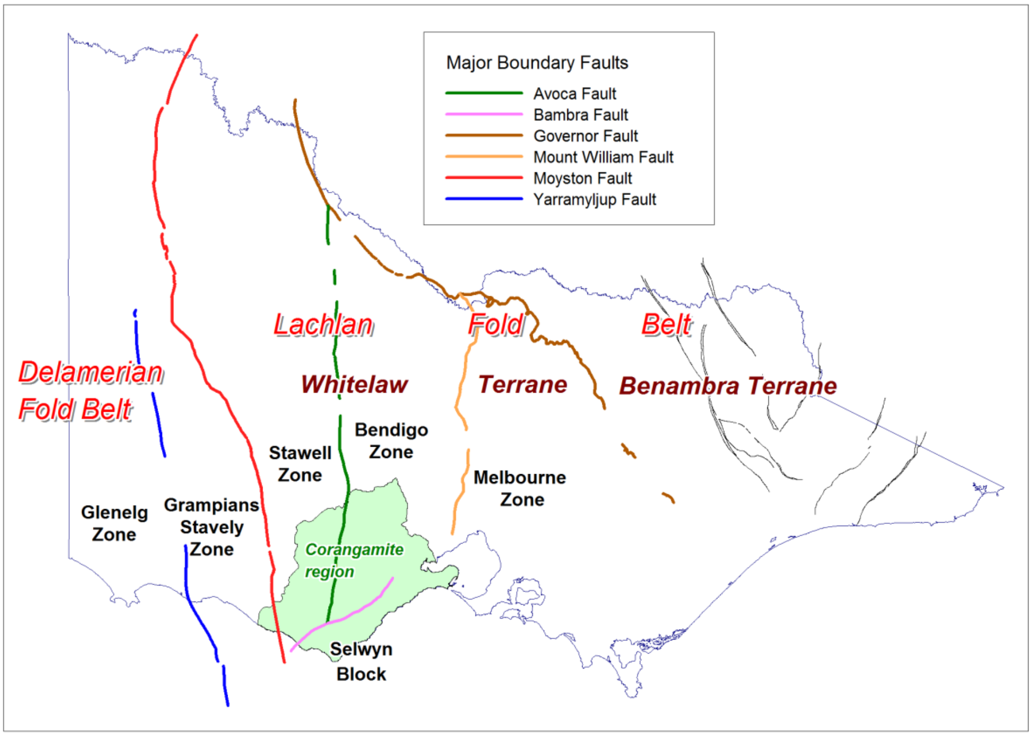
2.2 Geology

This synopsis of the geology of the Corangamite region is presented in two parts, *viz:* the structural framework and the geological evolution of the region. The intention is to provide a whole of region overview. More detailed descriptions of individual geological formations and units are provided in the thesis chapters where they are relevant to the research conducted in specific locations.

2.2.1 Structural evolution and framework

The following description is largely summarised from VandenBerg et al. (2000) and Birch (ed.) (2003).

In relation to the Palaeozoic structural framework of Australia, the Corangamite region lies wholly within the Tasman Fold Belt System which comprises those rocks accreted to the eastern margin of the Australian craton during Phanerozoic orogenesis (VandenBerg et al. 2000). In western Victoria, the major fault zones are used to divide the structural ranking (Figure 2.4). Two fold belts (Delamarian and Lachlan), one terrane (Whitelaw) and three structural zones (Grampians-Stavely, Stawell, and Bendigo) lie within the boundaries of the Corangamite region.



(after VandenBerg et al., 2000)

Figure 2.4. Major structural zones of Western Victoria

2.2.1.1 Fold belts

The Moyston Fault, one of the largest in the Tasman Fold Belt System, forms the boundary between the Delamarian Fold Belt and the Lachlan Fold Belt (Cayley and Taylor 1998). Although not seen at the surface within the Corangamite region, the Delamarian Fold Belt mainly comprises the Neoproterozoic-Cambrian rocks deformed in the Late Cambrian Delamarian Orogeny. Only the extreme south west corner of the Corangamite region is underlain by the Delamarian basement and the majority lies within the Lachlan Fold Belt, comprising mainly Cambrian to Devonian rocks deformed during several orogenic events from the Late Ordovician to the Carboniferous.

2.2.1.2 Terranes

The Lachlan Fold Belt Rocks within the Corangamite region form part of the Whitelaw Terrane, which has its boundary in eastern Victorian at the Governor Fault. The Whitelaw Terrane is characterised by northerly structural trends, resulting from east-west compression in a series of orogenic episodes from the Late Ordovician to Middle Devonian (VandenBerg et al. 2000). In the east, Silurian to Devonian sediments of the Whitelaw Terrane were deposited onto the Selwyn Block, a north-dipping basement of Neoproterozoic – Cambrian rocks which fits with the western Tasmanian Palaeozoic terrane of rocks deformed during the Late Cambrian Tyennan Orogeny. The Governor Fault bounds the eastern edge of the Selwyn Block. South of the Bambra Fault the Cretaceous Otway Group rocks probably lie directly on the Selwyn Block.

2.2.1.3 Structural Zones

The Grampians-Stavely structural zone forms the eastern margin of the Delamarian Fold Belt and underlies the extreme south western corner of the Corangamite region (Figure 2.4). The basement rocks are interpreted as low-grade metasedimentary rocks, such as black slates and quartz-rich turbidites (VandenBerg et al. 2000).

Apart from the south west corner, the western half of the Corangamite region is underlain by rocks of the Stawell Zone, which is bounded by the Moyston Fault on the west and the Avoca Fault on the east. The Stawell Zone is interpreted as a thin-skinned fold and thrust belt composed of Cambrian oceanic volcanics overlain by Cambro-Ordovician turbidites, which were derived from the Delamarian Fold Belt. Along the western margin, the Lachlan Fold Belt was thrust over the Delamarian Fold belt, resulting in a 15 km wide metamorphic complex in the hanging wall of the Moyston fault. Across the zone the structures are complex, resulting from major deformation early in the Benambran Orogeny. The majority of the rocks exposed at the surface are the sandstones and mudstones of the St Arnaud Group, comprising thick Cambro-Ordovician turbiditic sediments which were folded along north-south axes. Post-tectonic intrusion of I-type granites occurred in the Upper Devonian.

The eastern portion of the Corangamite region lies within the Bendigo Zone, bounded by the Avoca Fault on the west and the Mount William Fault on the east. The majority of the Bendigo Zone rocks are turbiditic sediments of the Ordovician Castlemaine Group, deformed into tight chevron folds by east-west compression. The main deformation has been interpreted as a thin-skinned fold and thrust belt formed in the Late Ordovician to Early Silurian, at the commencement of the Benambran Orogeny. The sandstones and mudstones of the Castlemaine Group are exposed at the surface in the northern upland area of the Corangamite region. The Castlemaine Group rocks were intruded by granites during magmatic activity in the Late Devonian.

Rocks of the Melbourne Zone may form the basement of the Bellarine Peninsula, but it remains unknown. In the Barrabool Hills, near Geelong, a small outcrop of metagabbro, the Ceres Gabbro, has been interpreted as an outcrop of the Neoproterozoic Selwyn Block (Morand 1995). The metagabbro is overlain by Cretaceous sediments and it is assumed that a similar relationship occurs further east, under the Bellarine Peninsula (Dr Vincent Morand 2008 pers. comm.).

2.2.1 *Geological development of the region*

This section provides a brief summary of the geological evolution of the Corangamite region to provide the context for the spatial distribution of the surface geology (Figure 2.5), the geomorphology (section 2.3) and the distribution of the hydrogeology (section 2.6). It has been largely summarised from the latest edition of The Geology of Victoria (Birch 2003) and those additional references cited throughout.

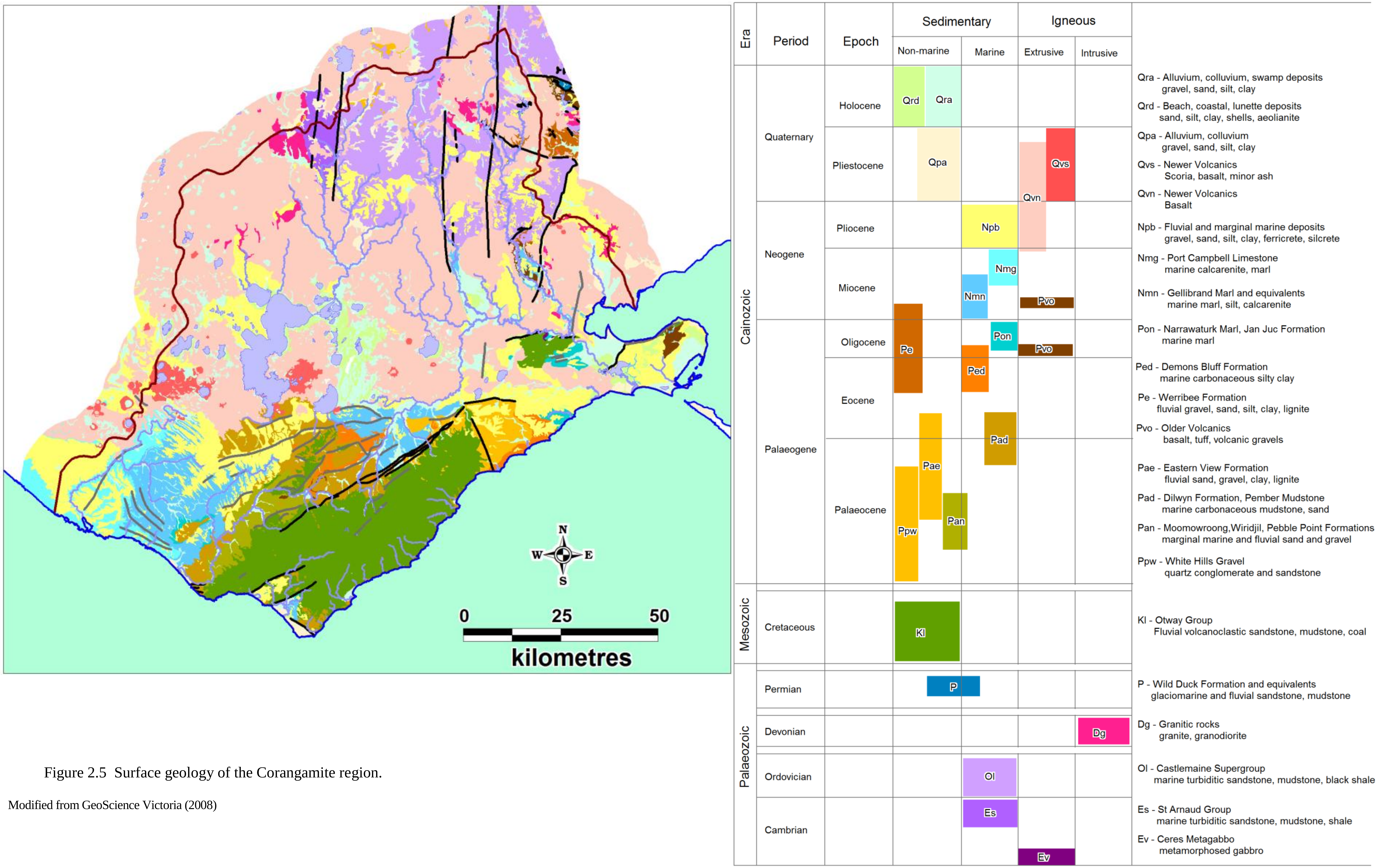


Figure 2.5 Surface geology of the Corangamite region.

Modified from GeoScience Victoria (2008)

2.2.1.1 Palaeozoic

At the commencement of the Palaeozoic, the majority of the Corangamite region lay within the ocean basins off the eastern edge of the Australian craton, which formed part of Gondwanaland. In the Late Cambrian, the Delamarian Orogeny folded, faulted and regionally metamorphosed the rocks of the Grampians-Stavely Zone to form the Delamarian Highlands, adjacent to the western boundary of the Corangamite region. At the same time the Tyennan Orogeny affected the Neoproterozoic rocks of the Selwyn Block, which now underlies the eastern and southern parts of the region.

The Delamarian Highlands provided the source for extensive deposition of sediments from the Late Cambrian to the Upper Ordovician, which covered the Cambrian thoeleiitic volcanics of the ocean floor. The sediments were deposited as turbidites in a deep marine environment along the edge of the Australian (Gondwana) craton. The sediments form a remarkably monotonous sequence of turbidites which extend across much of the Lachlan Fold Belt. The Cambrian sediments – the St Arnaud Group – outcrop west of the Avoca Fault, in the Stawell Zone. The Ordovician sediments – the Castlemaine Group – widely outcrop in the Bendigo Zone. The distinction between the two groups is on the basis of fossil (graptolite) content. East of the Avoca Fault, the turbidites are unfossiliferous, contain Delamarian zircons (Williams et al. 1994), and are assumed Cambrian in age, whereas west of the Avoca Fault, the turbidites are similar in character to fossiliferous Ordovician sediments further north (Fergusson and VandenBerg 2003).

The turbidite sequences comprise quartz-rich sandstone and mudstone with minor granule conglomerate and black shale. The St Arnaud Group rocks and the base sequences of the Castlemaine Group generally lack black shale beds, since the overall sediment transport was from the west. In general, the Castlemaine Group contains more thick beds, with sandstone dominated facies metres to tens of metres thick, intercalated with similarly thick mudstone facies.

The turbidite fan sediments were regionally deformed by the Benambran Orogeny, a relatively long-lived event that began in the Upper Ordovician. The evidence for deformation is largely based on field mapping and the dating of metamorphic mica growth. The orogeny was caused by east-west convergence, between the Selwyn Block to the east and the margin of the Delamarian Fold Belt to the west. The east-dipping Moyston fault formed along the western edge of the Stawell Zone as the Cambrian ocean-floor volcanics and turbidites were thrust over the Delamarian margin. Further east, thin-skinned tectonic deformation produced major listric faults, the most significant of which - the Avoca Fault – separates the Stawell Zone from the Bendigo Zone. The Avoca Fault Zone is a west-dipping thrust which brought slivers of the Cambrian sea floor volcanics to the surface. Away from these major faults, large upright folds developed, disrupted by reverse faults with throws of hundreds of metres (Taylor et al. 1996).

The majority of the deformation in the Corangamite region (Stawell and Bendigo Zones) had probably occurred by the Mid Silurian, resulting in substantial shortening and thickening of the turbidite sediments through thrusting, folding, cleavage development and faulting. The deformation was also responsible for the injection of quartz veins (hydrothermal emplacement) mostly into the spaces created by the faulting and folding. Some mineralisation accompanied the quartz emplacement, including gold, sulphides and carbonates.

By the end of the Silurian, the rocks had been accreted to the edge of the Australian (Gondwana) craton. The regional metamorphism is generally low grade (greenschist facies or lower), except in a 15km wide zone along the western edge of the Stawell Zone, where the higher grades occur in the hanging wall of the Moyston Fault. During the Early Devonian, intrusion of post-tectonic granites occurred in the Stawell and Bendigo Zones, although outside of the Corangamite region. The thermal history of these intrusions suggests that several kilometres had already been eroded off the regionally deformed and uplifted Cambro-Ordovician turbidites by the time of their emplacement.

The next significant event recorded in the Palaeozoic rocks of the region is the Mid Devonian Tabberabberan Orogeny, which had little effect on the rocks of western Victoria. The orogeny reactivated Benambran faults, generated some new brittle fault structures and produced some kinking and cleavage formation in the eastern edge of the Bendigo Zone. Following the Tabberabberan Orogeny, Late Devonian post-tectonic granitic magmas intrusions were emplaced across the Stawell and Bendigo Zones. These intrusions mark the last tectonic events of the Palaeozoic and cut across all the regionally developed structural fabrics and mineralised faults.

A long period of tectonic stability existed throughout the late Palaeozoic and early Mesozoic. By the Late Carboniferous and Early Permian this part of Gondwana lay close to the South Pole and was subjected to glaciation. Remnants of glacial, glaciofluvial, glaciomarine and shallow marine sediments have been preserved in down faulted blocks adjacent to the north east boundary of the Corangamite region (O'Brien et al. 2003).

