Framework for a Regional Water Balance Model for the South Australian Limestone Coast Region

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Editors

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Executive Summary

Background

A lack of understanding of the regional water balance is still a fundamental knowledge gap limiting the water allocation planning process for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). A regional scale three-dimensional numerical groundwater flow model of the Lower South East region of South Australia, and in particular of the LLC PWA, is required to:

- Help quantify regional water balance components as well as inter-relationships between regional recharge, flows between the unconfined Tertiary Limestone Aquifer (TLA) and the Tertiary Confined Sands Aquifer (TCSA), groundwater storage, and groundwater discharge.
- Address questions relating to specific components of the regional water balance that arise through the water allocation planning process.
- Contribute to a consistent framework for the future development of local-scale numerical groundwater flow models which may be designed to address local-scale issues and thereby further support water resources planning in the Lower South East region.
- Guide future technical work in the Lower South East region by refining the understanding of critical processes influencing water movement and availability, and by identifying locations where such processes are most significant.

Phase 1 of the South East Regional Water Balance project is the first component of a longer-term research program to develop a regional water balance model for the LLC PWA. It has involved three tasks, all aiming to lay the foundations for the development of the regional water balance model:

1. Development of a regional water balance framework.
2. Preliminary assessment of the spatial variability and indicative fluxes of groundwater discharge to the marine environment.
3. Assessment of the role of geological faults on regional groundwater flow and inter–aquifer leakage.

The area of interest for the project is the LLC PWA; however the study area and likely model domain have been selected, based on inferred hydrogeological boundaries, to be broader than this. As a result, the study area for the project extends across the South Australian/Victorian border and includes a significant portion of the Border Designated Area.

The regional water balance framework, which has been developed in Phase 1 of Task 1 includes a database of all available relevant datasets and conceptual information about the system to be modelled, as well as the design of the modelling approach to be taken. The latter includes development of the modelling objectives from the over-arching policy questions, an assessment of how the model should interact with other models for the region, as well as development of recommendations for various aspects of the model design, including the model platform, model domain, spatial and temporal discretisation and implementation of boundary conditions. This report describes the results of this, as well as some key products derived from the basic data. The Phase 1 outcomes of Tasks 2 and 3, which are technical component studies designed to address two critical knowledge gaps influencing model outcomes, (a) regional groundwater flow through faults and (b) submarine groundwater discharge, are also presented.

Key Results

Regional Model Framework

The proposed design for a regional numerical groundwater flow model of the LLC PWA has been outlined in detail in this report and most of the basic data required for its development collected, including aquifer property and hydraulic head data, surface water information, groundwater extraction and hydrochemistry data. Key features of the proposed model are that it would:

- Cover the Gambier Basin of the Otway Basin and the south-western margin of the Murray Basin.
- Have three hydrogeological layers, including the regional unconfined aquifer, the regional confined aquifer, and the intervening aquitard unit.
- Have a maximum grid size of 1000 m x 1000 m, with refinement of this grid where required, to enable reasonable computational times.
- Be developed within the modelling platform MODFLOW-2000 or a recent update (MODFLOW-USG).

The purpose for the model will be to address regional scale problems, such as the response of the groundwater system to changes in water allocation policy, land use or climate. The model would also give a regional context to more local problems, such as when evaluating environmental water requirements for individual wetlands. However, the regional groundwater model will need to be complemented with finer-scale models to evaluate these local scale impacts in detail.

Stratigraphy

As part of the regional water balance model framework for Task 1, a new hydrostratigraphic model was developed for the inter-jurisdictional study area. Whilst separate hydrostratigraphic models existed for the South Australian and Victorian sides of the border, a model of the entire Gambier Basin, allowing for cross-border hydrogeological assessments did not previously exist. Similarly, previous groundwater flow models have also focused on either one or the other side of the SA-Victorian border. DEWNR was in the process of revising the hydrostratigraphic model for the South Australian portion of the study area and, in collaboration with this project, this was extended to the Victorian portion by obtaining and collating the relevant Victorian data and re-interpolating the stratigraphic surfaces. A preliminary model has been produced and checked against existing cross-sections and local hydrogeological knowledge. The model domain includes the Gambier Basin as well as the south-west margin of the Murray Basin, with the domain governed by natural groundwater flow barriers and divides. Although the model generally matches well with existing hydrogeological interpretations, some areas that disagree with the local hydrogeologists' understanding have been identified (J. Lawson, pers. comm., 2013). These are predominantly areas around the border area where stratigraphic layers appear to pinch out in the model but drilling records suggest that this is not the case. The datasets causing this inaccurate interpolation are currently being revised.

Recharge

The groundwater recharge component of Task 1 estimated recharge for the entire study area from observational data using (1) the watertable fluctuation method (WTF), (2) the chloride mass balance method (CMB), and (3) a water balance using satellite-derived estimates of actual evapotranspiration (Satellite ET). These methods vary in the type of recharge they estimate (gross or net), and are complimentary but not comparable. Estimates of mean recharge rate over the entire study area from the three methods were:

- WTF method: gross recharge of 84 mm/year (ranging from 2–259 mm/year at a given location).
- CMB method: net recharge of 21 mm/year (with a plausible range of 13–34 mm/year).
- Satellite ET method: net recharge of -5 mm/year (that is a net discharge), which equates to -0.9% of modern annual rainfall.

For the LLC PWA, estimates of total annual recharge influx were 1,241 GL/year (gross) for the WTF method, 411 GL/year (net) for the CMB method, and 37 GL/year (net) for the Satellite ET method. A decreasing trend in gross recharge of almost 1 mm/year was observed over the period 1970 to 2012 from the WTF method. The cause of this trend (whether climate or development related) was not determined during this study.

The mean net recharge (as percentage of rainfall) was estimated by vegetation type using the Satellite ET method as follows (with negative values representing a net discharge):

- crops: +2.8%
- pastures: +1.4%
- native vegetation: -3.6%

- softwood forestry: -9.7%
- hardwood forestry: -16.4%
- irrigation areas: -13.4%.

It should be noted that, in these results, considerable variability exists within each vegetation type. The Satellite ET method produced some interesting results with regards to the relationship between net recharge and depth to watertable (DTWT) under plantation forestry. Estimated recharge for softwood forestry land use over sandy (i.e. lighter textured) soils is consistent with the results of Benyon et al. (2006), with greatest discharge occurring when the DTWT is less than a few metres and reducing with depth until negligible beyond 6 m DTWT. For heavier textured soils (i.e. clay content 5–25%), maximum groundwater discharge occurred when DTWT was within 3–7 m of ground surface, with discharge decreasing to zero at depths of greater than 7 m. The maximum DTWT at which vegetation could access groundwater was 9, 13 and 16 m for soils with clay contents of 5–10%, 10–15% and 15–25% respectively. For soils with higher clay contents, the depth at which trees could access groundwater was estimated to be greater than 20 m.

Historical land use

The value of historical land use data sets in relation to understanding historical patterns in recharge was recognised in the development of the framework for the regional water balance model. These historical patterns in recharge are especially important for the calibration phase of regional groundwater models. Two methods for developing land use datasets were investigated as part of Phase 1 of Task 1 of this project. These methods are the interpretation of Landsat satellite image data for the years 1975 to 1995 and collation and interpretation of historical Agricultural Census data for the years 1857 to 1974 (South Australia only). Demonstration land use maps have been developed in Phase 1 of this project for the years 1890, 1925, 1935, 1955, 1964 and 1995.