2.2.1.2 Mesozoic

During the early Mesozoic, western Victoria was subjected to extensive denudation, recognised as the Mesozoic palaeosurface. Northwest of the Corangamite region, remnants of the Mesozoic palaeosurface form plateaus (Mount Cole, Mount Lonarch and Mount Avoca) close to the roof level of some of the Late Devonian granites, which suggests that erosion stripped at least two kilometres from the surface (Cayley and McDonald 1995).

The commencement of the Australian – Antarctica split in the final Gondwana break-up was marked in western Victoria by a mafic dyke swarm. Ultramafic (Lamprophyre) dykes were intruded during the Late Jurassic, including one near the Moorabool River at Meredith with a K-Ar age of 167±8 Ma (McKenzie et al. 1984; Duddy 2003). The dykes are related to crustal tension which developed a series of half-grabens separated by Palaeozoic basement highs in the southern portion of the Corangamite region. The majority of these east to north-east trending half-grabens are bounded by north-dipping normal faults on their southern margins and numerous minor south-dipping faults on their northern margins. However, east of Port Campbell, the fault polarity changes and is attributed to the influence of the pre-rift structures of the Palaeozoic basement (the Moyston fault?) (Edwards et al. 1996).

The Mid Cretaceous subsidence of the rift was accompanied by kilometre-scale uplift of the Palaeozoic rocks in the north of the region, creating rapid erosion and incision (Duddy 2003). Large debris fans formed at the base of the Palaeozoic slopes (Edwards et al. 1996). The rejuvenated drainage deeply dissected the Mesozoic palaeosurface and a drainage divide, which is a precursor to the present Great Dividing Range, developed parallel to the present coast (Taylor et al. 1996; Holdgate et al. 2006).

Following a minor depositional break in the Early Cretaceous, subsidence and sedimentation resumed in the south of the Corangamite region, although the major transport direction was now from the east. Large high-energy braided river systems deposited a massive volume of volcanolithic sediments, derived from large volcanoes to the east of Victoria (Edwards et al. 1996; Duddy 2003). These thick sediments of the Lower Cretaceous are exposed as the Otway Group sandstones and mudstones which form the present day southern upland areas of the Corangamite region.

As the sea-floor spreading developed, oceanic crust had developed by the Late Cretaceous and a narrow sea formed which cut the supply of volcanolithic sediment. Significant uplift of the Otway Ranges occurred at the start of the Late Cretaceous prior to the first marine incursion and deposition of the Sherbrook Group sediments within the Early Cretaceous troughs (Duddy 2003). The reduced sediment supply was mainly from the rejuvenated erosion of the Palaeozoic highlands to the north, and three major depositional basins – the Gippsland, Bass and Otway Basins – developed as subsidence occurred in discrete regions (Edwards et al. 1996).

The depositional environments of the Late Cretaceous Sherbrook Group sediments in the Otway Basin suggest that the marine transgression commenced in the west with littoral, deltaic and tidal environments giving way to shallow estuaries and marginal marine environments. The marine transgression was at its peak by 85 Ma, when deep marine environments persisted. A rapid marine regression followed, during which extensive deposition of fine-grained deltaic sediments was recorded, which progressively gives way to fluvial sediments as the delta prograded into the basin. This phase of deposition was terminated by widespread uplift at about 65 Ma (Edwards et al. 1996).

2.2.1.3 Cainozoic

By the early Tertiary the renewed erosion of the Mesozoic palaeosurface in the north of the Corangamite region had created broad valleys of scree, outwash and braided river deposits between meridional ridges of Palaeozoic bedrock. The elevation and position of the remnant gravels suggests that the Mesozoic palaeosurface had been dissected to depths of 500 to 700 m by the early Tertiary, creating a topography which persisted in its general form throughout the Tertiary (Taylor et al. 1996; Holdgate et al. 2006).

In the Otway Basin, extensional faulting continued as the continent moved north and major subsidence and marine transgression deposited a series of sediments – the Wangerrip Group – in the Port Campbell Embayment and Colac Trough (Holdgate and Gallagher 2003). Initially, a gently undulating, seaward sloping plain which had had formed by the early Tertiary was covered by sediment brought down by rivers from the north. These deposits of fluvial gravels were reworked along the coast to form coastal sands. As the marine transgression proceeded, marginal marine and then deep water sediments followed (Edwards et al. 1996).

By the Early Eocene large deltaic sedimentary systems had developed in places, depositing sands and gravels from the north. As the delta prograded, the environments of deposition changed from shallow marine to littoral to back beach lagoonal. Elsewhere non-marine fluvial environments dominated the upper delta plain and floodplains of the river systems. The deposition of the Wangerrip Group ceased with regional uplift at the commencement of the Middle Eocene (Holdgate and Gallagher 2003).

As the rate of sea-floor spreading increased, a wide seaway formed between Australia and Antarctica, creating open marine depositional environments. The middle Eocene to early Oligocene was a time of major global climate change and significant turnovers in marine and terrestrial biota. The change is attributed to the development of the circum-Antarctic current, which resulted in the formation of significant ice sheets on the Antarctic continent (Berggren and Prothero 1992). In particular, the opening of the Drake Passage at about 30 Ma and the closure of the equatorial ocean currents by the approach of India to Eurasia created a massive drop in global temperatures in the early Oligocene (Williams et al. 1993).

In the north of the Corangamite region, the onset of drier conditions reduced streamflows, resulting in smaller streams following the broad valleys dissecting the Mesozoic palaeosurface. Dendritic drainage patterns developed and the streams gradually incised the deposits of coarser gravels deposited in the earlier, higher energy environments, to expose the highly weathered bedrock. By the late Oligocene these valleys in weathered Palaeozoic rocks had been well developed (Taylor et al. 1996).

Further south in the subsiding Otway Basin, deposition recommenced to form the Nirranda Group sediments. Around the basinal margins, erosion of the uplifted Wangerrip Group provided a sediment source for beach, estuarine and lagoonal sediments, whereas further south, open water marine carbonate sediments were laid down. A marine regression in the mid-Oligocene halted the Nirranda Group deposition (Holdgate and Gallagher 2003).

The late Oligocene and early Miocene is marked by a major marine transgression, which resulted in significant changes to the deposition regimes throughout the Corangamite region. As the stream base level rose, alluvial sediment began to fill the valleys of the dissected northern highlands, forming 'deep lead' channels. In the Otway Basin, the terrestrial sediment source lessened and biological sediment (carbonates) predominate. Initial carbonate sedimentation occurred in high-energy shallow marine conditions, but by the early Miocene, deep water continental shelf conditions had formed (Holdgate and Gallagher 2003). The marine sediments truncate the deep leads to the north, as the invading sea dispersed the former drainage channels (Taylor et al. 1996). By the mid to late Miocene the depositional environment had changed to intermediate depths as a marine regression was underway, and limestone was deposited in the southern part of the Otway basin within the Corangamite region.

The Late Miocene regression coincided with a change in tectonic stress for the Australian Plate, as it collided with the Pacific Plate (Edwards et al. 1996). In the Otway Basin, extensional faulting ceased as the north-south tensional system was replaced by compressional forces along a northwest - southeast axis. The compressional tectonics formed broad folds in the Otway Group, reactivated older faults and activated new ones. The Otway Ranges began uplift, as the some of the north dipping normal faults became south dipping reverse faults. The majority of the Miocene structures trend northeast, perpendicular to the axis of compression (Edwards et al. 1996).

By the early Pliocene, the Otway Ranges had reached their current elevation and the majority of the Corangamite region was subjected to aerial erosion (Joyce et al. 2003). Thin fluvial outwash from the northern uplands, the emerging Otway Ranges and surrounding sediments covered the western parts of the Corangamite region with a veneer of sands. A marine transgression, commencing in the southeast, formed shallow seas which eventually covered much of the region during the Pliocene (Wallace et al. 2005). In the valleys of the northern highlands, sands and gravels were locally deposited in response to the changes in stream base level.

Contemporaneous with the marine transgression was the commencement of volcanism (Price et al. 2003). Initially sporadic, the lava flows filled the base of the valleys in the northern dissected uplands. Compressional activity continued, gently warping the emergent coastal plain.

As the Pliocene sea retreated a relatively thin but aerially extensive deposit of sandy sediment covered most of the central and southern Corangamite region. Uplift is associated with the extensive volcanism which had commenced in earnest by 2 Ma (Price et al. 2003). Up to 150 m of uplift in the northern part of the Corangamite region had preserved the littoral deposits of the Pliocene marine regression from being covered by the volcanic lavas (Carey and Hughes 2002). The lava filled many of the deeply dissected valleys to the north and extensively covered the Pliocene sediments to the south. Disruption to the drainage systems forced the drainage divide further north to its present position and formed large lakes on the plains.

By the Pleistocene the exposed fluvial and marine sands had been extensively ferruginised and silicified, and karstic features developed in the limestone in the south of the region. The locally raised base levels and temporal blockages to streamflow caused by the volcanism resulted in localised deposition of lacustrine and alluvial sediments along the drainage lines. Climatic fluctuations of the Pleistocene and Holocene formed extensive lunettes on the eastern shores of the lakes (Edwards et al. 1996). Fluctuations in sea level created stranded and submerged coastal features (Holdgate et al. 2001; Joyce et al. 2003).

2.2.2 Geological data sources

The sources of geological data used in this thesis are generally those supplied by GeoScience Victoria (Department of Primary Industries, Victoria) as their regularly updated Geoscientific Data Packages available in GIS-ready format. Additional resources utilised include GeoScience Victoria's Geophysical Data Packages, Open File Mineral Tenement Data Packages, Geological reports and maps, and the on-line GeoVic website.

Compilations of geophysical data were specifically commissioned for this research to assist in the interpretation of the regional geology. These included the most recent Bouger gravity surveys, airborne magnetic surveys and airborne radiometric surveys. The integration of the individual geophysical surveys was undertaken by Linderman Geophysics Pty Ltd and supplied as georeferenced images and grids for the entire Corangamite region (Appendix B).

2.3 Geomorphology

The geomorphology of the Corangamite region reflects the geological history and subsequent landscape evolution and is therefore a factor in the occurrence and distribution of salinity. The brief overview in this section provides the regional context for the more detailed descriptions in later chapters.

The geomorphological framework of Victoria has its origins in the work of Murray (1887) and Gregory (1903) who used morphology as the main landscape factor (Jenkin 1989). The seminal geomorphology framework of Hills (1940) included the influence of structural geology and later work by Jenkin (1982) emphasised the importance of landscape processes. The availability of high-resolution terrain models, remote sensing technology (including geophysical techniques) and regolith maps (including soil series mapping) have provided additional insights to the geomorphology of the region in recent years (Joyce et al. 2003).

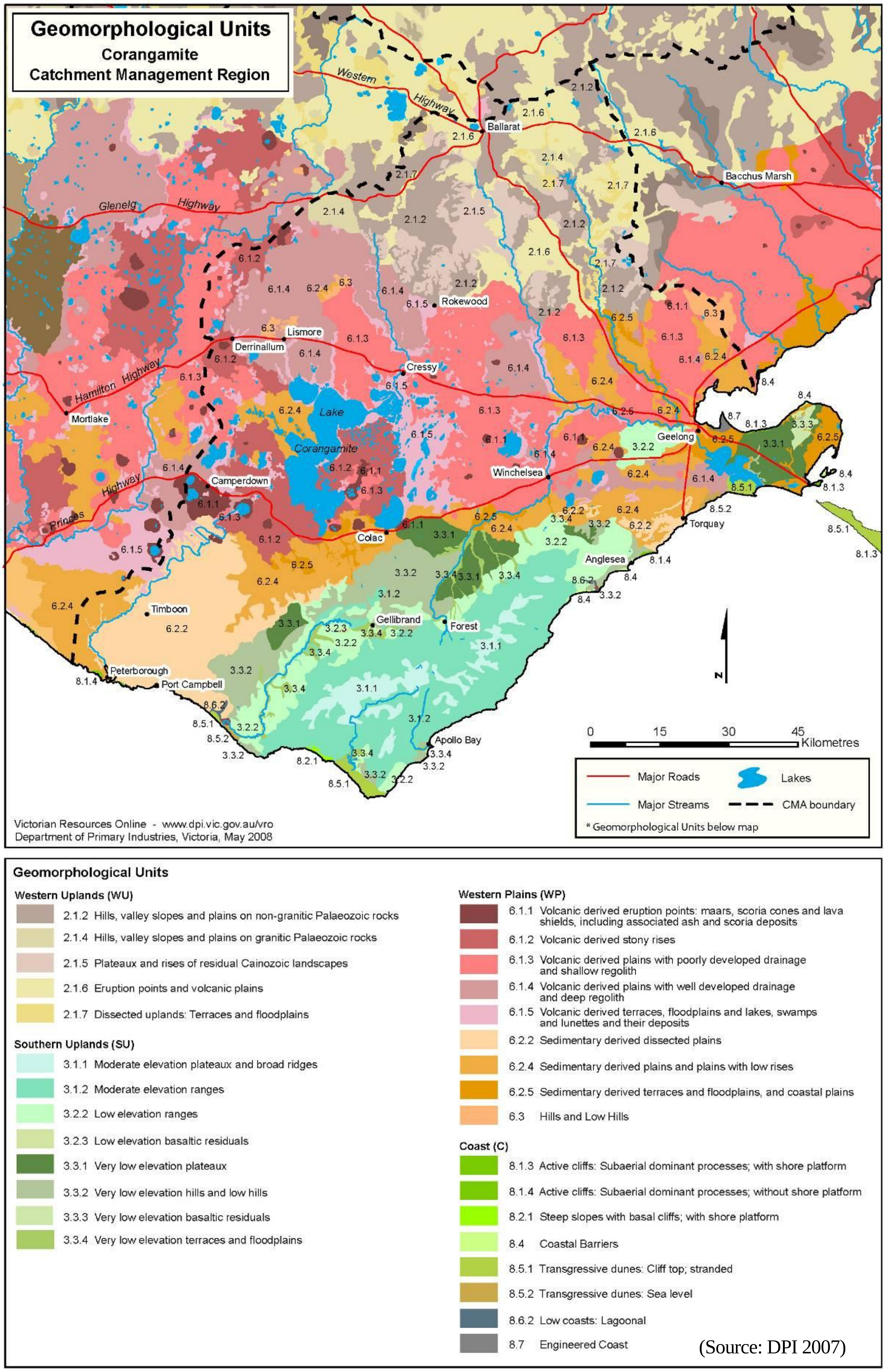
As a result, the geomorphological framework for the state has been recently reviewed by the Geomorphology Reference Group of Victoria (of which this author is a member) and a revised version was published in 2007 (DPI 2007). This revised hierarchical framework based on a tiered system has been adopted by the Victorian Government as the basis of soil and land management units and is the one used in this thesis (Figure 2.6).

2.3.1 Western Uplands

The Victorian Western Uplands form the northern highlands of the Corangamite region. In general, the landscapes of the Palaeozoic sedimentary rocks (unit 2.1.2) are characterised by undulating low hills dissected by a dendritic drainage pattern that forms the upper catchments of the Moorabool River, Leigh River, and Woady Yaloak River drainage systems. The primary drainage trends follow the strike of the bedrock strata and the directions of the secondary drainage systems are controlled by geological boundaries (i.e. lithological boundaries) and rock structures (i.e. faults, joints).

The larger landscape elements are remnants of the Mesozoic palaeosurface, which was deeply weathered during the Palaeogene and largely terminated by uplift in the late Eocene (Carey and Hughes 2002). At Ballarat, the weathering extends up to 100 m below the surface, with secondary mineral development (e.g. kaolin clay) producing the typical bleached and pallid regolith profiles in the Palaeozoic rocks. The oxidation of iron-rich groundwaters has precipitated iron cement into joints and the upper regolith materials.

The Palaeozoic granites (unit 2.1.4) generally form subdued landforms. In some areas the metamorphic aureoles around the granites are resistant to weathering and form prominent wooded to cleared ridges, such as the northern boundary along the Glenelg Highway.



(Source: DPI 2007)

Figure 2.6 Geomorphic Units of the Corangamite region.

(Source: DPI 2007)

Palaeogene and Neogene gravels and sands are the erosional remnants of extensive sheets of fluvial and regressive marine sediments that once covered much of the Western Uplands (unit 2.1.5). The coarser-grained Palaeogene fluvial sediments form a quartz-pebble conglomerate, often ferruginised and sometimes silicified. Thickness varies from a few metres to a maximum of 30 m. Landforms include isolated flat-topped mesas overlying Palaeozoic rocks, break-of-slope deposits between overlying basalts and underlying Palaeozoic rock, and broad tablelands fringing the overlying basalt. Neogene sands (regressive marine) generally fringe the Western Uplands as a dissected tableland and are often ferruginised (ferricrete) and silicified (silcrete).

The recently formed volcanic landscapes in the Western Uplands (unit 2.1.6) contrast with the older landscapes as the basalts of the Newer Volcanics fill many of the large ancient valleys. Elongate basalt plains are usually fringed by streams of the displaced drainage, although occasional basalt gorges have developed where streams have cut into the basalt flows. The eruption points form prominent scoria cones, lava cones, composite scoria/lava cones, lava discs and the rare maar (Rosengren 1994).

Regolith and soils development is directly related to the underlying geology and subsequent landform evolution (Robinson et al. 2003). In areas where they have been undisturbed, the Palaeozoic sedimentary rocks generally have gradational to strongly duplex soils, often with well developed, bleached A_2 horizons. However, the land-use change over the past 150 years has stripped the profile over large areas, particularly where intensive shallow gold mining has disturbed the original profile. The regolith on the granites varies from deep (>40 m) saprolite to surface tors. Soils have generally developed profiles varying from uniform or weakly gradational sands to strongly duplex ferruginised podsolic soils. The soils on both the sedimentary rocks and the granites are regarded as agriculturally ‘poor’ compared to the soils of the Newer Volcanics, which exhibit gradational clayey soils (kraznozems) on the younger rocks to coarsely structured duplex soils on the older rocks.

2.3.2 *Southern Uplands*

The southern portion of the Corangamite region is dominated by the Victorian Southern Uplands, which form the deeply dissected Otway Ranges, moderately dissected Barrabool Hills and low hills of the Bellarine Peninsula. All three landscapes have formed by the uplift of a structurally controlled block of lithic sedimentary rocks of the Lower Cretaceous Otway Group.

Significant uplift of the Otway Ranges has occurred in the recent geological past along two reverse faults: the westerly dipping Torquay Fault to the east and the easterly dipping Bambra Fault to the west (Sandiford 2003). The continued uplift of the Otway block is partially responsible for the incision of steep river valleys. The broad plateaux at the crest of the ranges (unit 3.1.1) forms a drainage divide which trends north east to Mount Chapple (550 m), then easterly to Mount Sabine (583 m), and northeast to parallel the coast through the highest point at Mount Cowley (686 m) towards Anglesea.

On both sides of the divide rugged topography has developed comprising ridges and spurs separated by deeply dissected steep valleys (unit 3.1.2). The drainage is strongly controlled by the geological structure. Parallel to the south east coast, the drainage is generally south east and north west, whereas west of Mount Sabine, the drainage is generally north and south. The depth of dissection is less along the ridge, while the south eastern flanks of the ranges have developed the steepest topography, probably in response to the Quaternary sea level fluctuations, changing the base level of the rivers and streams that drain the landscapes. The coastline has been eroded within the past 6000 years, and the recession has been estimated as 105 m on mudstones and 53 m on sandstones along the Otway coast (Bird 2000).

North of the Bambra Fault, the landscapes comprise more gently undulating hills formed on Cainozoic sedimentary rocks (units 3.2.2 & 3.3.2) that have not experienced the same tectonic uplift as the Otway Ranges. The wide flood plain of the Barwon River (unit 3.3.4) is associated with the damming of the river by Newer Volcanic basalt flows to the north (unit 6.1.4).

The Barrabool Hills and Bellarine Peninsula are smaller fault-bounded uplift blocks of the Otway Group rocks. These blocks are at lower elevations than the Otway Ranges and are generally more planar and less deeply dissected. The Barrabool Hills (unit 3.2.2) block is tilted, with more uplift along the northern edge (Barrabool Fault) resulting in deeper dissection by tributaries of the Barwon River on the north and east of the block. The Bellarine Peninsula (unit 3.3.1) has more variety in rock type with basalts of the Older Volcanics (unit 3.3.3) and Pliocene marine sands more prevalent than the Otway Group.

The lithologies of the Southern Uplands rocks vary considerably, resulting in a diversity of regolith and soil profiles. The volcanoclastic Otway Group rocks west of Cape Otway and in the Barrabool Hills are highly fractured and bleached compared to the rock exposed in comparable landscape positions east of Cape Otway. Soils vary from shallow stony loams in the steep and actively eroding parts of the landscapes to brown and yellow gradational soils and colluvium on the slopes. Thick deposits of colluvium and landslide debris are common. In the foothills and on the Bellarine Peninsula, soil profiles vary considerably. As a generalisation, weakly structured sandy gradational soils are more common on the Palaeogene sedimentary rocks, and coarse structured duplex soils are more common the Neogene and Quaternary sedimentary rocks (Robinson et al. 2003).

2.3.3 *Western Plains*

The central Corangamite region lies within the Victorian Western Plains, comprising undulating plains formed on both volcanic and sedimentary rocks. The landscapes of this geomorphic unit are formed on some of the youngest rocks of the Corangamite region (Gray and McDougall 2009).

The volcanic plains were built up by sporadic volcanic eruptions over a period of about 4.6 Ma (Price et al. 2003; Gray and McDougall 2009). The eruptions resulted in lobes of lava flowing from the eruption points, which overlap to form a variable thickness of basalt, interleaved with sporadic pyroclastic deposits of scoria and tuff. At times, lengthy breaks between eruptions allowed soils to form on the upper surface of the basalt which was subsequently covered by later eruptions, forming buried palaeosol horizons.

The volcanic eruptions often resulted in blocking the drainage systems (Joyce et al. 2003) and the palaeogeography of the rivers has been well documented (Hunter 1909; Rosengren 1973; Coulson 1977; Canavan 1988; Bishop and Li 1997; Cunningham 1998; Hughes and Carey 2002; Taylor and Gentle 2002; Evans 2006; Holdgate et al. 2006). Drainage across the volcanic plains is generally poorly developed. The uplift of the Otway Ranges and the disruption of drainage by the volcanic eruptions resulted in the formation of a shallow basin in the central Corangamite region, where the majority of lakes, including Lake Corangamite, are situated. The fluctuating lake levels related to the climate changes during the Pleistocene resulted in lunette formation, especially prominent in the area north of Colac and south of Cressy (Edwards et al. 1996).

Eruption points vary in form (scoria cones, lava cones, composite scoria/lava cones, lava discs, maars) and have been documented by Rosengren (1994). The stony rises (unit 6.1.2) represent the lava flows associated with the most recent volcanic activity, the most prominent of which forms the platform from which the Mount Porndon scoria cones rise. This feature has been dated as 59 ka, placing it among the youngest landforms in Australia (Stone et al. 1997).

The sedimentary plains (units 6.2.2, 6.2.4, & 6.2.5) mainly comprise the sands deposited by the retreating Pliocene sea and the exposed underlying Neogene marls and limestone. In the Heytesbury region the drainage has been strongly influenced by the deposition of strand lines from the retreating sea, forming parallel arcuate tributaries perpendicular to rivers draining southwest. The deep dissection has resulted in numerous landslides in the marl, many of which remain active (Dahlhaus et al. 1996). Remnants of the undissected plain are preserved along ridge lines and further north to Colac. Along the coast near Port Campbell, the limestone plain has developed many karstic features, particularly sinkholes. Spectacular cliffs and rock stacks formed by the rising sea levels since the last glacial mark the edge of the plain at the Southern Ocean.

Soils on the Western Plains reflect the underlying lithology and age of the rocks. The youngest landscapes – the stony rises – have very thin skeletal soils, whereas the older landscapes on basalts have developed clay-rich soils varying from gradational kraznozems to coarsely duplex profiles. The finely brown gradational soils developed on the scoria cones represent some of the most valuable agricultural country. The soils developed on the Pliocene sand plains are often sandy, sometimes ferruginised or podsolic soils. Further south on the marls and limestones, the soil profiles vary from clay-rich gradational to strongly duplex, generally comprising heavy clays.

2.3.4 Geomorphic data sources

2.3.4.1 Geomorphology and soil landform units

The geomorphic framework and soil-landform units for the Corangamite region were published in 2003 (Robinson et al. 2003) and included the delineation of geomorphic units and descriptions contributed by this author through this project. The geomorphic and soil-landform mapping, known as the Corangamite Land Resource Assessment (LRA), provides detailed descriptions of 18 geomorphic units to the third-tier and 204 soil-landform units (*de facto* forth-tier units). The units are available as GIS layers and the final LRA is appended in electronic form (Appendix B).

2.4 Climate

Climate, especially rainfall and evapotranspiration, impacts on the hydrologic budget and therefore groundwater and salinity processes (e.g. Cartwright and Simmons 2008).

Being situated between 37.4^{o} and 38.9^{o} South latitude, the Corangamite region experiences a Temperate climate with dominant westerly winds, variable cloud, moderate precipitation and cool temperatures (Linacre and Hobbs 1977). The majority of rain falls in winter and spring, with August as the wettest month across the region. The Bureau of Meteorology (BoM 2009a) records Weeaproinah at the crest of the Otway Range with the highest mean annual rainfall (1930.1 mm for the period from 1901 to 2009); and Avalon Airport on the northern side of Corio Bay with the region's lowest mean annual rainfall (448.4 mm for the period from 1965 to 2009). Rainfall across the region is closely related to elevation and latitude (Figure 2.7). Based on the rainfall model (refer to section 2.4.1.1 for details), average annual rainfall (1921 - 1995) varies from 469 mm in the low elevation plains west of Geelong to 1892 mm along the ridge of the Otway Range.

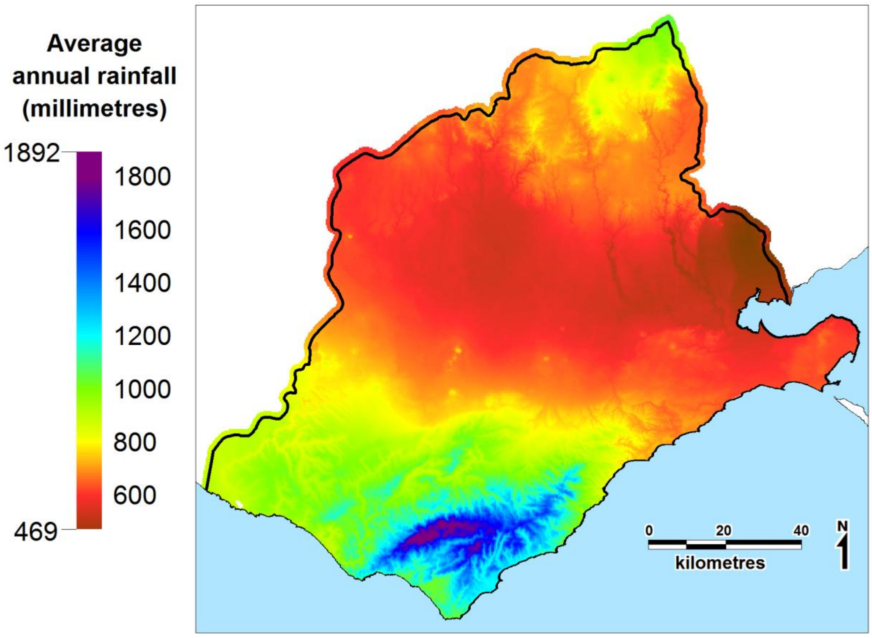


Figure 2.7 Modelled average annual rainfall for the Corangamite region

Evaporation across the region is also closely related to altitude and latitude (solar radiation) (Figure 2.8). Only four Bureau of Meteorology evaporation stations (i.e. pan evaporation) are situated in the Corangamite region.

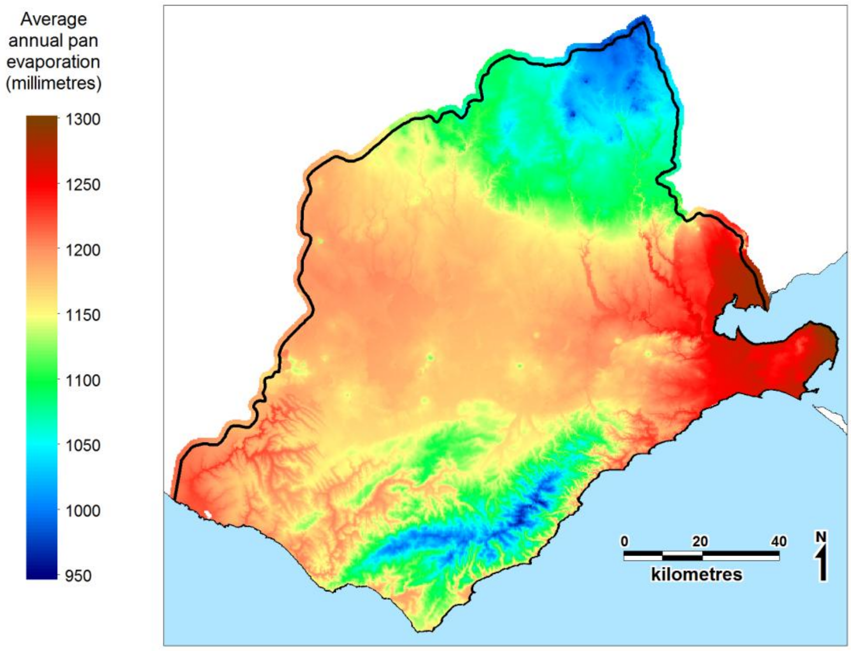


Figure 2.8 Modelled average annual pan evaporation for the Corangamite region

2.4.1 *Climate data sources*

The Bureau of Meteorology SILO is the main source of climatic data for specific site studies (BoM 2009e), in particular: Patched Point Datasets, which use the original measurements of a meteorological station with interpolated data to fill missing values; and Data Drill which is uses splining and kriging interpolation to derive a dataset for any location in the region.

2.4.1.1 Climate surfaces

For the purpose of this research, sixteen climate variables (Table 2.1) have been modelled for the Corangamite region using ANUCLIM (v1.8), a software package containing a suite of programs that enable the user to obtain estimates of mean monthly climate variables, bioclimatic parameters, and indices relating to crop growth. The modelling software was developed at the Centre for Resource and Environmental Studies (CRES) at the Australian National University (ANU), Canberra (Houlder et al. 2000).

The climate surface coefficients are contained within the program and have been generated using the ANUSPLIN technique of thin-plate smoothing splines used for the spatial interpolation of meteorological variables from irregular networks (Hutchinson 1998aa; 1998bb). The input data are long-term monthly averages of the climate variables from selected Bureau of Meteorology and other stations. Most climatic surfaces were constructed using data recorded in the 1920 to 1995 period, with short-term data regressed against long-term data to determine the 75 year means.

The modelling of the climate surfaces for the Corangamite region utilised ESOCLIM, a program for EStimation Of CLIMate by calculation of the monthly mean climate surfaces on a regular grid. The individual grids of climate variables contain data modelled on square 300 m grid cells (model has 576 x 529 cells) and the methods are detailed further in Appendix B. The climatic variable surfaces have a horizontal positional accuracy of 100 m and a vertical positional accuracy of 10 m (Houlder et al. 2000).

Table 2.1 Climate variables modelled for the Corangamite region

Variable	units	data source	period
Rainfall	mm	2161 stations	Jan 1921 - Dec 1995
Rain days	number of days rain > 0.1mm	2161 stations	Jan 1921 - Dec 1995
Pan evaporation	mm	287 stations	1920 - 1995
Maximum temperature	^{o}C	1123 stations	1920 - 1995
Minimum temperature	^{o}C	1119 stations	1920 - 1995
Dry-bulb temperature at 9am	^{o}C	not known	
Wet-bulb temperature at 9am	^{o}C		
Dew-point temperature at 9am	^{o}C		
Dry-bulb temperature at 3pm	^{o}C		
Wet-bulb temperature at 3pm	^{o}C		
Dew-point temperature at 3pm	^{o}C		
Solar radiation	MJ/m^2/d	modelled from time, geographic latitude, and altitude	
Solar radiation related to cloud cover	MJ/m^2/d		
Wind speed 9am	m/s	modelled from time, geographic latitude, distance from coast.	
Wind speed 3pm	m/s		
Wind run	km		

2.5 Vegetation and land use

Current government policies (CoAG 2000; DNRE 2000) and previous studies (Ghassemi et al. 1995) consider changes to native vegetation through historical and present land uses a major factor in the onset of salinity in Australia. This section provides a brief overview of the vegetation, land-uses, and their history of change in the Corangamite region to provide a context for some of the research and discussion in the following chapters of the thesis.