These maps showed remarkable changes in land use over relatively short periods of time. For example, in the County of Grey, the original wheat-sheep farming of the late 1800s was replaced by a more varied production system in the 1920s and 1930s, but the area under cultivation was smaller. In the 1950s and 1960s the area under cultivation further decreased, but the production systems became less diverse again. Importantly to the estimation of historical recharge, the historical land use study has identified and mapped patterns of clearance of native vegetation in the South Australian portion of the study area since the mid-1800s. These maps are preliminary and require refinement using ancillary data and further analysis, but this is a major step forward in understanding historical recharge rates in the South East.

Submarine groundwater discharge

Determining boundary conditions at the coastline is a challenge for regional groundwater models. A suite of environmental tracers were evaluated to determine the ones most suitable to locate and quantify submarine groundwater discharge (SGD) in the Port MacDonnell to Victoria sections of the study area. The tracers tested included temperature, salinity, radon-222, the radium quartet (Ra-223, -224, -226 and -228), the stable isotopes of water and helium-4. The usefulness of the tracers was evaluated by measuring their characteristic signatures in different water sources (regional groundwater, creeks and drains, coastal springs and recirculated seawater) relative to seawater.

Salinity and radon activity in the surf zone or in intertidal groundwater could locate point or diffuse groundwater discharge at the coastline, but it remains unclear whether these tracers could be used in a similar fashion offshore. Helium-4 was not found to be a useful tracer because it was at background concentration in most source waters. Radium-derived offshore diffusivity estimates (i.e., a measure of the tendency for solutes released at the coastline to move offshore) and the offshore radium-226 flux were the highest measured to date in Australia. This indicated that strong hydrodynamic mixing occurs over the continental shelf in the Southern Ocean. While the offshore radium-226 flux was high, the main source of radium appears to be recirculated seawater, not groundwater discharge. Based on the available evidence, most of the SGD between Port MacDonnell and the Victorian border occurs close to the coastline (<1 km), not offshore. However, offshore groundwater discharge could mix with seawater in the seabed rather than at the seabed surface, making its detection with the tools used here more difficult.

Faults

The task on the influence of geological faults on groundwater flow involved the sampling of twelve groundwater wells located adjacent to two regional geologic faults (Tartwaup and Kanawinka) for hydrochemistry and environmental tracers. The results did not identify significant, consistent trends associated with well location or sampling depth, but this was likely to be due to the wells being unscreened (that is, being open holes intersecting several geological formations rather than discrete ones). However, the results achieved, and some preliminary modelling of groundwater flow and age transport suggest that the completion of these wells as multi-level piezometer nests would enable discrete hydrochemical and environmental tracer sampling of hydrogeological units at different depths. The results of such sampling could enable the quantification of groundwater flow rates which could then be used to help constrain the estimation of hydrogeologic parameters in the regional numerical groundwater flow model.

Conclusions and Recommendations

The first phase of the South East Regional Water Balance project was more than a simple data-gathering exercise as several higher-level products were developed. A preliminary cross-border hydrostratigraphic model has been developed for the study area and this is continuing to be refined. In the recharge estimation study, an assessment of modelling requirements have led to the conclusion that a look-up table approach is the most appropriate way to represent the spatial variability of recharge in the regional groundwater flow model. Such look-up tables would be based upon the variables that influence the magnitude and direction of recharge: monthly rainfall, month of the year, vegetation type, soil type and depth to watertable. The land use change evaluation has provided snapshots of land-use in the South East since the days of European settlement. These land use maps are extremely valuable in developing models of recharge as they can provide more realistic historical calibration, as well as having other diverse applications.

Despite the development of a large dataset to support the model development and clear recommendations for the model design, as well as some high value stand-alone outputs, a number of challenges remain to develop the regional water balance model, including to:

- determine suitable boundary conditions at the coastal boundaries
- realistically but practically represent the role of drains and other watercourses in the regional groundwater balance
- determine how to include the impact of faults in the regional flow systems.

A number of recommendations can be made to help future developments of the regional model. For land-use mapping:

- There is scope to further develop the methodology used to generate the land use maps for the South East, for example incorporating ancillary information with the Agricultural Census and Landsat data used to date.
- Due to the quality of the historical information available, a potential exist to generate a 'seamless' record of land-use in the South East since the 1850s by applying the methodology developed in this project to all years where information is available. This may improve the calibration phase for the regional groundwater model by enabling more precise estimations of historical variations in recharge rates.

For submarine groundwater discharge:

- Inshore (<1 km) groundwater discharge could be evaluated in more detail using high resolution surveys of salinity, temperature and radon-222 in seawater and intertidal groundwater.
- Offshore submarine groundwater discharge may be best evaluated by looking for evidence of freshwater in the seabed rather than in the water column.
- Two dimensional cross-sectional models could be used to further characterise SGD processes along the coastline, including for evaluating the role of the large coastal lakes (Lake George, etc) on regional groundwater flow processes.

- Use ground-based and aerial geophysics to further determine variations in the depth to the saline interface along the coastline

For future investigations of groundwater flow across the Tartwaup and Kanawinka faults:

- Complete the recently-drilled (c.2009) wells as multi-level piezometer nests.
- Extend the deep (i.e. >100 m depth) wells to intersect the confined Dilwyn Sands aquifer to investigate the upward flow of older water from the regional confined aquifer into the regional unconfined aquifer. Deeper well completions (followed by installation of multi-level piezometer nests) could provide significant insight into connections between the confined and unconfined aquifers.
- Undertake additional drilling along the Kanawinka Fault transect to better identify the location and offset of stratigraphic displacement.

It is also recommended that local scale models of groundwater – surface water interaction in wetlands be developed to help evaluate impacts on individual wetlands within the context of regional changes in groundwater flow systems. These models should be developed in close collaboration with the regional water balance model project so that the two scales of models can interface most effectively.

1 Introduction

Sébastien Lamontagne and Nikki Harrington

1.1 Project background

The South East Water Science Review (2011) concluded that, based upon existing knowledge, water use is currently within sustainable limits at the Prescribed Wells Area level for the Lower Limestone Coast. However, due to a number of gaps in understanding of processes that affect the regional water balance, there is uncertainty about the amount of water that can be extracted sustainably from the region as a whole. The review also concluded that surface water and groundwater are intrinsically linked and should be managed in an integrated fashion. However, it is not clear how this is to be achieved. Proposed management for the Lower Limestone Coast Prescribed Wells Area (PWA) through the Water Allocation Plan currently relies on triggers (including groundwater drawdown, increasing salinity and seawater intrusion) to indicate a decline in groundwater condition. Allied to the close surface water – groundwater interrelationship, the majority of wetlands in the South East (77% by number and 96% of total wetland area) are highly likely to be groundwater dependent and this relationship is consistent for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). Because of the close link between groundwater and surface water resources in the region, surface water resources and ecosystems are particularly vulnerable to groundwater exploitation.

This 12 month project is considered to be the first phase of a longer-term research program to develop a regional water balance model for the Lower Limestone Coast PWA. The Lower Limestone Coast PWA is considered to be the area of interest for this project; however the study area has been selected, based on inferred hydrogeological boundaries, and to include the area of interest. As a result, the study area for the project extends across the South Australia/Victorian border and hence the domain of the final regional model developed is likely to be inter-jurisdictional, incorporating Zones 1A/1B to 7A/7B of the Border Designated Area. Phase 1 of the project has involved collating data from the Victorian component of the study area as well as the South Australian component.

This research program was developed in close consultation with state and local management agencies to address their critical knowledge needs to enable the development of an integrated water management policy in the Lower Limestone Coast Prescribed Wells Area.

1.2 Developing a regional water balance model

The centrepiece for the research program is the development of a regional scale three-dimensional numerical groundwater flow model. Such a model is required to:

- Help quantify regional water balance components as well as inter-relationships between regional recharge, flows between the unconfined Tertiary Limestone Aquifer (TLA) and the Tertiary Confined Sands Aquifer (TCSA), groundwater storage, and groundwater discharge.
- Address questions relating to specific components of the regional water balance that arise through the water allocation planning process.
- Contribute to a consistent framework for the future development of local-scale numerical groundwater flow models which may be designed to address local-scale issues and thereby further support water resources planning in the Lower South East region.
- Guide future technical work in the Lower South East region by refining the understanding of critical processes influencing water movement and availability and by identifying locations where such processes are most significant.

The development of such a model first requires addressing some of the key knowledge gaps and consolidation of all available information into a **conceptual model**. The definition of a conceptual (hydrogeological) model is (Barnett et al., 2012):

'*a descriptive representation of a groundwater system that incorporates an interpretation of the geological and hydrological conditions (Anderson and Woessner, 1992). It consolidates the current understanding of the key processes of the groundwater system, including the influence of stresses, and assists in the understanding of possible future changes*. '

The definitions of various types of **groundwater model** are provided by Barnett et al. (2012). A groundwater model is a simplified representation of a groundwater system, based upon the conceptual model. A **mathematical model** describes the physical processes and boundaries of a groundwater system using one or more governing equations. In the case of this project, a **numerical groundwater model** will be developed due to the complexity of the system to be represented. A **numerical** model allows mathematical models to be applied to complex systems by allowing the division of space and/or time into discrete pieces. Features of the governing equations and boundary conditions (e.g. aquifer geometry, hydrogeologogical properties, pumping rates or sources of solute) can then be specified as varying over space and time. This enables more complex, and potentially more realistic, representation of a groundwater system than could be achieved with other approaches. Numerical models are usually solved by a computer. There are numerous stages in the development of a numerical model, including model design, model development, calibration, sensitivity analysis and predictions.

1.3 Project structure

The first phase of the program comprised of three tasks, all of which aimed to lay the foundations for the development of the numerical regional water balance model:

1. Development of a regional water balance framework, including a review of regional groundwater recharge rates, a reassessment of the regional hydrogeological stratigraphy and an evaluation of post-European settlement land-use.
2. A preliminary assessment of the spatial variability and indicative fluxes of groundwater discharge to the marine environment.
3. Preliminary assessment of the role of regional geological faults on regional groundwater flow and inter-aquifer leakage.

Task 1 involved collation of all available data and assimilation of this into a conceptual model for the water balance of the study area, as well as design of the framework and methodology for development of the regional groundwater model. Tasks 2 and 3 involved preliminary activities for two research projects aimed at addressing specific critical knowledge gaps in the conceptual model.

This report summarises the findings of the first phase of the program. Chapter 2 presents an overview of the South East region, in particular its water resources. Chapter 3 reviews the key challenges involved in the development of a regional water balance model for the study area. In Chapter 4, an analysis of historical land use is presented, a topic of significance because of its influence on historical groundwater recharge rates. An extensive review of the available information on groundwater recharge in the South East is presented in Chapter 5, along with an evaluation of key controls for this process in this environment. Key outputs from these investigations were historical land use maps and groundwater recharge maps.

Chapters 6 and 7 present the results of Tasks 2 and 3, which aimed to gather new information about submarine groundwater discharge (SGD) and groundwater flow across regional faults, two key hydrogeological processes in the region. The LLC PWA has unique coastal springs and wetlands which are highly prized for their biodiversity. However, the significance of SGD for the regional water balance is unclear. This is caused, in part, by the fact that locations of groundwater discharge in the landscape are not always obvious. One of the few approaches available to get a regional perspective on SGD is through the use of environmental tracers (Burnett et al., 2006). In the first component study, a suite of environmental tracers was tested to determine which ones are most useful to locate and quantify SGD in this environment (Chapter 6). The focus of the SGD work was along the coast between Port MacDonnell and the Victorian border, where SGD is known to occur through coastal springs. The SGD study was also designed to complement a previous study using temperature in the study area (Herpich, 2010). In the second component study (Chapter 7), environmental tracers were also used to evaluate flow across two regional faults (the Tartwaup and Kanawinka faults). Key aims of this study were to use analyses of groundwater samples from existing observation wells to evaluate the influence of the faults on lateral groundwater flow and identify and potentially quantify any interaquifer exchange, currently major uncertainties in the conceptual model of the South East region.

Chapter 8 presents a summary of the assimilation of available information carried out as part of Task 1 and how this relates to the conceptual model of the regional water balance. Key outputs from this were a revised hydrostratigraphic model for the whole study area, an assessment of historical groundwater extraction data and a synthesis of information on the position of the seawater interface in the region to the south of Mount Gambier. The proposed framework and methodology for development of the regional groundwater model are presented in Chapter 9. Key conclusions from Phase 1 and recommendations for Phase 2 of the program are presented in Chapter 10.

2 Overview of the study area

Nikki Harrington, Juliette Woods, Chris Turnadge, Phil Davies and Chris Li

The objective of this chapter is to provide the reader with an overview of the main characteristics of the study area to assist with interpretation of subsequent chapters. Chapters 4 to 8 provide more detail on various aspects of the conceptual model and some of this background information is repeated there. As described in Chapter 1 above, the area of interest for this project is the Lower Limestone Coast Prescribed Wells Area (LLC PWA) (Figure 2.1). However, the study area is broader than this, being roughly bounded by the structural highs of the Padthaway Ridge and the Dundas Plateau, extends northward to ward Keith and also includes parts of western Victoria. Hydrogeologically, it includes the Gambier Basin of the Otway Basin and the south-western margins of the Murray Basin. The following provides a broad overview of the characteristics of the South East region as an introduction. Harrington et al. (2011) provide an extensive overview of the region and much of the following has been derived from that report.

2.1 Physical characteristics

2.1.1 TOPOGRAPHY

The study area comprises an undulating coastal plain which generally slopes to the west and south-west toward the Southern Ocean (Figure 2.1). Topographic relief in the study area is generally low, rising to a maximum of 50 mAHD (metres above Australian Height Datum) along a series of north-west to south-east trending stranded coastal ridges. Topographic lows (i.e. < 30 mAHD) occur in inter-dunal regions. The highest points in the landscape are the Mount Gambier and Mount Schank volcanic cones, rising to 190 m and 120 mAHD respectively (Figure 2.1). Other, but less significant topographic highs in the study area include the Mount Burr and Naracoorte Ranges.