2.5.1 Vegetation

As expected in a large region with varied geology and climate, there is a broad range of vegetation types in the Corangamite region. As a generalisation, before the widespread clearing associated with agricultural settlement and mining over 150 years ago, the native vegetation of the Central Highlands generally comprised dry sclerophyll forests and grassy woodlands; the Western Plains were largely grasslands and grassy woodlands; the Coastal Plains were mainly scrublands and grassy woodlands; and the Otway Ranges were dense temperate rainforest and wet sclerophyll forests (CCMA 2003; 2005).

Bio-geographic regions, or bioregions, are the state framework adopted for vegetation management (CCMA 2005). Five bioregions are present in the Corangamite region, *viz:* Central Victorian Uplands, Otway Plain, Otway Ranges, Victorian Volcanic Plain; and Warrnambool Plain (Figure 2.9). Of these, only the Otway Ranges bioregion retains the majority of its original native vegetation cover (81.6 %), of which 79.1 % remains in public ownership. By contrast, the largest bioregion, the Victorian Volcanic Plains, retains only 3.5 % of its native vegetation, 74.5 % of which is on private land (Table 2.2).

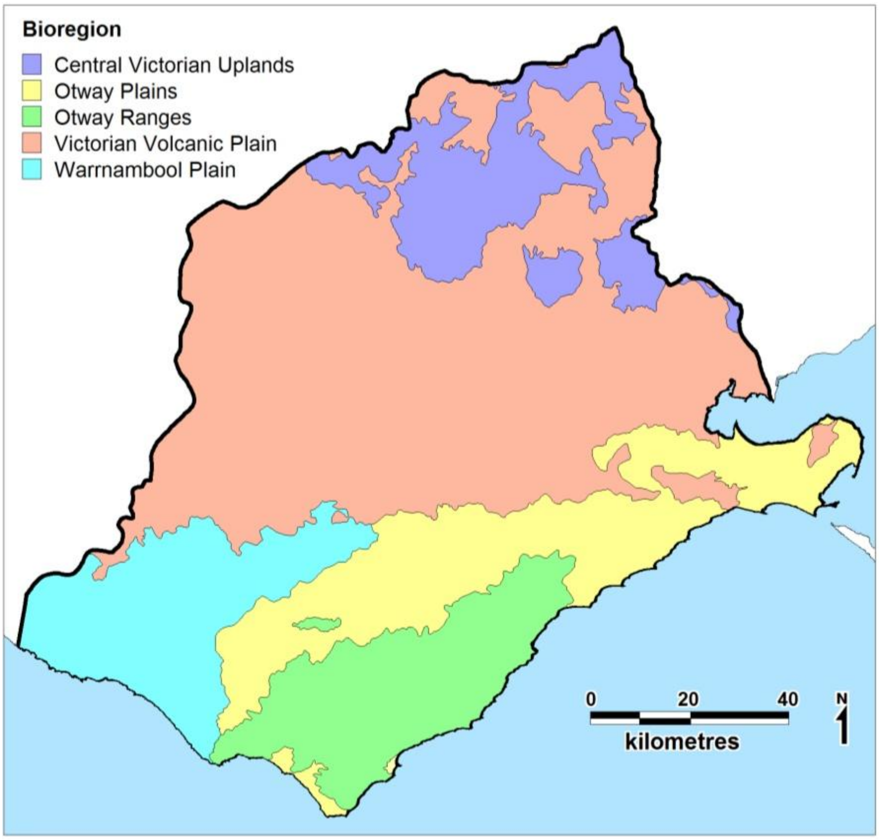


Figure 2.9 Bioregions of the Corangamite region

The distribution of native vegetation is further refined into Ecological Vegetation Classes (EVCs) which are distinct assemblages of native vegetation that are recognised by vegetation structure and floristics. There are currently 90 EVCs described in the Corangamite region (CCMA 2005). These are listed and described in Appendix B.

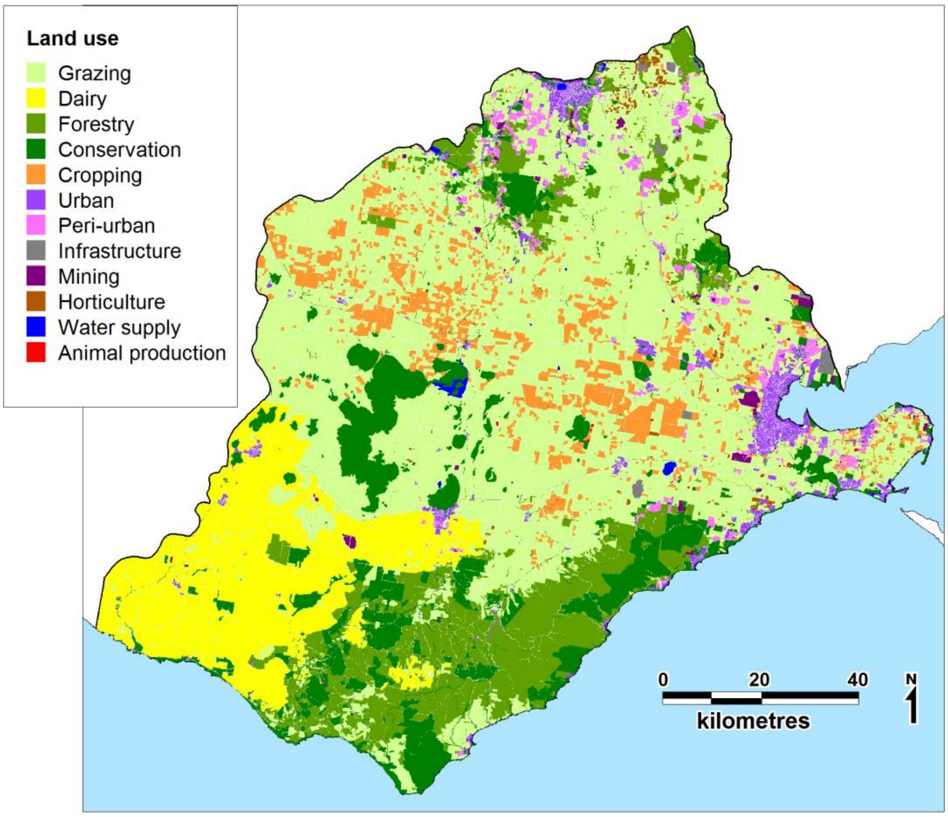
Table 2.2 Extent of native vegetation within the Corangamite region (2002)

Bioregion	Total (including water bodies)	Remnant vegetation cleared	Remnant vegetation remaining
Central Victorian Uplands	145,694 ha	89,303 ha (61.4 %)	56,045 ha (38.6 %)
Otway Plain	222,117 ha	148,915 ha (67.5 %)	71,745 ha (32.5 %)
Otway Range	150,067 ha	27,597 ha (18.4 %)	122,306 ha (81.6 %)
Victorian Volcanic Plain	665,062 ha	594,361 ha (96.5 %)	21,355 ha (3.5 %)
Warrnambool Plain	150,949 ha	126,993 ha (84.1 %)	24,009 ha (15.9 %)
Total	1,333,881 ha	987,169 ha (77.0 %)	295,460 ha (23.0 %)

(Source: CCMA 2005)

2.5.2 *Land use*

In terms of area, the dominant land uses are livestock grazing, dryland agriculture, forestry and dairying (Figure 2.10; Table 2.3).



(source: modified from DSE 2003)

Figure 2.10 Land use in the Corangamite region (2003)

Table 2.3 Land use within the Corangamite region (2003)

Land use	Area (ha)	% of total
Grazing	637,484	49.26
Dairy	170,840	13.20
Forestry	165,594	12.80
Conservation	156,154	12.07
Cropping	94,386	7.29
Urban	26,966	2.08
Peri-urban	21,308	1.65
Infrastructure	6,831	0.53
Mining	5,839	0.45
Horticulture	5,058	0.39
Water supply	2,907	0.22
Animal production	647	0.05
Total	1,294,014	100.00

(source: modified from DSE 2003)

Since the data tabulated above was collected (2003) there has been a significant shift from grazing to cropping across the Western Plains, due to the drier climate and increased commodity prices in recent years (ABS 2009c). In a report released in May 2009, the Australian Bureau of Statistics (ABS) records 3,306 agricultural businesses covering 976,000 ha of the Corangamite region. Of the land used in agriculture, 75.7 % is grazed and 18.3 % used in cropping (ABS 2009c). Of the 61.3 % of agricultural businesses who made land use changes in the past 5 years, 9.3 % undertook activities to manage salinity.

2.5.3 *History of land use change*

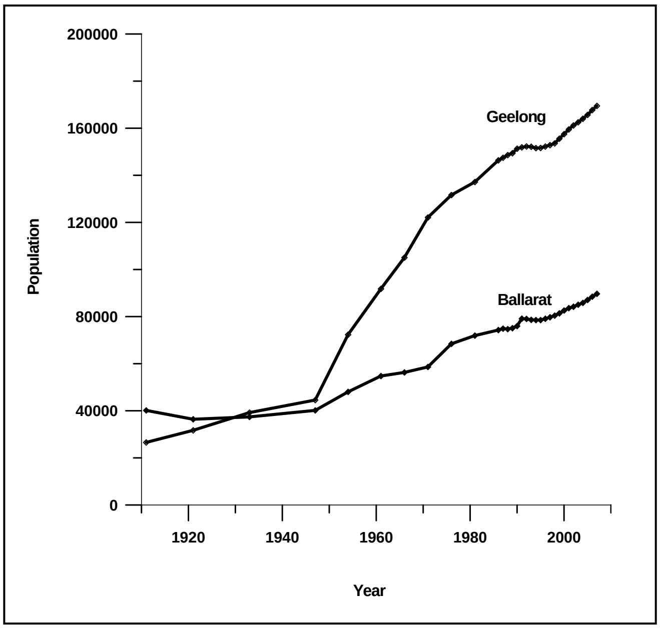
Humans have inhabited the Corangamite region for at least 35,000 years (Mulvaney and Kamminga 1999) although little is known of the early inhabitants. The ethno-historical observations at the turn of the 19th Century suggest that the region's landscapes supported an indigenous population - the *Wathaurong, Gulidjan, Gadubanud, Djargurdwurung* and *Giraiwurung* Aboriginal language communities - estimated to be between 2500 and 4000 persons (Clark 1990; Horton 2000). The grassy plains, rivers and wetlands provided an ample supply and variety of food. In particular, shellfish were gathered from the coast, fish and eels were hunted and trapped in significant quantities in the rivers, lakes and estuaries, land mammals and reptiles were hunted on the plains and birds (especially water birds) were taken from the lakes and estuaries (Marshall and Webb 1997; Flannery 2002). The Aboriginal communities used fire as a vegetation management tool, promoting fresh growth and maintaining open plains and woodlands in some areas to encourage grazing animals for hunting (CCMA 2005).

Explorers of European origins had mapped the Corangamite coast by the early 19th century (Fleming 1802; Flinders 1814). The first pastoral settlers ventured westward from Geelong and Melbourne in 1835 (Rusden 1872), and by 1837 the Learmonth brothers had explored the upper Moorabool and Leigh rivers (Bride 1898) and in the same year McLeod 'discovered' Lake Corangamite (Hebb 1888). By 1841 almost all of the available grazing land on the volcanic plains was occupied by squatters (Bride 1898). The observations and experiences of the early settlers are important in establishing the extent and rate of land-use change and the implications for salinity. The significance of these accounts is discussed further in Chapter 3.

The discovery of gold at Buninyong and Ballarat in 1851 had a significant impact on settlement and land-use in the northern area of the Corangamite region. Thousands of immigrants flocked to the region and the native vegetation was rapidly cleared for mining, agriculture and timber supply (Langtree 1887; Withers 1887). Forests on the basalt plains around Ballarat gave way to grazing and cropping, as potatoes, wheat, oats and vegetables were produced and dairy herds established (Nathan 2004).

The cessation of the gold mining towards the end of the 19th century brought a demand for closer land settlement. A series of Land Acts throughout the 1860s changed the distribution of land holdings and the land-use throughout the region (Powell 1970). Clearing of native vegetation was accelerated as the holdings decreased in size, and in some areas, clearing of the native vegetation was a required condition for agricultural settlement (CCMA 2005). The Closer Settlement and Soldier Settlement Schemes were implemented during the first half of the 20th century, further decreasing the size of land holdings (Nathan 2000). The last of the large-scale land use changes in the Corangamite region was the Heytesbury Settlement Scheme, when approximately 40,000 hectares of *"unproductive bush"* was cleared for agriculture during the period from 1952 to 1971 (Fisher 1997). This region now supports a significant dairying industry (Figure 2.10).

Following the 2nd World War (1939-1945), migration schemes and the mechanisation of agriculture has expanded the populations of the urban centres. During the past 30 years the major provincial cities of Ballarat and Geelong have continued to expand (Figure 2.11) (ABS 2009a). As the population of the Corangamite region rose 20 % from 282,575 to 339,015 between 1986 and 2006, the peri-urban region has expanded (Mendham and Curtis 2007). Population growth has been highest in the transport corridors between the major urban centres and along the coast. Around the cities the size of holdings has steadily reduced with a growing population acquiring parcels of land at the urban fringe for lifestyle and recreational pursuits (URS 2003). All municipalities in the Corangamite region recorded growth during 2007 – 2008 (Table 2.4) (ABS 2009a). It has been predicted that 52 % of the rural properties in the Corangamite region will change ownership by 2016 (Mendham and Curtis 2007). The salinity risk implications of this increasing urbanisation of the Corangamite region is further discussed in Chapter 6.



(Data from ABS 2009a)

Figure 2.11 Population of Ballarat and Geelong

Table 2.4 Population by municipality in the Corangamite region

Municipality	Est. Population 30 June 2008	Growth 2007-2008	Comment
City of Ballarat	91,787	2.0 %	small percentage outside of region
Colac Otway Shire	21,448	0.8 %	entirely with region
Corangamite Shire	17,270	0.2 %	small percentage outside of region
Golden Plains Shire	17,681	2.0 %	entirely with region
City of Greater Geelong	211,841	1.4 %	small percentage outside of region
Moorabool Shire	27,247	1.1 %	large percentage outside of region
Moyne Shire	16,405	1.3 %	large percentage outside of region
Borough of Queenscliff	3,256	2.2 %	entirely with region
Surf Coast Shire	24,442	3.6 %	entirely with region

(Data from ABS 2009a)

2.5.4 *Vegetation and land-use data sources*

Vegetation data includes the GIS layers supplied by DSE for the Corangamite region, including: bioregions; predicted EVC cover in the year 1750; current EVC cover; native vegetation conservation significance; and EVC bioregional conservation status.

Land use data is taken from a GIS layer derived from remote sensing and aerial photography dated from 1999 to 2002, with most data relating to the 2000 – 2001 period (DSE 2003). The layer was modified to amalgamate land uses into the categories listed in Table 2.3 and necessitated the addition dairying as a land use. Naturally, the spatial cover of various land-uses, especially grazing and cropping, dramatically changes on an annual basis. Public land distribution and status was modified and corrected from the 2003 statewide coverage using the cadastre supplied by DSE (2008b).

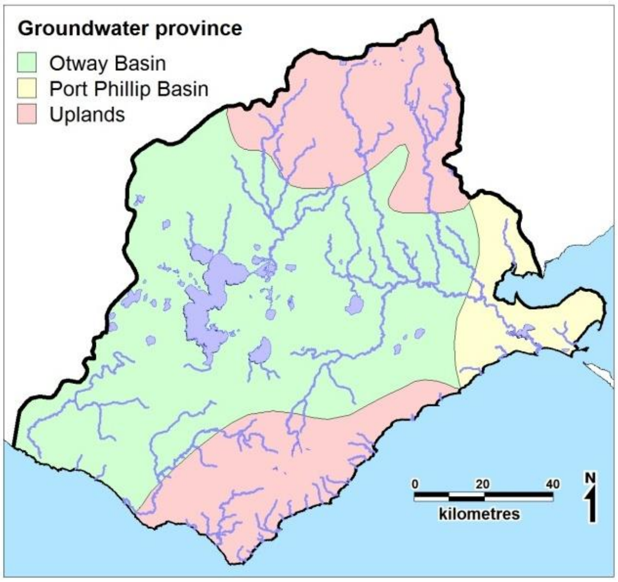
Aerial photographs dating from 1934 were used for various components of the research detailed in the following chapters of the thesis. These included a series of georectified aerial orthophotomosaics, generally supplied by the Corangamite CMA, municipalities or the DSE. The latest aerial georectified orthophoto coverage for the Corangamite region was acquired at the same time as the LIDAR terrain data (detailed in section 2.1.1.1) and has a pixel resolution of 0.35 m. Higher resolution photography (0.12 m) is also provided for selected urban areas including Geelong and Ballarat.