2.1.2 CLIMATE

The climate in the South East region is Mediterranean, with hot dry summers and cool wet winters. Daily maxima range up to 40 °C in the summer months and as low as 10 to 12 °C during the winter months. A north-south rainfall gradient exists, with generally higher rainfall occurring in the southern part of the region and lower rainfall occurring further north. Figure 2.2 displays mean annual rainfall for the South Australian portion of the study area, which ranges from 835 mm/year in the elevated Mount Burr Ranges (north-east of Millicent), to 450 mm/year in Bordertown. Approximately 75% of annual rainfall falls between April and October, which is typically when recharge occurs (i.e. when precipitation exceeds evapotranspiration). An approximate north-south evapotranspiration gradient also exists, with potential evapotranspiration ranging from approximately 1400 mm/year in Mount Gambier to approximately 1700 mm/year in Keith, which is just north of the study area.

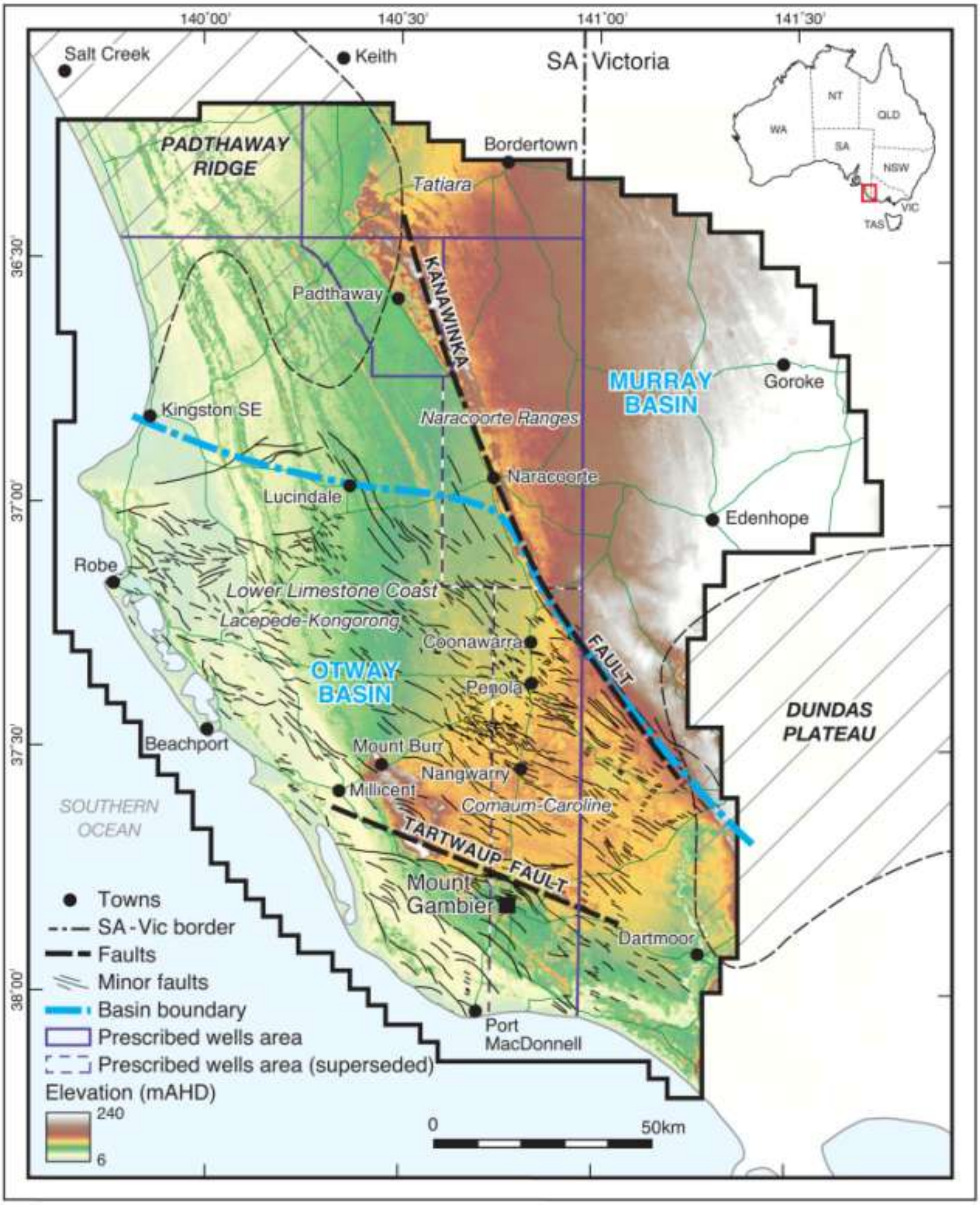


Figure 2.1 Location of study area, showing topography, the Padthaway and Dundas Plateau structural highs, geologic faults, the recently re-interpreted Murray-Otway Basin boundary (Lawson et al., unpublished) and South Australian Prescribed Wells Areas (note: faults have only been mapped for the Otway Basin portion of the study area).