2.6 Hydrogeology

In the available scientific literature, the hydrogeology of the Corangamite region is not as well described as many of the other biophysical parameters. There are no whole of Corangamite region studies known, although a few regional-scale groundwater models have been undertaken. The vast majority of hydrogeological studies are confined to localised areas, generally focussed on groundwater resource management (cf. salinity management), and documented in unpublished literature (such as consulting reports, university theses, and government reports). Nevertheless, these studies number in the hundreds and they are a considerable source of information and data for this thesis.

In the broad hydrogeological framework of Victoria, the Corangamite region straddles three groundwater provinces, *viz:* Uplands, Otway Basin and Port Phillip Basin (Leonard 2003).

Figure 2.12 Groundwater provinces of the Corangamite region

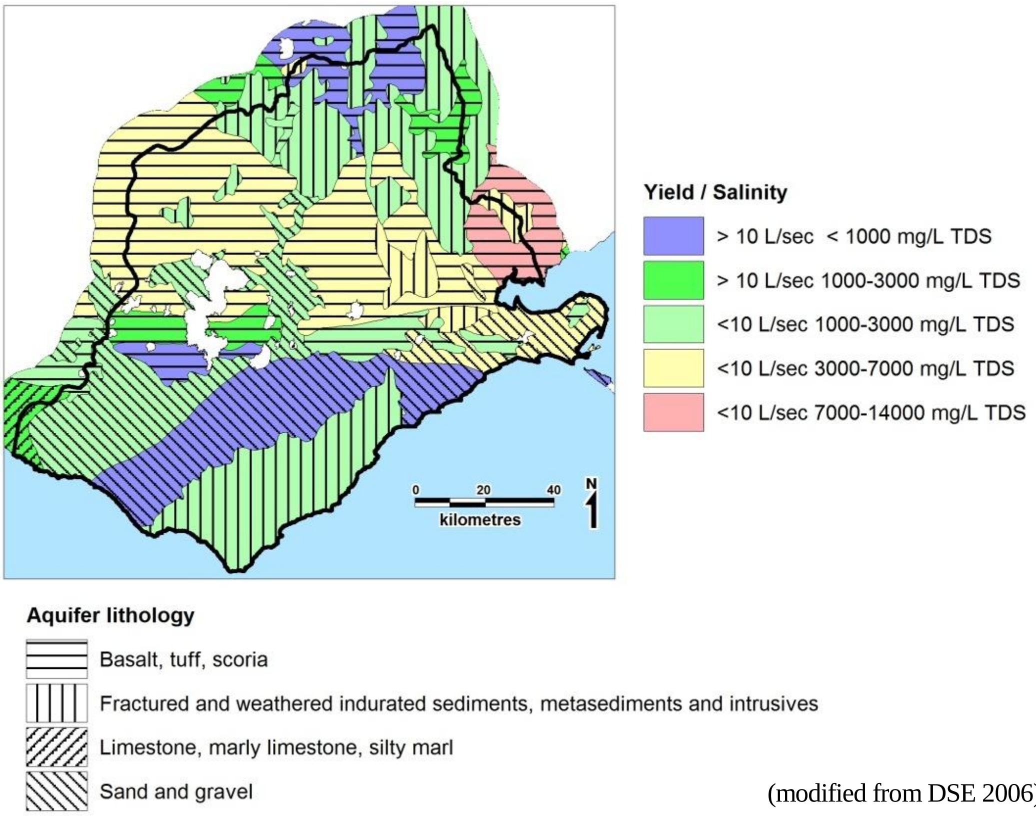


(source: DSE 2007)

The main groundwater resource aquifers of the provinces and their general properties have been described by Leonard (2003). Since the aquifers have been delineated on the basis of groundwater as a resource (for human uses) many are not implicated in the processes that contribute to salinity. A summary of the groundwater resources of the Corangamite region is illustrated in Figure 2.13.

When considered across the whole of the Corangamite region, the hydrogeological framework generally reflects the geological framework. The most recent region-wide classification of aquifers is that by Sinclair Knight Merz

(SKM) consulting group for the Southern Rural Water (SRW) authority, reported in Gill (2009). The classification is an initial attempt at a nationally consistent approach for hydrogeological mapping instigated by the Bureau of Meteorology. The consolidation of the geology into this framework for the Corangamite region has been attempted in Table 2.6.



(modified from DSE 2006)

Figure 2.13 The general groundwater resources of the Corangamite region

<u>2.6.1</u> *Groundwater flow systems*

Groundwater flow systems (GFS) have been developed in the National Land and Water Audit (Audit) as a framework for dryland salinity management in Australia (NLWRA 2001). They *"…characterise similar landscapes in which similar groundwater processes contribute to similar salinity issues, and where similar salinity management options apply"* (Coram et al. 2001). At the continental scale, twelve GFS have been identified in Australia on the basis of nationally distinctive geological and geomorphological character.

In the Corangamite region 17 GFS are recognised (Dahlhaus et al. 2002a), the spatial distribution of which are shown in Figure 2.14 in which they are draped over the DEM to demonstrate the relationship to the underlying landscapes. It should be noted that this delineation of the GFS for salinity management is not an attempt at a hydrogeological mapping, but rather the development of a tool for assessing the responsiveness of a catchment to salinity management options.

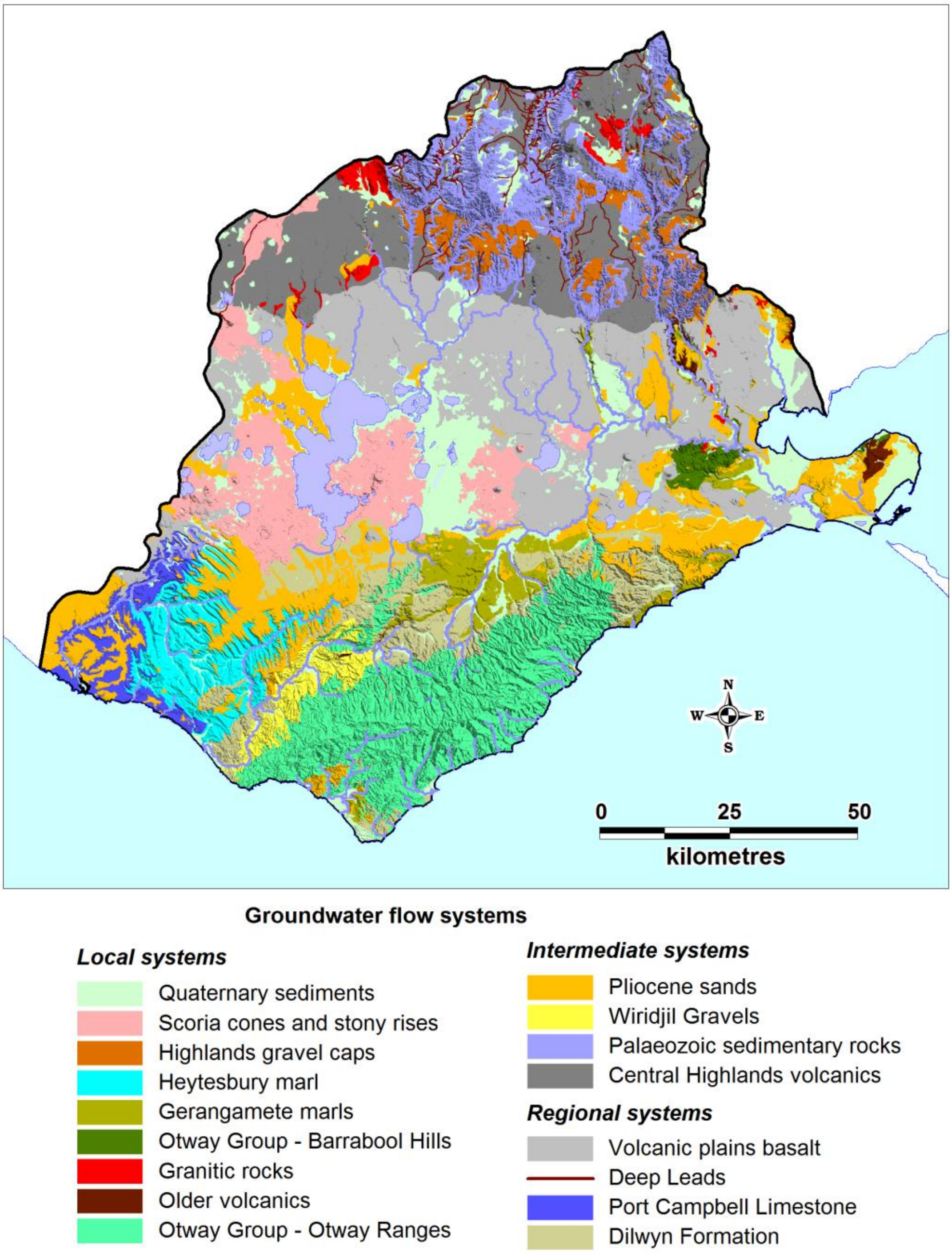


Figure 2.14 GFS of the Corangamite region (draped on terrain)

In the Audit, GFS are characterised by their hydrological responses and flow paths into local, intermediate and regional systems. This terminology is not to be confused with that used for the nested flow systems that develop in groundwater basins, depending on the basin length to depth ratio and the topographic undulation, as described by Tóth (1963). The terminology used by the Audit describes local, intermediate and regional GFS by their flow path length and corresponding ability to respond to hydrological change caused by alteration to the natural environment. The underlying assumption is that salinity is caused by increased recharge leading to rising groundwater tables, which have resulted from changes in land management over the past 200 years (NLWRA 2001).

The Audit provides definitions of flow systems as tabulated below (Table 2.5).

Table 2.5 GFS definitions in the Audit

Attribute	Rating	Meaning/Value
Scale	Local	Groundwater flows over distances <5 km
	Intermediate	Groundwater flows over distances 5 – 30 km
	Regional	Groundwater flows over distances > 50 km
Aquifer transmissivity	Low	Less than 2 m^2/day
	Moderate	2 m^2/day to 100 m^2/day
	High	Greater than 100 m^2/day
Groundwater salinity	Low	Less than 2000 mg/l
	Moderate	2000 mg/l to 10000 mg/l
	High	Greater than 10000 mg/l
Catchment size	Small	Less than 10 km^2
	Moderate	10 km^2 to 500 km^2
	Large	Greater than 500 km^2
Annual rainfall	Low	Less than 400 mm
	Moderate	400 mm to 800 mm
	High	Greater than 800 mm
Salinity rating	S1	Loss of production
	S2	Saline land covered with salt-tolerant volunteer species
	S3	Barren saline soils, typically eroded with exposed sub-soils
Responsiveness to land management	Low	Salinity benefits accrue over timeframes > 50 years
	Moderate	Salinity benefits accrue over timeframes from 30 to 50 years
	High	Salinity benefits accrue over timeframes < 30 years

(source: NLWRA 2001)

The boundaries of the GFS are based on the region's surficial geology units (Figure 2.5) which have been grouped according to their hydrogeological characteristics, as determined by consensus of opinion reached at a 3 day GFS workshop (November 2001) with 55 regional experts who have conducted numerous investigations over the past decades. Each GFS has been described by Dahlhaus et al (2002a) according to the attributes listed in the Audit (Table 2.5) and the suggested description in the national Evaluation Framework (Coram et al. 2001). Additional descriptive information provides historical and landscape context to each system. This work is appended (Appendix A).

A comparison of the GFS with the initial SRW classification of aquifers (as reported by Gill 2009) is shown in Table 2.6. The comparison clearly demonstrates the differences between the GFS and the conventional hydrogeological mapping for groundwater resource management. For example, the pre-Cretaceous age rocks are grouped together in the SRW classification as the basement aquifer (BSE), whereas the same geological units are divided into 7 GFS. The logic for resource management is that all BSE are low yielding fractured rock aquifers, whereas for salinity management there is a substantial difference in the quality of the groundwater discharge from each system. Even in the same geological formation - the Otway Group - the groundwater discharge from GFS6 (Barrabool Hills) has led to significant land salinisation compared to none at all in GFS9 (Otway Range).

In accord with the national and state policies, the salinity management actions in the Corangamite region are based on the response of the GFS implicated in the salinity process (Dahlhaus 2004). This is mainly achieved through the establishment of vegetation in areas targeted for recharge or discharge management (Nicholson et al. 2006).

Table 2.6 A comparison of regional hydrogeologic frameworks.

Geological unit (refer to Figure 2.5)	SRW framework (Gill 2009)	GFS framework (Dahlhaus et al. 2002)
Qra - Holocene alluvial, colluvial & paludal deposits	QA - Quaternary Aquifer	GFS1 - Quaternary sediments
Qrd - Holocene coastal and lunette deposits	QA - Quaternary Aquifer	GFS1 - Quaternary sediments
Qpa - Pleistocene alluvial & colluvial deposits	QA - Quaternary Aquifer	GFS1 - Quaternary sediments
Qvs - later Newer Volcanics		GFS2 - Scoria and stony rises
Qvn - earlier Newer Volcanics		GFS13 - Central Highlands volcanic rocks GFS14 - Volcanic Plains basalt
Npb - Pliocene sands	UTA - Upper Tertiary Aquifer	GFS 3 - Highlands gravel caps GFS10 - Pliocene sands GFS15 - Subsurface Deep Leads *(subsurface unit)*
Nmg - Port Campbell Limestone	UMTA - Upper Mid-Tertiary Aquifer	GFS16 - Port Campbell Limestone
Nmn - Gellibrand Marl and equivalents	UMTD - Upper Mid-Tertiary Aquitard	GFS4 - Heytesbury Marls GFS5 - Gerangamete Marls
Clifton Formation *(subsurface unit)*	LMTA - Lower Mid-Tertiary Aquifer	
Pon - Narrawaturk Marl & Jan Juc Formation	LMTD - Lower Mid-Tertiary Aquitard	GFS4 - Heytesbury Marls
Ped - Demons Bluff Formation	LMTD - Lower Mid-Tertiary Aquitard	GFS4 - Heytesbury Marls
Upper Mepunga Formation *(subsurface unit)*	LMTD - Lower Mid-Tertiary Aquitard	
Lower Mepunga Formation *(subsurface unit)*	LTA - Lower Tertiary Aquifer	
Pe - Werribee Formation	LTA - Lower Tertiary Aquifer	GFS 3 - Highlands gravel caps
Pvo - Older Volcanics	LMTD - Lower Mid-Tertiary Aquitard LTA - Lower Tertiary Aquifer	GFS8 - Older Volcanics
Pae - Eastern View Formation	LTA - Lower Tertiary Aquifer	GFS17 - Dilwyn Formation
Pad - Dilwyn Formation & Pember Mudstone	LTA - Lower Tertiary Aquifer	GFS17 - Dilwyn Formation
Pan - Moomowroong, Wiridjil & Pebble Point Formations	LTA - Lower Tertiary Aquifer	GFS11 - Wiridjil Gravel and equivalents
Ppw - White Hills Gravel		GFS 3 - Highlands gravel caps
Kl - Otway Group	BSE - Basement	GFS6 - Otway Group (Barrabool Hills) GFS9 - Otway Group rocks (Otway Range)
P - Wild Duck Formation & equivalents	BSE - Basement	GFS 3 - Highlands gravel caps
Dg - granitic rocks	BSE - Basement	GFS7 - Palaeozoic granitic rocks
Ol - Castlemaine Supergroup	BSE - Basement	GFS12 - Palaeozoic sedimentary rocks
Es - St Arnaud Group	BSE - Basement	GFS12 - Palaeozoic sedimentary rocks
Ev - Ceres Metagabbro	BSE - Basement	GFS7 - Palaeozoic granitic rocks

2.6.2 *Groundwater bore monitoring*

Regular groundwater monitoring for resource management commenced in the early 1970s following the introduction of the *Groundwater Act 1969*, and today there are at least 209 state observation bores located in the Corangamite region. Groundwater monitoring for salinity management commenced with the introduction of the first state and regional salinity strategies in the late 1980s (documented in Chapter 3). Approximately 580 salinity monitoring bores were believed to have been constructed in the Corangamite region during the first decade (1993 - 2003) of salinity management (Nicholson 2002). Although most bores were constructed by government drillers, few records of the construction details and lithological logs were kept.

Initially the monitoring and collation of the data was undertaken by a single state government department, but became increasingly fragmented following a series of reorganisations within the government departments and authorities from the late 1980s onwards. At present, the groundwater resource bores are regularly monitored by commercial contractors for the Department of Sustainability and Environment (DSE). The groundwater levels and salinities of the salinity bore monitoring network were initially measured by government monitors, but from the mid 1990s, the task was partly outsourced to community-based Landcare groups. The results of the monitoring was reported to the Corangamite CMA (and precursors) on an intermittent basis (e.g.Heislers 1995; Pillai and Heislers 2000). By 2003 the majority of the salinity monitoring bores were no longer monitored.

As a component of this research project, the Corangamite CMA funded a review of the salinity monitoring bore network in 2003 (Dahlhaus et al. 2004b). The research identified that 519 of the 580 salinity monitoring bores that were believed to have been constructed were registered on the government databases. Of these, a field checking program located 409 bores, with the remaining 110 consisting of 42 bores that could not be located with the information available, 62 that apparently did not exist at all in the area of their stated location (based on landholder information), and 6 that were located but their identity could not be determined. Of the 409 bores field checked, 75 (19 %) had broken standpipes, with 52 (13 %) broken at or below ground level and 23 (6 %) broken above ground level. The field checking measured 266 bores shallower than recorded (either due to silting or initially misrecorded) and 81 bores deeper than recorded. The report detailing the survey methods and results is appended (Appendix A).

One outcome of the review was the construction of a consolidated groundwater bore database for the Corangamite region (Dahlhaus et al. 2004b). The 9254 bores in the initial database were combined from 8058 bores on the state groundwater database, 677 bores on the state geology database, and 519 bores on the state salinity database. Of these, 956 had a groundwater level monitoring record (includes both monitoring for resource management and salinity management). In 2008 the bore database was completely rewritten and translated to a web-based GIS format, which is now continuously updated by data cleaning (removing duplicates, correcting data, etc.), adding new records and linking where possible to the original data sources. Quarterly monitoring of the salinity bores recommenced in the salinity management target areas in 2007 and the data is captured into the web-database (Dahlhaus et al. 2008b). In June 2009 the Corangamite bore database contains records of 9675 bores, of which 826 are monitoring bores (Figure 2.15). The bore database can be viewed at: http://www.ubspatial.com.au

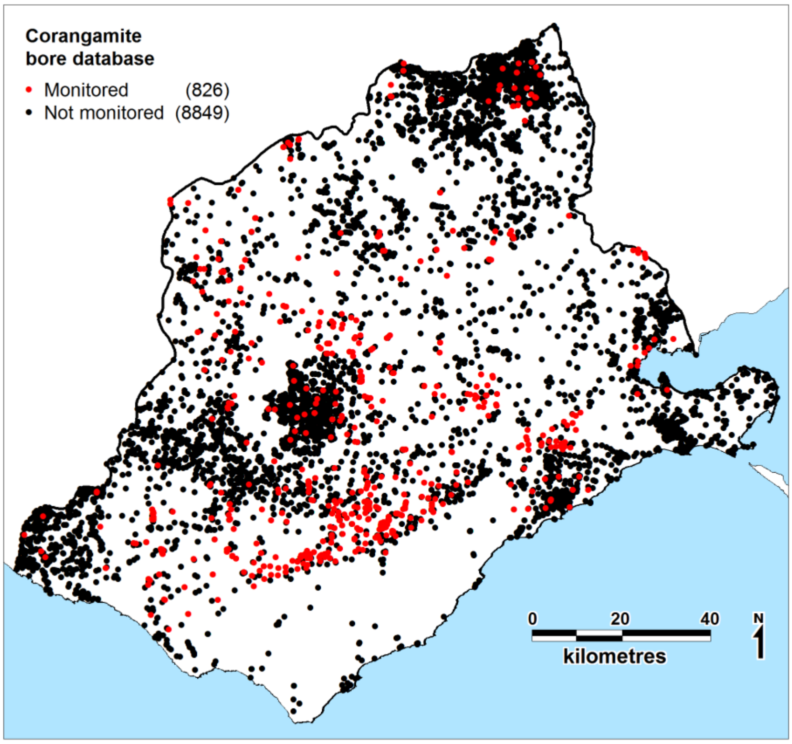


Figure 2.15 Distribution of bores in the Corangamite region

2.6.3 *Conceptual and numerical models*

In excess of 200 groundwater studies have been undertaken in the Corangamite region over the past 40 years, the vast majority of which are groundwater resource investigations at the local scale. In addition numerous hydrogeological models - both conceptual and numerical - have been constructed for the region, with the vast majority being numerical models constructed in the past decade. This section provides a brief summary of the more significant regional studies and models that provide insights to the hydrogeological systems which are relevant to the salinity processes.

2.6.3.1 Volcanic plains and lakes

The majority of the previous hydrogeological studies have focused on the volcanic plains and their shallow saline lakes, since this area combines the challenge of managing fresh groundwater resources adjacent to internationally significant saline lakes. The first significant hydrogeology study was that by Thompson (1971; 1972) who detailed the hydrogeology of the Warrion - Dreeite region. Thompson concluded that the groundwater evolves from low-salinity Ca-Mg-HCO_3 type at the recharge area (Mt Warrion) to high-salinity Na-Cl type further along the flow path towards discharge at the lakes. He attributes the source of the salts to connate oceanic water trapped in the underlying marls which were incorporated into the aquifer materials during volcanism. Thompson also recognises that the groundwater is a factor in the transfer of salts to and from the lakes, maintaining the lake salinities within narrow limits.

Limnology studies of the volcanic plains lakes in the Corangamite region (Bayly and Williams 1966; Maddocks 1967; Currey 1970; Timms 1976; Williams 1981; De Deckker 1982; Timms 1983; De Deckker and Williams 1988; Williams 1992; Gell et al. 1994; Gell 1995; Williams 1995; Gell 1998; Radke et al. 2002; De Deckker 2003; Tibby and Tiller 2007) have added a great deal of knowledge to the history of lake salinity throughout the Quaternary. This knowledge has contributed to the conceptualisation of a generalised temporal hydrogeological model of groundwater levels responding to climate oscillations throughout the Quaternary. This model is further supported by the studies of lunettes (Dimmer

1992; Tickell and King 1992; Edwards et al. 1996) and is discussed in more detail in Chapter 3.

With the introduction of salinity management plans a series of investigations were instigated by the water and salinity management authorities to examine the groundwater and salinity processes with the aim of protecting Lake Corangamite and the Barwon River from rising salinity (Nicholson et al. 1992b). Investigations by the Rural Water Commission/Corporation (RWC) in the late 1980s and early 1990s (Gill 1988; RWC 1989; Adams 1990; Nolan et al. 1990; Pamminger 1991) were enlightening in that they contrasted the salinity of the Western Uplands with that of the Western Plains, suggesting that the latter was a natural feature, whereas the former was induced by land use change. Rudimentary salt balance calculations showed that cyclic salt input over 2900 years could account for the salinity of Lake Corangamite, suggesting that periodic overflow or leakage are required to maintain the salinity levels (Gill 1988; RWC 1989).

Research undertaken by Coram (1996b; Coram et al. 1998) focused on the groundwater-surface water interactions around the shallow lakes using potentiometric surface analysis and water and salt balances. Coram confirmed interaction between the lakes and the groundwater system and identified some as 'throughflow lakes' (lakes Murdeduke, Bookar, Colongulac and Gnarpurt) or 'discharge lakes' (Lake Beeac and the other lakes of the Lough Calvert). Her thesis argues that differences are due to: variations in the local hydrostratigraphy downgradient of the lakes; differences in the relative proportion of groundwater discharged from the lakes compared with other inflowing waters; and differences in the TDS content and relative proportions of major ions in the lakes.

Coram found the chemical characteristics of lake waters to be dominated by Na^+ and Cl^-. Water budgets indicated that precipitation and evaporation were the dominant control on lake hydrology, at least an order of magnitude greater than the contribution of average surface inflows (which vary seasonally) and average groundwater inflows and outflows (which are relatively constant). Her salt budget analysis showed that groundwater and surface water contribute substantial amounts of salt to the lakes with the concentration of these salts dependent on the extent to which discharge of evaporatively concentrated lake waters occurs.

Coram proposed a density driven system in which the TDS content determines the groundwater discharge characteristics of lakes, with throughflow lakes having a salt mass discharge in the same order of magnitude as salt mass inflow.

The work of Gill (1988) and Coram (1996a) proposed that highly saline groundwater leaked from Lake Murdeduke into the Barwon River north of Winchelsea. This theory was tested by a series of investigations (Roderick 1988; Lamson 1990; SKM 1997a; Blackam 1999; Giles 2004) and found to be correct, with baseflow discharge occurring along an 8 km reach between Winchelsea and Inverleigh, causing a 40 % – 50 % increase in river salinity (SKM 1997a).

A series of numerical models using MODFLOW, a modular finite-difference flow model (McDonald and Harbaugh 1988) have been constructed in the volcanic plains region. The purpose of these varies from graduate research (Dickinson 1995; Blackam 1999); flow system mapping (Cox et al. 2007); prediction of land salinisation (Smitt 2007); and farm forestry impacts (Hawkins et al. 2007). The most informative on hydrogeology was that by Cox et al. (2007) who undertook an extensive research program to: construct the aquifer geometry in 3-dimensions; undertake hydrogeochemistry and isotope sampling to map flow paths; investigate the sources of salt and mobilisation processes; and map groundwater flow systems. This author contributed to the work by preparing the aquifer structure surfaces and isopach models based on the geology (section 2.2) and GFS (section 2.6.1) and sampling the groundwater for analysis. The methods and outcomes of the project are appended (Appendix A).

The steady state numerical model was constructed by Cox et al. (2007) used a 250m regular grid of two layers: the upper layer representing GFS1, 2, 10 & 14 (refer to Table 2.5) which are the unconfined aquifers; and the lower layer representing the pre-Pliocene aquitards and basement aquifer. Recharge was set at 1.0e-5 m/d (3.65 mm/yr) on the plains and 1.0e-4 m/d (36.5 mm/yr) on the scoria and stony rise areas. The hydraulic conductivity of the aquifer was modelled as 5 m/d based on historic pump tests and the hydraulic conductivity of the aquitard 1e-3 m/d. The resultant head contours are shown in Figure 2.16. Groundwater paths were modelled using Modpath (Pollock 1994), as shown in Figure 2.17 (Cox et al. 2007).

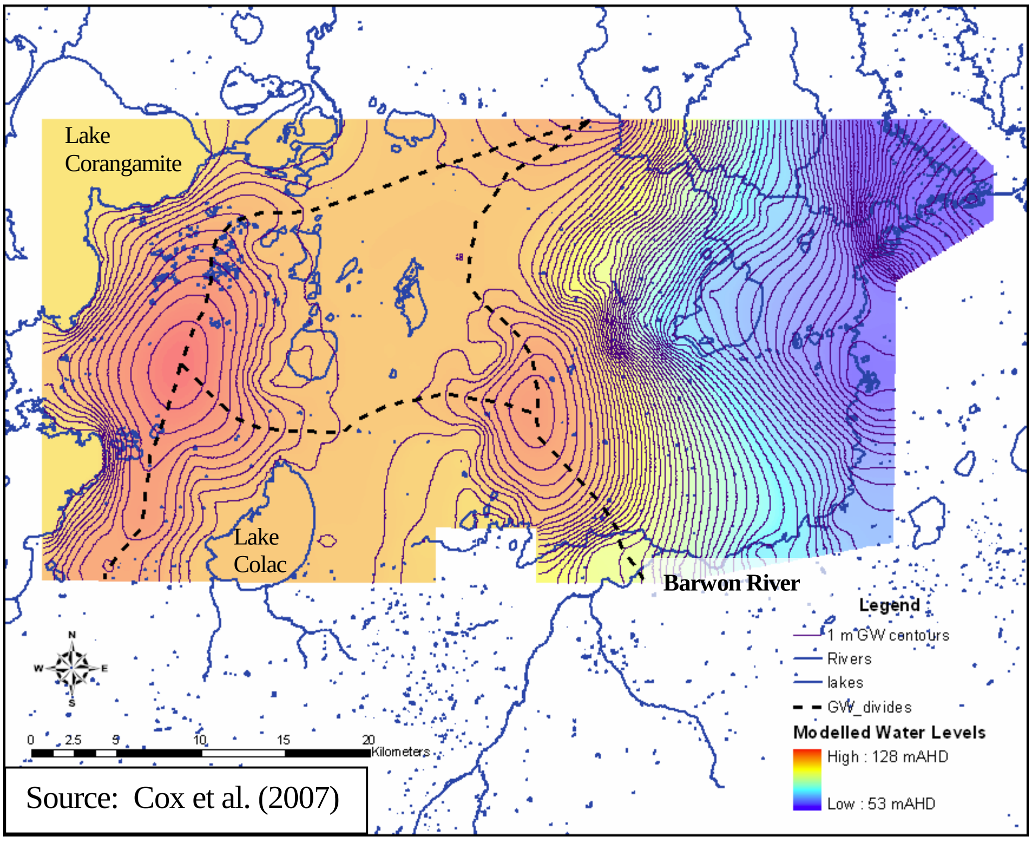


Figure 2.16 Model of watertable elevation and groundwater divides.

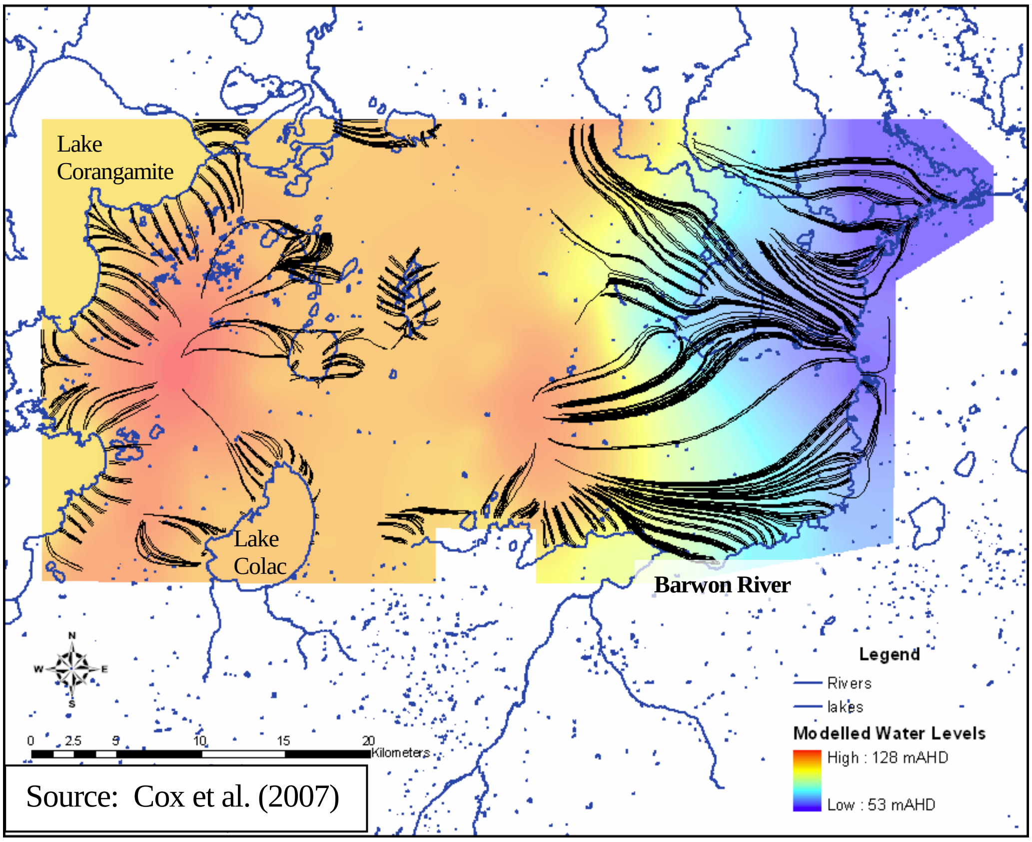


Figure 2.17 Pathlines around lakes and rivers in the model domain.