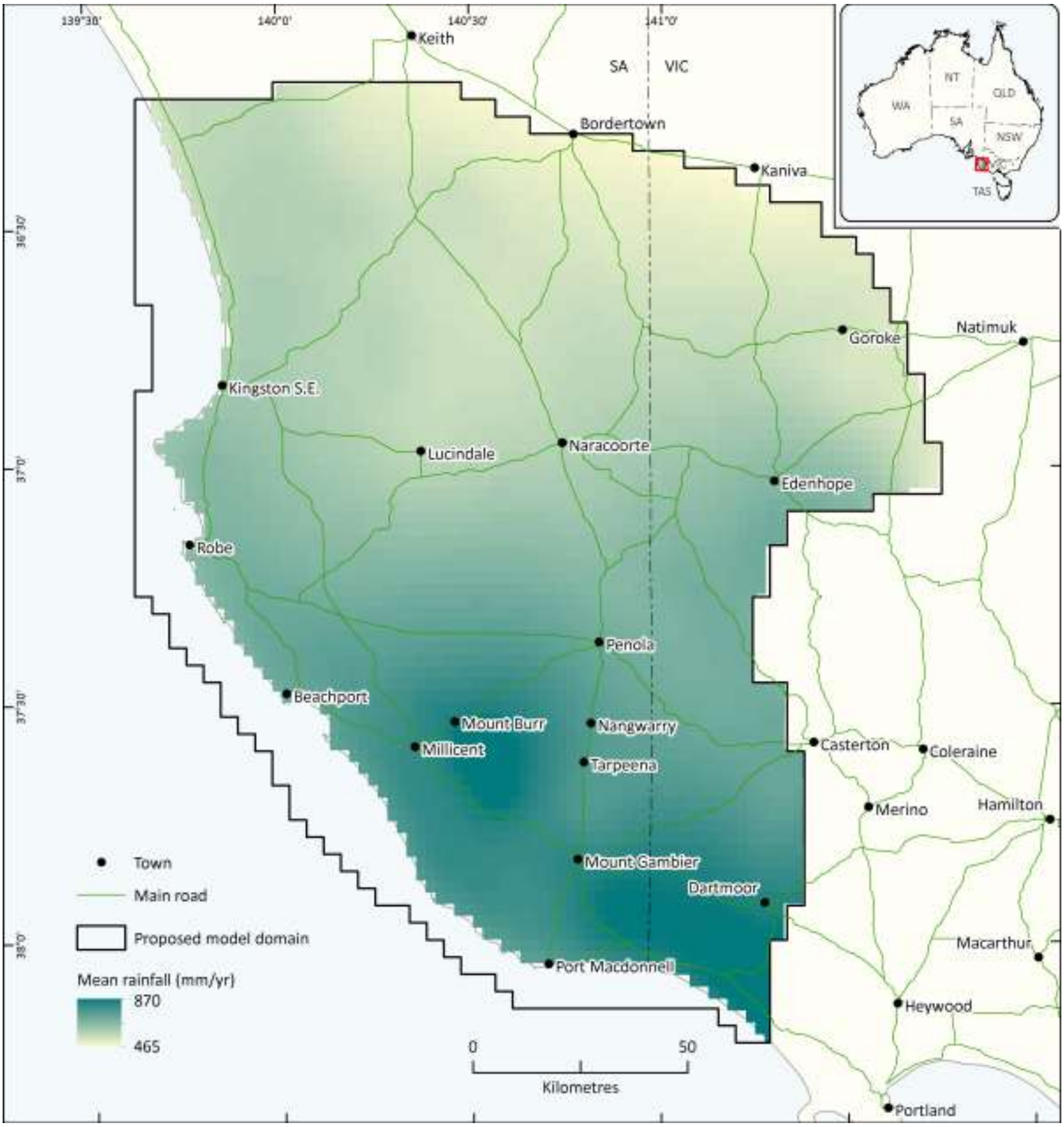


Figure 2.2 Long term mean (1971 to 2000) annual rainfall for the South East region of South Australia.

2.2 Geological setting

The study area consists of the Gambier Basin, which is a Tertiary groundwater basin of the Otway Basin, and part of the south-western Murray Basin (Figure 2.1).

2.2.1 GAMBIER BASIN OF THE OTWAY BASIN

The Otway Basin is an east-west elongate basin of approximately 100,000 km^2 containing a thick accumulation of mixed marine and terrestrial sediments deposited during the Cretaceous and Tertiary Periods (Figure 2.3)(Smith et al., 1995). The Gambier Basin is the most westerly of the groundwater sub-basins of the Otway Basin. It is separated from the Murray Basin to the north by the Padthaway Ridge, a granitic basement high and by the Kanawinka Monocline to the north-east (Cobb and Barnett, 1994). It is bounded in the east by the Dundas Plateau (Love et al., 1993), where the watertable lies within the pre-Cainozoic bedrock (Mann et al., 1994) (Figure 2.1). In the south-east, it is separated from the neighbouring

Tyrendarra Embayment of the Otway Basin by the Lake Condah High (Ryan et al., 1995; SKM, 2009). The basin extends offshore (Ryan et al., 1995).

A number of prominent structural features within the Gambier Basin are believed to exert significant influence on regional groundwater flow. In particular, the north-west trending Kanawinka Fault occurs in the north-east of the Basin and the west to north-west trending Tartwaup Fault occurs in the south of the basin (Figure 2.1). Both faults feature throw towards the south-west, with the magnitude of stratigraphic offset diminishing toward the surface. The Tartwaup Fault forms part of a major structural hinge line, with Cretaceous and Tertiary sediments rapidly increasing in thickness to the south (Gravestock et al., 1986). A number of smaller parallel faults are associated with the Tartwaup Fault (Figure 2.1) (Lawson et al., 2009). An important structural high, the Gambier Axis (Kenley, 1971) occurs to the north of the Tartwaup Fault. Recent mapping of fault locations in Tertiary sequences (Figure 2.1) has revealed that the northern boundary of the Gambier Basin is likely to occur approximately along the Kingston-to-Naracoorte line, and is associated with a magnetic high located between Lucindale and Struan (Lawson et al., 2009). This can be approximated by following the northern extent of mapped faults in Figure 2.1.

Sedimentation in the Gambier Basin commenced in the Early Cretaceous with deposition of shales, lacustrine volcanogenic sand and fluvial clays of the Otway Group. This was followed by the deposition of the claystone, mudstone, and sand of the Late Cretaceous Sherbrook Group. Sedimentation in the Palaeocene to Early Eocene included deposition of the Wangerrip Group, containing the Pember Mudstone and the Dilwyn Formation. The latter unit includes the Tertiary Confined Sands Aquifer and the Dilwyn Clay aquitard. Increasing marine influence led to deposition of the Middle to Late Eocene marginal-marine Nirranda Group (including the Mepunga Formation and the Narrawaturk Marl). In the Late Eocene to Middle Miocene the marine Gambier Limestone was deposited, which is currently part of the regional unconfined aquifer. Since the Pleistocene the southern area of the Gambier Basin has been altered by volcanic activity, with the remnant volcanic cones of Mount Gambier, Mount Schank and Mount Burr now prominent topographic features in the landscape.

Eustatic sea level rise during the Pleistocene resulted in a number of marine transgressions that extended as far inland as the Kanawinka Fault and caused reworking of Tertiary sedimentary units. A series of fossiliferous sand dunes derived from Bridgewater Formation sediments formed in strand lines sub-parallel to the coastline as the ocean regressed, with the shallow marine limestone of the Padthaway Formation being deposited in inter-dunal areas. These units, where present, overly the karstic Gambier Limestone and form part of the regional unconfined aquifer.