The 41 hydrochemistry analyses undertaken in the study by Cox et al. (2007) showed that groundwater quality in the basalts varied from very fresh (204 mg/L Total Soluble Salts - TSS) to quite saline (13,249 mg/L TSS). Groundwater in GFS13 - the Central Highlands volcanic rocks - showed uniformly lower salinity and higher HCO^{3-}/Cl^{-} than that observed in GFS14 - the Volcanic Plains Basalts - suggesting little connection between those two systems. The Pliocene Sands (GFS10) exhibit intermediate salinities and HCO^{3-}/Cl^{-} ratios distinct from GFS14, suggesting limited vertical connectivity. These results when combined with the more enriched ^{18}O isotopes in GFS14 suggest that there is little connectivity (i.e. groundwater fluxes) with the surrounding aquifers, relative to diffuse vertical recharge and lateral discharge.

Apparent ages of the water based on ^{14}C (38 samples) and CFC analyses (10 samples) indicated variation from decades to about 20,000 years (Cox et al. 2007). The youngest ages were associated with the low salinity waters of GFS13 and GFS2, whereas the oldest ages were associated with GFS14 and GFS15 (Subsurface Deep Leads). Groundwater ages along one west-east transect from Lake Corangamite to Winchelsea (Barwon River) suggested a horizontal flow rate of 15m/yr, which is quite rapid given the low hydraulic gradients.

Based on the comparison of Br^{-} and Cl^{-} ions to seawater, the source of the salt is clearly marine-derived aerosols (Cox et al. 2007). However the estimated residence time for the salt (1500 years) suggests that it is removed from the aquifer system, probably through historic flood events. Such events have not been recorded since European settlement.

More recent work on the lakes includes the assessment of the impact of irrigation (Adler 2003; Adler and Lawrence 2004; Barton et al. 2009 (in prep)). Extensive studies of groundwater - surface water interactions using mainly hydrogeochemistry and isotopes have been completed (Barton et al. 2006; Turnbull 2006; Barton et al. 2007; 2008; Herczeg et al. 2008) but are as yet largely unpublished in the scientific literature. The main outcome has been the development of tools to determine whether the Corangamite region lakes are surface water or groundwater dominant, and throughflow or terminal lakes. The studies use $(Ca^{2+} + Mg^{2+})/(Na^{+} + K^{+}) < 0.2$ and $HCO^{3-}/Cl^{-} < 0.1$ as indicators of groundwater dominance. The deuterium excess, where $d_{xs} = (\delta^2H - 8.\delta^{18}O)$ indicates the residence time of water in a wetland, with $d_{xs}<0$ indicates increasing groundwater dominance (Herczeg et al. 2008). More detailed reports on this work are appended (Appendix A).

2.6.3.2 Uplands

By comparison to the volcanic plains, the hydrogeology of the Uplands is much less studied, with most of the previous investigations focused on groundwater resource management than salinity management.

The hydrogeology of the volcanic and deep lead aquifers in the Upper Moorabool and Leigh rivers has been the most documented (Laing 1976; Nolan-ITU 1988; HydroTechnology 1994; SKM 1998b; URS 2002; SKM 2003; GHD 2004; Evans 2006), although mainly for resource assessment. The most comprehensive research related to salinity is that of Evans (2006), which is discussed in detail in Chapter 5.

The hydrogeology of the Palaeozoic basement aquifers is arguably the least known, since they are not widely utilised as a groundwater resource, except where mineral waters are found (Shugg 2004). Importantly to salinity management they are the source of much of the saline groundwater discharge (refer to Section 2.7 for confirmation). For that reason, some studies were undertaken in the Corangamite region that document conceptual models of groundwater flows and their implication in salinity processes (Kevin 1993; Mann 1993; MacEwan and Dahlhaus 1996; Dahlhaus and MacEwan 1997; SKM 1997b; Heislers and Pillai 2000; Smith 2001; Dahlhaus 2003; Church 2004; Horgan 2006; Mockunas 2007). Apart from the earlier conceptualisations that were borrowed from outside of the region (e.g. Kevin 1993), the models were developed to understand the salinity processes in specific landscapes. Taken as a whole, they confirm that the hydrogeology and salinity processes are uniquely dependent on the geology, geomorphology, climate and environmental history of each area studied.

As an example, the research undertaken by this author (Dahlhaus 2003 - Appendix A) included conceptual models for each of the salinity management target areas in the Uplands groundwater province (i.e. West Moorabool River catchment (Chapter 5); Morrisons - Sheoaks; Illabarook; and Pittong (Chapter 4)). The initial conceptual models of the Morrisons - Sheoaks and Illabarook areas were based solely on field observations of the geology, geomorphology and saline groundwater discharge. Both models proposed that the majority of the saline groundwater was discharged from the base of the erosional remnants - the Highlands gravel caps (GFS3) - overlying the Palaeozoic sedimentary rocks (GFS12). These theories were tested by Horgan (2006) in the Morrisons - Sheoaks region and Mockunas (2007) in the Illabarook - Mt Mercer area. Both studies used drilling, aquifer testing and hydrochemistry to formulate new conceptual models of the hydrogeology and salinity processes. Horgan concluded that the majority of the salinity was probably contributed from the Palaeozoic sedimentary rocks (GFS12), since the gravel caps (GFS3) were not as extensive as previously mapped. Mockunas concluded that the majority of the salinity was contributed by discharge from the Palaeozoic sedimentary rocks (GFS12) at Illabarook, whereas at Mt Mercer it was sourced from the Palaeozoic sedimentary rocks (GFS12), Deep Leads (GFS15) and Central Highlands volcanic rocks (GFS13).

The GFS in the Otway Group rocks are divided into the Otway Ranges (GFS9) and the Barrabool Hills (GFS6) on the basis of mapped salinity (Dahlhaus et al. 2002a). Saline groundwater discharge is known in the Barrabool Hills, but not in the Otway Range. The hydrogeology of the fractured aquifers of the Southern Uplands is largely unknown (Leonard 2002; 2003), especially the aquifer characteristics or groundwater flow regime in the Otway Group rocks. However, the Early Cretaceous Otway Group rocks are currently being actively explored for their geothermal potential (Greenearth Energy Ltd. 2009; Hot Rock Ltd. 2009), and the Late Cretaceous Sherbrook Group rocks (which do not occur in outcrop) are being explored for the potential to sequester carbon (CO2 CRC 2009). Leonard (2002) reports that the groundwater from the Otway Group (Eumeralla Formation) sampled in a number of petroleum exploration wells shows salinity (TDS) ranging from 1,000 mg/L and approaching seawater (35,000 mg/L) at depths over 1.5 km.

2.6.3.3 Otway basin

By contrast the Tertiary aquifers of the Otway Basin have been investigated for their groundwater resource (Blake 1978; 1980; Lakey and Leonard 1982; Leonard 1983; Lakey and Leonard 1984; Leonard 1985; Johnston 1992; CMPS&F 1997; Shugg and Jayatilaka 1998; Leonard 2002; 2003; Petrides and Cartwright 2006) almost all of which has been focused on the Lower Tertiary confined aquifers in the Barwon Downs Graben, used to supplement the urban water supply for Geelong.

Hydrogeological studies focussed on salinity have investigated the surface units, regarded as aquitards (Table 2.6). These have been delineated into two GFS on the basis of their hydraulic characteristics and response (Dahlhaus et al. 2002a) - the Heytesbury Marls (GFS4) and Gerangamete Marls (GFS5). Investigation of salinised land at selected sites in the Heytesbury (GFS4) has associated the salinity with the discharge of saline groundwater along preferred pathways associated with dramatic increase in landsliding since clearing (Dahlhaus et al. 1996; MacEwan et al. 1996; Dahlhaus and MacEwan 1997; Heislers and Pillai 2000; MacEwan et al. 2008). In the Gerangamete area (GFS5) extensive research at one site (Heislers 1998; Heislers and Pillai 2000; SKM 2002) has concluded that the salinity is due to the presence of shallow groundwater almost uniformly distributed across the undulating landscape (i.e. the watertable reflects the topography). In both areas, the waterlevels have remained relatively constant over the past 15 years, suggesting that the watertable in the aquitards may be influenced by the potentiometric head of the underlying confined aquifers (Dahlhaus 2003).

2.6.3.4 Port Phillip Basin

The hydrogeology of the Port Phillip Basin is relatively complex and has been extensively documented (e.g. Leonard 1981; 1988; 2003; Dahlhaus et al. 2004a). Within the boundaries of the Corangamite region (Figure 2.12), investigations of the hydrogeology have largely been confined to groundwater resources in the Eastern View Formation of the Torquay Embayment at Anglesea, used for power generation at the Anglesea coal mine (Hancock 1967; Stanley 1993; SKM 1998a; Alcoa 2002; Beattie 2003) and proposed to supplement the urban water supply for

Geelong (GHD 2008). On the Bellarine Peninsula exploration for groundwater resources (Esplan 1956; Medwell 1957; 1958; Esplan 1962) was unsuccessful. Mineral springs along the northern edge of the Bellarine block were used by the early settlers (Shugg 2004), the source of which is believed to be the Older Volcanics (GFS8) and the Fyansford Formation (GFS5) (Shugg 2001; SKM 2005; Miner and Dahlhaus 2008).

Hydrogeological investigations for salinity management are scarce. Limited research for this thesis (Dahlhaus 2003) and recent investigations of the groundwater - surface water interactions of the lower Barwon River, wetlands and estuary (Mockunas 2006; Dahlhaus et al. 2007; Keogh 2009) confirm the complexity of these systems, which are known to be critical for sustaining the biodiversity values (Ecological Associates 2006).

2.6.4 Groundwater data sources

Many of the unpublished groundwater studies have been made available through the Corangamite Knowledge Base, which was established to make available the 'grey literature', related to all aspects of catchment management. The database is available at: http://www.ccmaknowledgebase.vic.gov.au/ccma/page/search.htm.

2.6.4.1 Corangamite groundwater monitoring and research database

As described in section 2.6.1, the Corangamite groundwater bore and monitoring database is available at: http://www.ubspatial.com.au/. The groundwater database is an outcome of this PhD project and managed by this author. An on-going project is adding value to the data by: linking to the original data sources where possible; checking and cleaning each bore record; adding enhanced import and export tools; adding red-lining and wiki capability; and establishing interoperative GIS links to other bore databases managed by others.

2.6.4.2 Groundwater flow systems

The Corangamite GFS are provided with the full list of attributes described by Dahlhaus et al (2002a - Appendix A). In most cases the GFS polygons match seamlessly to those of the Port Phillip and Westernport GFS to the east (Dahlhaus et al. 2004a) and Glenelg Hopkins GFS to the west (Dahlhaus et al. 2002b) (Appendix B).

2.6.4.3 Depth to watertable mapping

One of the initial factors for the selection of the Corangamite region in the National Action Plan for Salinity and Water Quality (CoAG 2000) was the depth to watertable predictions for the region in the National Land and Water Resources Audit (NLWRA 2001). The initial predictions were based on coarse resolution data available at the time (Figure 2.18; SKM 2000). In late 2005 statewide re-evaluation of the depth to groundwater maps and predictions were completed by Sinclair Knight Merz (SKM) for the Audit. The revised version was based on finer resolution digital elevation models and a different interpolation algorithm (Peterson et al. 2003; Peterson and Barnett 2004a; 2004b). The resulting numerical surfaces show considerably less area predicted to experience shallow watertables in 2050 than previously predicted. Concerns over the validity of the models (DPI 2008a) resulted in another version generated in 2008 (SKM 2008) in which predictive scenarios were no longer made.

The depth to groundwater models were made available as grids as detailed in Appendix B.

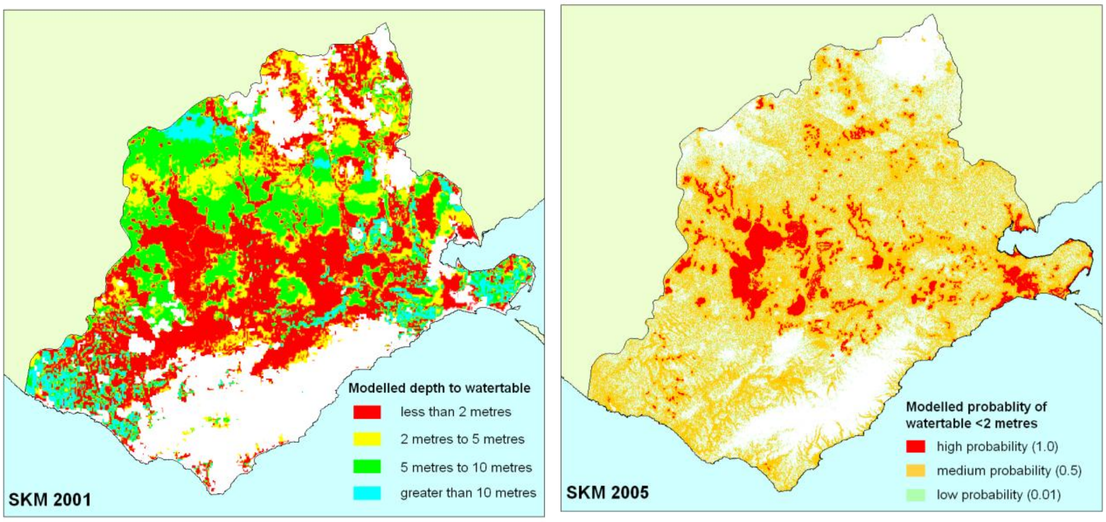


Figure 2.18 Depth to groundwater models predicted for 2050 (worst case).

2.7 Mapped salinity

The area of land salinised in parts of the Corangamite region has been assessed on numerous occasions over the past 30 years. A brief summary of known surveys is listed in Table 2.7 and some of these reports are appended (Appendix B). All areas of the Corangamite region have been mapped by at least one survey, although the spatial extent and quality of salinity mapping has probably been influenced by the funding available at various times. Some of the investigations are discussed in more detail in Chapters 3 and 4.

Table 2.7 Known salinity mapping projects in the Corangamite region.

Date	Author	Study / Region
1952 - 1958	Cope (1955; 1958)	Victorian salinity study: Salinity sites at Barrabool Hills, Berringa, Birregurra, Cressy, Mount Moriac, Murroon, Pitfield, Pittong, Ross Creek, and Winchelsea districts.
1976 - 1980	Duff (1983)	M.Ag.Sci. thesis: Whole of the Corangamite region except the Otways.
1988	Sturmfells (1988)	Salinity Control Strategy project: Ballarat region.
1988	Calcutt (1988)	Shire of Heytesbury salinity project: Heytesbury region.
1991 - 1992	Scott (1992)	Salinity Management Plan project: Geelong and Bacchus Marsh regions.
1994	Whattam (1995)	Corangamite Regional Salinity Strategy project: Heytesbury region.
1999 - 2008	Clark & Hekmeijer (2004; 2008)	Victorian Dryland Salinity Monitoring Network sites: Beeac, Gerangamete, Moriac, Pittong & Wingeel.
2001	Gardiner (2001)	Corangamite Discharge Mapping project: Random selection of 15% of mapped salinity in the Corangamite region.
2002	Nicholson et al. (2003)	Corangamite Salinity Action Plan project: Community identified additions to mapped salinity in target areas.
2003	Wagenfeller (2004)	Woady Yaloak Catchment Group project: Pittong and Illabarook areas.
2005	DPI (2006)	Salinity Management Overlay project: Designated growth corridors in Colac Otway, Corangamite, Golden Plains and Surf Coast shires.
2008	DPI (2008b)	Salinity Management Overlay project: Designated growth corridors in City of Ballarat, City of Greater Geelong, Moorabool Shire and Borough of Queenscliff.
2008-2009	DPI (unpublished)	Corangamite land salinity monitoring project: 24 sites in the salinity management target areas.

The mapped salinity polygons were initially amalgamated and rationalised into a single GIS data layer. However the consistency of the data varied considerably between the surveys, with some surveys capturing wetland and stream salinity as well as land salinity. As a result, three categories of salinity emerged as useful to this research, *viz:* dominantly primary salinity; dominantly secondary salinity; and saline wetlands.