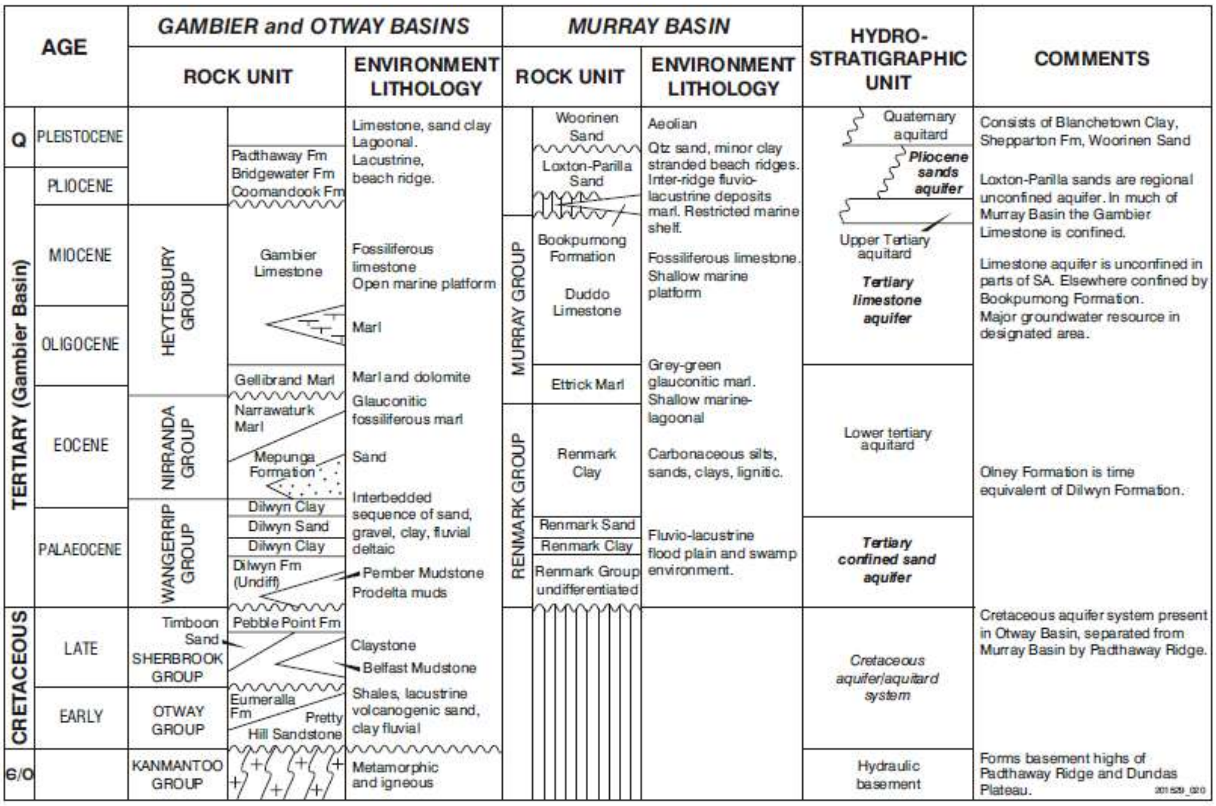


Figure 2.3 Stratigraphic and hydrostratigraphic units of the Otway and Murray Basins (Rammers and Stadter, 2002).

2.2.2 SOUTH-WEST MARGIN OF THE MURRAY BASIN

The Murray Basin is a large, Cainozoic, intercratonic sedimentary basin located in south-eastern Australia (Brown, 1989; Rogers et al., 1995). It is one of the Tertiary continental margin basins of southern Australia, which formed at the start of the Mesozoic Era due to rifting between Australia and Antarctica (McLaren et al., 2011). The Murray Basin is the most laterally extensive of these basins, with an area of 300,000 km^2. Murray Basin sediments are comparatively thin, being generally less than 200 m thick but no more than 600 m thick (Brown, 1989; McLaren et al., 2011).

The structural and stratigraphic framework of the Murray Basin is described in Brown(1989). The hydrogeology is described in greater detail in Evans and Kellett (1989). Lukasik and James (1998) revised the lithography and nomenclature of South Australian sediments of the Murray Supergroup. McLaren et al., (2011) summarised the current understanding of the palaeogeography, depositional environments and events of the south-western Murray Basin and the Western Otway Basin since the Late Miocene.

The Murray Basin contains two main sub-regions: the Riverine Plains in the east and the Mallee region in the west (Brown, 1989). Each sub-region features a local depocentre and is separated from the other by the Tyrell Fault and Neckarboo Ridge. Evans and Kellett (1989) further divided the Mallee region into two hydrogeological provinces: the Scotia province north of the Murray River and the Mallee-Limestone province south of the river.

The present study area includes the south-western margin of the Murray Basin, which is part of the Mallee region, and the Mallee-Limestone province. Within the study area, the Murray Basin abuts the Gambier Basin of the Otway Basin, the Grampians region and the Glenelg River region(Brown 1989). Most of the Murray Basin is bounded by Proterozoic and Palaeozoic fold belt rocks including the Dundas Plateau within the study area (Evans and Kellett, 1989). The Murray Basin is separated from the Gambier Basin by the shallow but largely concealed basement high of the Palaeozoic Padthaway Ridge (Brown, 1989; Lukasik and James, 1998); however, the stratigraphy of the two basins is considered equivalent.

The stratigraphy of the Mallee-Limestone province is summarised in Figure 2.3. The Renmark Group consists of predominantly fluvio-lacustrine sediments deposited in the Late Palaeocene to the Middle Eocene (Brown, 1989; Cobb and Barnett, 1994). During the Early Oligocene to Late Miocene the Ettrick Formation and Geera Clay were deposited in shallow to marginal marine environments. From the late Oligocene, Murray Group limestone was deposited in shallow marine environments (Brown, 1989). Pliocene marine transgression-regressions resulted in deposition of the Bookpurnong Beds and the Loxton-Parilla Sands (Brown, 1989). The Quaternary aeolian dunes of the Woorinen Formation represent reworkings of the Loxton-Parilla Sands (Evans and Kellett, 1989). The overlying Quaternary Bridgewater and Padthaway Formations occur in both the Murray Basin and the Gambier Basin within the Gambier coastal plain (McLaren et al., 2011).

2.3 Hydrogeology and groundwater flow

Groundwater of the Gambier Basin occur in a number of different hydrogeological systems in the Cainozoic and Cretaceous sequences. The Cretaceous aquifers are generally saline and generally too deep for economic utilisation (Love et al., 1993). Two major low salinity groundwater systems occur within the Cainozoic sequence: the Tertiary Confined Sand Aquifer system (TCSA), comprised primarily of Dilwyn sand and clay units in the Gambier Basin and the Renmark Group Sands in the Murray Basin, and the multi-lithological unconfined Tertiary Limestone Aquifer (TLA) system, comprised primarily of the Gambier Limestone (Figure 2.3). The confined system is separated in places from the underlying Cretaceous aquifers by the discontinuous Lower Tertiary Aquitard, comprising the Pember Mudstone; and from the overlying unconfined system by the Upper Tertiary Aquitard. This is comprised of the Narrawaturk Marl, the Mepunga Formation (which can occur in areas as a discontinuous aquifer) and a clayey unit of the Dilwyn Formation itself, known as the Dilwyn Clay (Figure 2.3). The unconfined aquifer system consists of the late Tertiary Gambier Limestone and the Quaternary age Padthaway and Bridgewater Formations. The Gambier Limestone consists of three sub-units: the Greenways, Camelback and Green Point members (Li et al., 2000; White, 2006)). The entire hydrogeological sequence of the Gambier Basin is wedge-shaped, thickening toward the south to up to 5000 m offshore. The Cainozoic groundwater system itself can be up to 1000 m thick near the southern coast.

Groundwater in both the unconfined and confined aquifers generally flows toward the coast; from east to west in the region to the north of Mount Gambier and from north to south in the region to the south of Mount Gambier. The hydrostratigraphic model and groundwater flow characteristics of the study area are further discussed in Sections 8.2 and 8.3.

The principal hydrogeological units of the Mallee-Limestone province of the Murray Basin are, in order of decreasing depth: the Renmark Group aquifer, the Ettrick Formation-Geera Clay aquitard, the Murray Group limestone aquifer, the Bookpurnong Beds aquitard, the Loxton-Parilla Sands aquifer, the Blanchetown Clay aquitard and the Woorinen Sands. The Blanchetown Clay is not present in the study area as it was deposited further north, within the palaeo-lake Bungunnia (McLaren and Wallace, 2010).

In the study area, groundwater in the Renmark Group and Murray Group aquifers generally flows in a westerly or north-westerly direction, away from the recharge areas of the southern Wimmera region located around the edges of the Dundas Plateau (Evans and Kellett, 1989). Other recharge areas for the Murray Group aquifer may include the Little Desert and local sinkholes (Evans and Kellett, 1989). Groundwater in the Loxton Sands aquifer, which is recharged by both rainfall and irrigation, flows in a north-westerly direction. Groundwater flows from the Riverine province into the Mallee-Limestone province within the Renmark and Loxton-Parilla Sands aquifers but not into the Murray Group aquifer, which does not extend laterally into the Riverine province (Evans and Kellett, 1989). Small volumes of flow occur out of the Murray Basin via the Renmark and Murray Group aquifers where they meet the coast over the Padthaway Ridge, including a portion of the study area (Evans and Kellett, 1989). It is assumed that prior to European settlement, the aquifer systems were in hydraulic equilibrium (Brown, 1989).

2.4 Surface water

2.4.1 SWAMPS, WETLANDS AND NATURAL WATERCOURSES

Natural watercourses in the Lower South East are generally impeded by the limited topographical relief and the transversely-oriented dune system, which results in the occurrence of numerous swamps and wetlands, lakes and sinkholes in inter-dunal corridors. Swamps and wetlands usually occur over a shallow watertable and clay horizons during the wet winter months as a result of clay soils holding surface water in low-lying depressions. These are typically found to the north of Mount Gambier. The construction of drains in the South East region, and subsequent changes in land use, are thought to have reduced the original areal extent of wetlands by 93% (Harding, 2009).

A number of natural creeks, such as Morambro Creek, Mosquito Creek and Naracoorte Creek, flow across the South Australian/Victorian border into the South East region of South Australia, with catchments that extend into western Victoria (Figure 2.4). Mosquito Creek discharges into Bool Lagoon, a Ramsar convention-listed wetland complex located south-west of Naracoorte. Morambro Creek discharges into Cockatoo Lake north-west of Naracoorte, and is the only prescribed surface watercourse in the South East. Flow in all of these creeks is ephemeral, and highly dependent upon winter rainfall. The Glenelg River is a permanent watercourse that flows mainly through the Victorian portion of the study area and discharges to the coast at Nelson, located less than 5 km east of the South Australian/Victorian border (Figure 2.4).

Numerous karst sinkholes (also referred to as dolines and cenotes) are located south of Mount Gambier, where the regional unconfined aquifer is particularly calcereous. These tend to occur along structurally weak fault zones. Sinkholes are formed by the dissolution of the carbonate matrix by infiltrating rainfall and generally either partially fill with soil and sediment or, are exposed to the watertable. Other significant karst features include the ‘rising springs’ located south of Mount Gambier, such as Ewens Ponds and Piccaninnie Ponds. Ewens Ponds consists of a series of three ponds which are fed almost entirely by groundwater discharge through visible ‘bubbling sand’ springs. The ponds flow into Eight Mile Creek, which discharges to the coast. Piccaninnie Ponds is a much larger karst spring wetland complex, with a main pond that is up to 100 m deep in parts. Groundwater discharge from Piccaninnie Ponds also flows to the coast. Springs discharge groundwater to creeks such as Deep Creek, Jerusalem Creek and Cress Creek, which in turn also discharge to the coast to the south of Mount Gambier. Flow has been periodically gauged in these creeks since the 1970s and the total mean annual discharge to the coast from all sites, including Eight Mile Creek and Piccaninnie Ponds outlet, is estimated at approximately 97 GL/year.

2.4.2 DRAINS

Since the 1860s, approximately 2000 km of drains have been constructed throughout the South East region (Figure 2.4). Historically, they were constructed to drain inundated land and thereby increase agricultural production. More recently, drains have been constructed to mitigate flooding in high rainfall years and to manage dryland salinity issues in the Upper South East region.

The South East drainage network consists of a combination of shallow drains (i.e. typically less than 1–2 m deep) and deeper drains (i.e. approximately 2 m deep) designed to intercept shallow unconfined groundwater. The majority of surface water – groundwater interactions occuring around drains is groundwater discharging to the drains; however, the spatial and temporal variability of such interactions is not well understood. Chapter 8, Section 5.2 discusses this in more detail.