Dominantly primary salinity is regarded a site where the natural salinity was present in the landscape before widespread land use change by European settlement. The identification of primary salinity is difficult, but mainly made on the basis of salinity indicator vegetation (DPI 2006; DPI 2008b). By observing the structure and variety of halophytic plants, an inference can be made about the likelihood of the site being naturally saline. A site is more likely to be a primary site if it has a high diversity of native salt tolerant plants that have low capacities for colonising newly saline sites (Allen 2007). Naturally, if the area of the primary site has spread as a result of anthropogenic changes (i.e. secondary salinity), then the assertion is less valid. Similarly, a site with a few slow colonisers may in fact be a secondary salinity site, or it may be a degraded primary site.

The likelihood of a site being a primary salinity site was also determined using historic information, especially by correlating the site to historic aerial photographs and maps. For example, if a site was in an area indicated as an ephemeral swamp or 'land subject to inundation' on the early topographic maps (e.g. the 1:63,360 scale Army Ordinance Maps dating from 1916 onwards) or geological maps (e.g. the 1:31,680 scale 19th century Quarter Sheets and early 20th century Parish Plan series), then it was considered more likely to be a primary salinity site.

Dominantly secondary salinity is regarded a site where salinity has been induced by anthropogenic land use change since European settlement. It is also mainly recognised by vegetation indicators, with abundant halophytic species considered efficient colonisers, or ruderal species (DPI 2006; Allen 2007; DPI 2008b). It is acknowledged that degraded primary sites may be misidentified as secondary, especially where disturbance has decreased the diversity of non-ruderal species; and increased the diversity of ruderal species. However, where doubt existed as to the categorisation of the site, it has been nominated as dominantly secondary salinity by default.

Saline wetlands are those categorised by Corrick (1982) as either 'permanent saline' or 'semi-permanent saline'. Wetlands are classified as saline if the average annual salinity of the water exceeds 3,000 mg/L TDS (Corrick and Norman 1980). A permanent saline wetland includes coastal and intertidal wetlands, as well as inland salt lakes such as the deeper part of Lake Corangamite and Lake Murdeduke. A semi-permanent saline wetland may be inundated to a depth of

2 m for up to 8 months of the year. In addition salt works have been added to this category as these had been previously mapped (DSE 2004b). The Corangamite region includes significant proportions of Victoria's semi-permanent saline (13 %), permanent saline (58 %) and salt works (82 %) wetlands (Sheldon 2005).

In terms of distribution, the saline wetlands occupy the greatest area (Figure 2.19; Table 2.8). For land salinity, primary salinity sites occupy a greater area, but there are more than twice as many secondary salinity sites as there are primary sites.

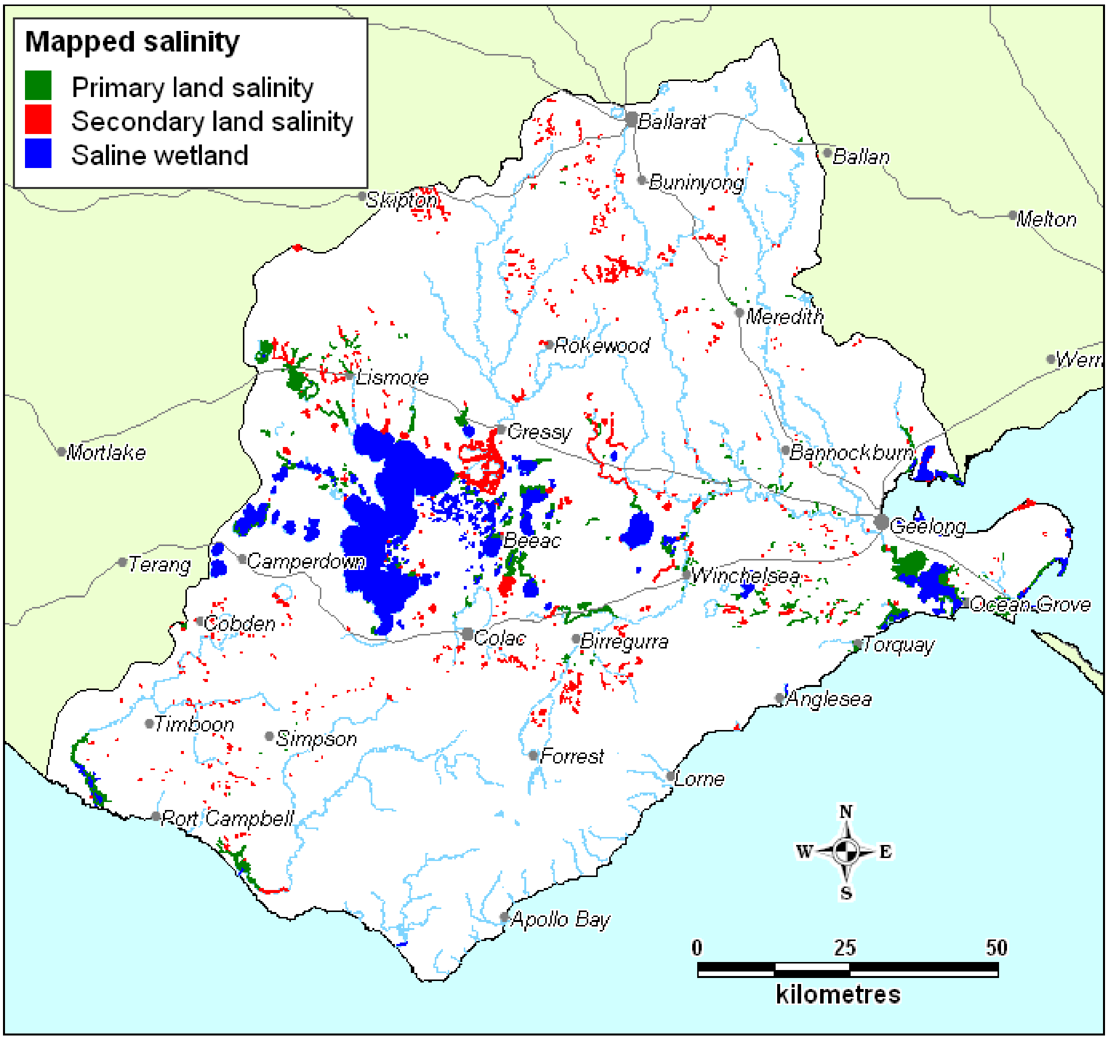
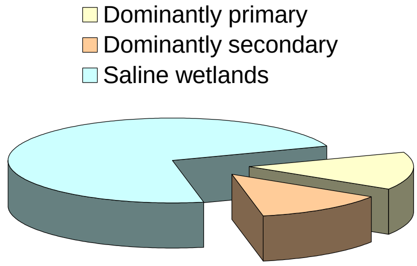


Figure 2.19 Mapped salinity in the Corangamite region.

Table 2.8 Types of salinity in the Corangamite region

Type of salinity	Saline sites (number)	Total salinity (hectares)
Dominantly primary	422	9,183
Dominantly secondary	1,075	8,084
Total land salinity	**1,497**	**17,267**
Saline wetlands	454	45,731
Total salinity	**1,951**	**62,998**



2.7.1 *Relationship of salinity to biophysical parameters*

To conclude this chapter, the relationship of the various biophysical elements to the distribution of salinity in the Corangamite region is investigated. A simple GIS analysis in which the distribution of mapped salinity within each element has been calculated, as tabulated below (Tables 2.9 & 2.10), is initially informative.

Obvious correlations fall out of this exercise, e.g. there is roughly equal area and number of sites of primary land salinity in the Barwon and Lake Corangamite drainage basins; the vast majority of salinity occurs on the Western Plains; comparatively few primary salinity sites occur in areas receiving over 700 mm annual rainfall compared to secondary sites; similarly for areas with less than 1050 mm annual pan evaporation; etc. These simple correlations assist in identifying the landscape elements in the distribution of salinity.

Similarly obvious relationships between salinity and GFS can be seen, e.g. the vast majority of sites in both number and area occur on GFS1; whereas there is virtually no salinity mapped in GFS8, GFS9 & GFS11.

However, while these data are informative in identifying some of the landscape elements correlated with the distribution of salinity, they do not take into account the temporal variations in the elements and the causal relations between the variables.

These factors are explored in the following chapters.

Table 2.9 Occurrence of salinity in relation to catchment parameters

	Dominantly primary		**Dominantly secondary**		**Saline wetland**	
	No. sites	Area (ha)	No. sites	Area (ha)	No. sites	Area (ha)
Drainage Basin						
Barwon	151	3688.9	359	2253.9	110	6671.5
Moorabool	25	176.0	54	232.7	16	937.4
Lake Corangamite	132	3517.2	384	4783.0	287	36352.0
Otway Coast	111	1359.8	279	724.3	40	1408.7
Geomorphic province						
Western Uplands	26	51.3	317	1362	0	0
Western Plains	355	8593.3	603	5951.2	447	45616.8
Southern Uplands	52	532.1	166	771.2	14	110.0
Average Annual Rainfall						
< 500 mm	3	38.5	7	37.3	3	92.0
500 - 600 mm	156	4055.4	226	3788.3	202	19016.0
600 -700 mm	231	4067.3	415	2876.4	241	24147.9
700 - 800 mm	24	96.9	209	597.5	6	1701.2
800 - 900 mm	10	640.2	139	518.9	23	357.9
900 - 1000 mm	19	189.4	115	239.9	5	16.7
>1000 mm	2	0.6	15	12.4	1	19.2
Average Annual Pan Evaporation						
<1050 mm	5	11.3	12	24.7	0	0
1050 - 1100 mm	18	38.6	180	747.5	0	0
1100 - 1150 mm	6	2.1	167	706.4	0	0
1150 - 1200 mm	232	4754.4	549	5612.1	317	37235.9
1200 - 1250 mm	122	1242.6	187	608.0	39	2949.5
>1250 mm	60	3039.4	47	372.2	111	5165.7
Bioregion						
Central Victorian Uplands	15	27.2	243	1057.6	0	0
Otway Plain	145	3454.8	225	1138.4	99	4500.3
Otway Range	0	0	1	1.3	0	0
Victorian Volcanic Plain	256	4875.3	430	5433.9	339	40632.6
Warrnambool Plain	24	824.4	211	453.3	23	597.9
Land use (2003)						
Grazing	607	5498.3	990	4965.4	493	3654.0
Dairy	79	453.1	314	484.0	38	357.6
Forestry	18	169.5	46	198.5	4	29.3
Conservation	217	2186.3	82	993.8	304	39503.2
Cropping	67	270.1	110	296.8	38	148.3
Urban	64	181.1	38	84.8	44	975.2
Peri-urban	23	25.4	54	95.5	6	1.9
Horticulture	10	15.4	5	6.1	0	0

Table 2.10 Occurrence of salinity in relation to GFS

	Dominantly primary		Dominantly secondary		Saline wetland	
	No. sites	Area (ha)	No. sites	Area (ha)	No. sites	Area (ha)
GFS1 Quaternary sediments	283	6369.0	423	4366.1	456	42704.8
GFS2 Scoria and stony rises	50	418.5	58	266.6	169	1291.9
GFS 3 Highlands gravel caps	8	15.0	70	290.4	0	0
GFS4 Heytesbury Marls	9	79.2	116	148.8	2	2.2
GFS5 Gerangamete Marls	39	126.4	91	455.8	8	49.5
GFS6 Otway Group (Barrabool Hills)	8	8.1	23	27.6	2	17.3
GFS7 Palaeozoic granitic rocks	11	23.5	54	287.7	0	0
GFS8 Older Volcanics	1	0.04	0	0	0	0
GFS9 Otway Group rocks (Otway Range)	0	0	6	4.5	0	0
GFS10 Pliocene sands	119	771.5	139	373.7	51	478.5
GFS11 Wiridjil Gravel and equivalents	0	0	1	17.5	0	0
GFS12 Palaeozoic sedimentary rocks	11	6.0	157	426.9	0	0
GFS13 Central Highlands volcanic rocks	30	133.5	75	272.0	0	0
GFS14 - Volcanic Plains basalt	92	966.5	106	836.2	60	731.0
GFS15 Subsurface Deep Leads (subsurface unit)	n/a	n/a	n/a	n/a	n/a	n/a
GFS16 Port Campbell Limestone	8	125.1	37	48.0	4	15.0
GFS17 Dilwyn Formation	7	104.6	61	244.0	1	240.7

2.8 Development of research questions

The purpose of this chapter is to explore the extent of the available data and assemble the sources of evidence that can be used to derive the holistic 'big picture' for salinity processes in the Corangamite region. In undertaking this collation, the extents, limitations and gaps in information and knowledge have been clarified. In summary:

- The available data on the Corangamite region includes high-resolution and current datasets for topography, climate, geology, geomorphology, soils, vegetation, land-use, stream hydrography, groundwater bores, and mapped salinity. In addition to these scientific data, sufficient qualitative data is available on the history of environmental change, salinity policy development and investment, which are relevant when researching the salinity risk using a systems thinking approach.
- The geological framework and evolution of the broad-scale landscapes is well researched and documented in government reports, scientific literature, and peer-reviewed scientific papers. The region's geology has been used as the basis for the broad-scale hydrogeological frameworks developed to date (Dahlhaus et al. 2002a; Leonard 2003; Gill 2009).
- Aspects of the hydrogeology of the Corangamite region have been investigated in numerous (estimated >200) government surveys and consultancies which are documented in unpublished reports, government documents and conference papers (including some by this author). By comparison, there are a small number (estimated <10) of hydrogeological papers published in peer-reviewed journals. The majority of previous work has been focused on specific issues, problems or sites, with the emphasis on groundwater resource management, rather than salinity management.
- Salinity has been well documented as an issue in the Corangamite region. Since the late 1980s, the extent of salinity and its impacts on economic, environmental and social assets is recorded in policy documents accepted by the Federal and State governments. Salinity has been universally regarded as a threatening process, although there is scant published peer-reviewed science on

the extents of the threats or the risk to assets. The few peer-reviewed published scientific papers on salinity processes have largely been in relation to the saline wetlands, especially their limnology, palaeolimnology, chemistry and ecology.

- In the majority of the previous investigations, the causes of salinity in the Corangamite region have been assumed, with salinity process models adopted from research in other regions of Australia. Although land use change has been assumed as the cause of salinity, none of the previous studies have examined the relationship between the environmental history and salinity processes. The numerous investigations on the causes of salinity in the region have adopted reductionist methods at a site scale, with none published in peer-reviewed scientific journals.

The extent of the available data (both quantitative and qualitative), and the gaps in the previous research (inside and outside the scientific domain), influence the research questions of this thesis. The three principal questions that emerge are:

1) Are the assumed causes of salinity valid in the Corangamite region?

   The relationship between widespread land-use change and the onset of salinity has not been tested in the Corangamite region. In particular, that the clearing of native vegetation has resulted in rising saline groundwater has been assumed from the research conducted in Western Australia (e.g. Wood 1924; Peck and Williamson 1987) or the Murray Darling Basin (e.g. Macumber 1991). The validity of this assumption is tested for the entire Corangamite region using evidence drawn from a variety of scientific and non-scientific sources in Chapter 3.

2) Are the assumed processes for secondary salinisation valid?

   In policy documents and previous investigations in the Corangamite region, the assumed cause of the secondary salinity threat to assets is the hydrologic response of groundwater levels following widespread land-use change. Government investment is based on this assumption (i.e. the GFS framework) and therefore remedial actions are based on restoring hydrologic equilibrium (CoAG 2000). The validity of this assumption is tested for two areas in the Corangamite region: one where agricultural land assets are threatened (the Pittong region, Chapter 4); and the other where urban water resources are threatened by stream salinity (the West Moorabool River catchment, Chapter 5).

3) Is the salinity threat and risk to assets valid?

   The salinity threat in the Corangamite region has always been assumed, but it could be argued that some salinity may also be an asset. This is implicit from the limnological and ecological (peer-reviewed) research on the wetlands. Williams (1995) argues that it is the rate of change of salinity in Lake Corangamite that threatens its ecological value, not the salinity itself. In fact, a certain range of salinity is essential for the health of the Ramsar wetlands, regarded as the region's foremost assets (CCMA 2003). The question of salinity risk is explored in Chapter 6.