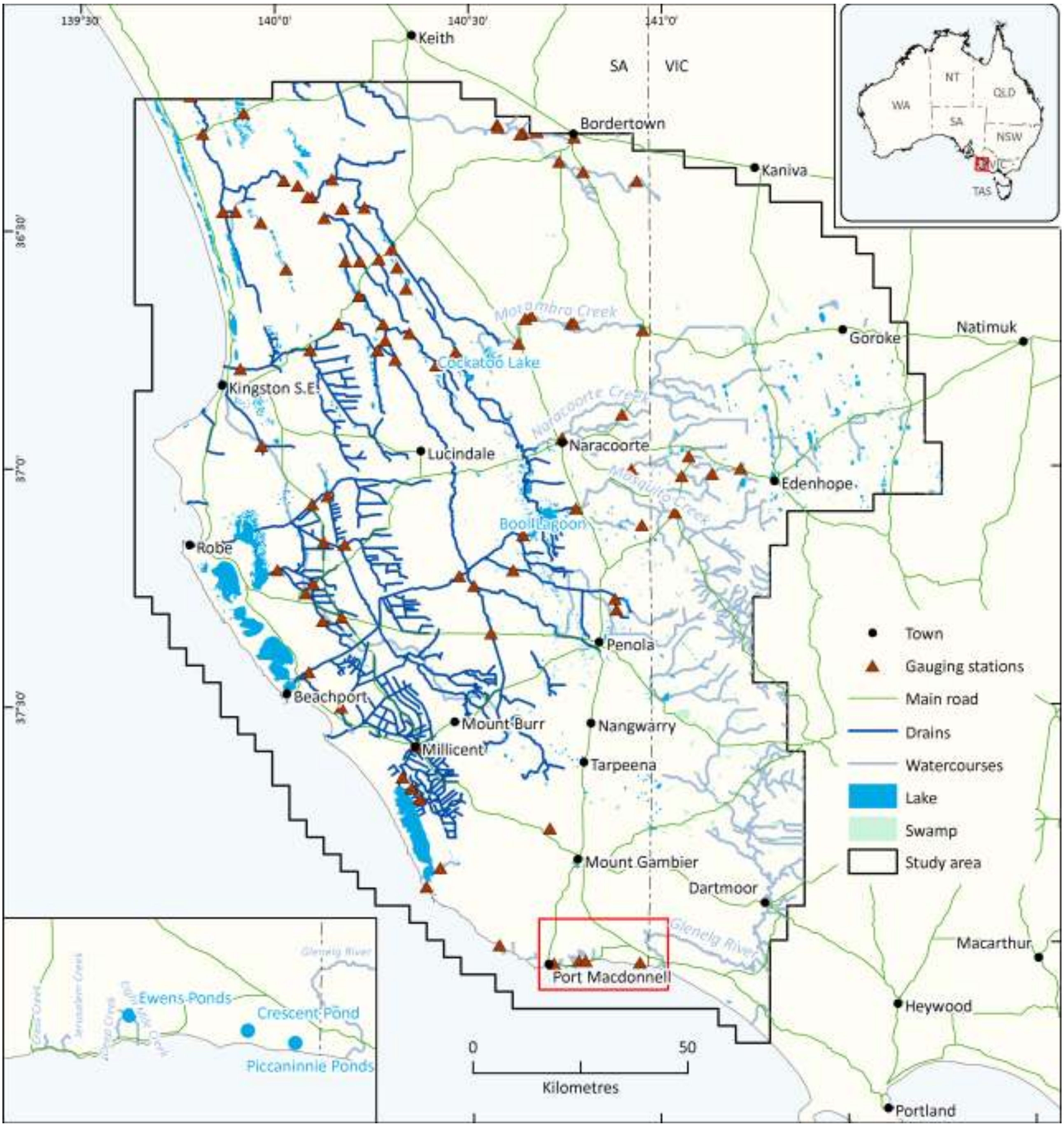


Figure 2.4 Natural watercourses and drains in the study area, showing locations of current streamflow gauging stations.

2.4.3 BLUE LAKE

One of the most significant surface water bodies in the South East region is Blue Lake, which serves as the primary source of town water supply for Mount Gambier with a mean annual extraction of between 3 GL and 4 GL. The Blue Lake is a volcanic crater lake, thought to have been formed at least 28,000 years ago (Leaney et al., 1995). It has a volume of approximately 30 GL and is fed by groundwater discharge. A geochemical mass balance performed by Ramamurthy et al. (1985) suggested that groundwater discharges at a rate of approximately 5 GL/year, 85% of which is sourced from the regional unconfined aquifer and 15% from the underlying regional confined aquifer.

2.5 Soils

Soil type is spatially variable across the study area. Lighter textured soils are mainly associated with dunes oriented parallel to the coast while heavier textured soils are associated with the inter-dunal flats. Figure 2.5 shows the distribution of soil types characterised by depth-weighted mean clay content, as based on Australian Soil Resource Information System data (ASRIS; http://http://www.asris.csiro.au; (Johnston et al., 2003). Soil type across the South Australian portion of the study area was based on Level 5 ASRIS data featuring five soil layers. Soil type across the Victorian portion of the study area was based on lower resolution Level 4 ASRIS data featuring two soil layers.

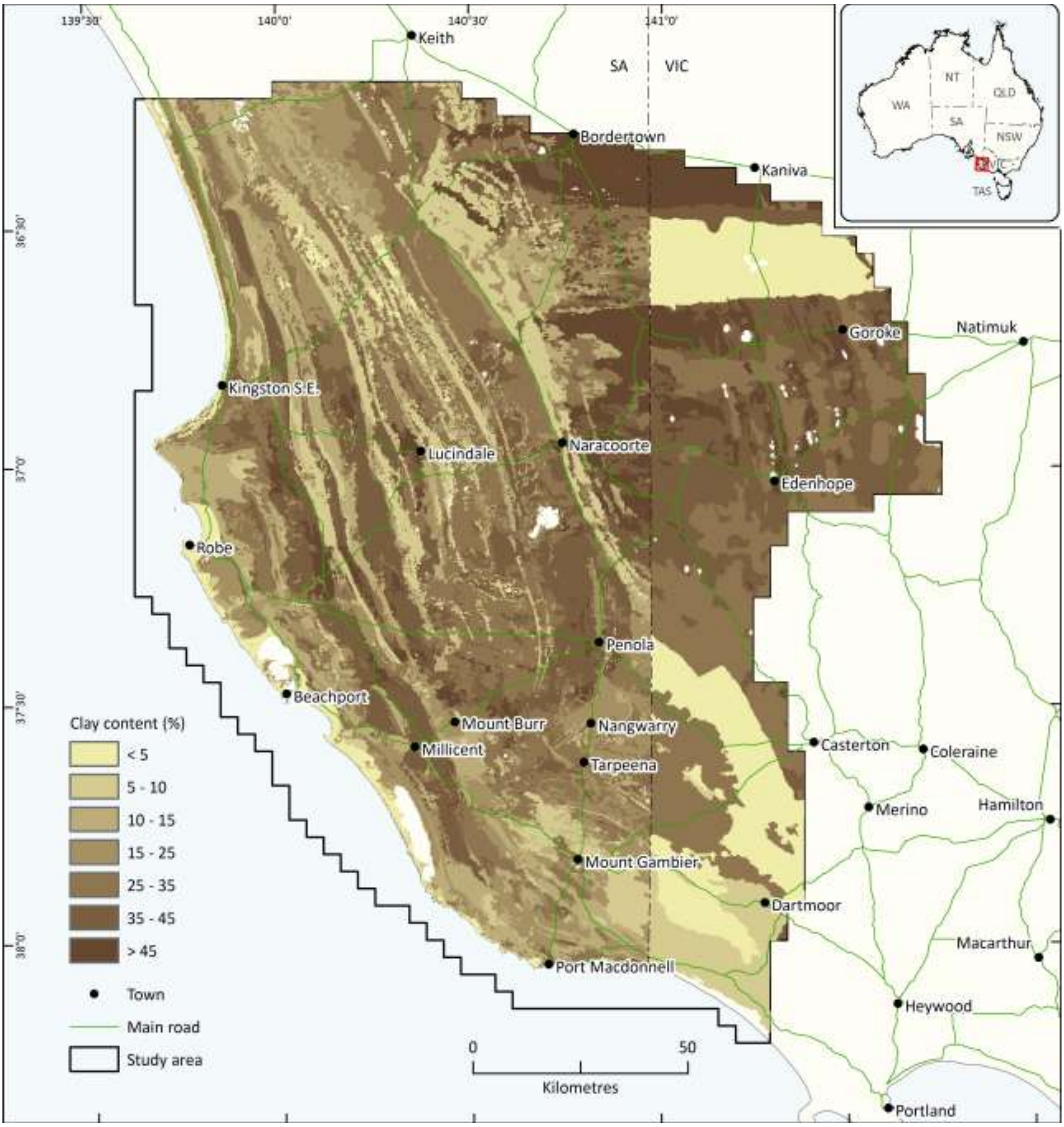


Figure 2.5 Depth-weighted mean clay content of soils across the study area based on Australian Soil Resource Information System data (http://www.asris.csiro.au; (Johnston et al., 2003).

2.6 Land use

Land use in the study area is dominated by livestock production, dryland and irrigated crop production and plantation forestry (Figure 2.6). Irrigation supplies are derived almost entirely from groundwater and are used for cropping and some pastoral use. Irrigation is used intensively in viticultural areas concentrated along the Naracoorte Range and its western footslopes. The Coonawarra and Padthaway areas have seen intensive development of vineyards on both the Terra Rossa soils of the slopes and the loamy soils of the flats respectively. The South East region has been an important timber production area since the first plantation was established in 1879; however, areas under softwood plantation forestry (predominantly *Pinus radiata*) increased significantly from the 1960s onwards. Large areas of hardwood blue gum forestry (*Eucalyptus globulus*) have been established since the mid-1990s in both the South Australian and Victorian portions of the study area.

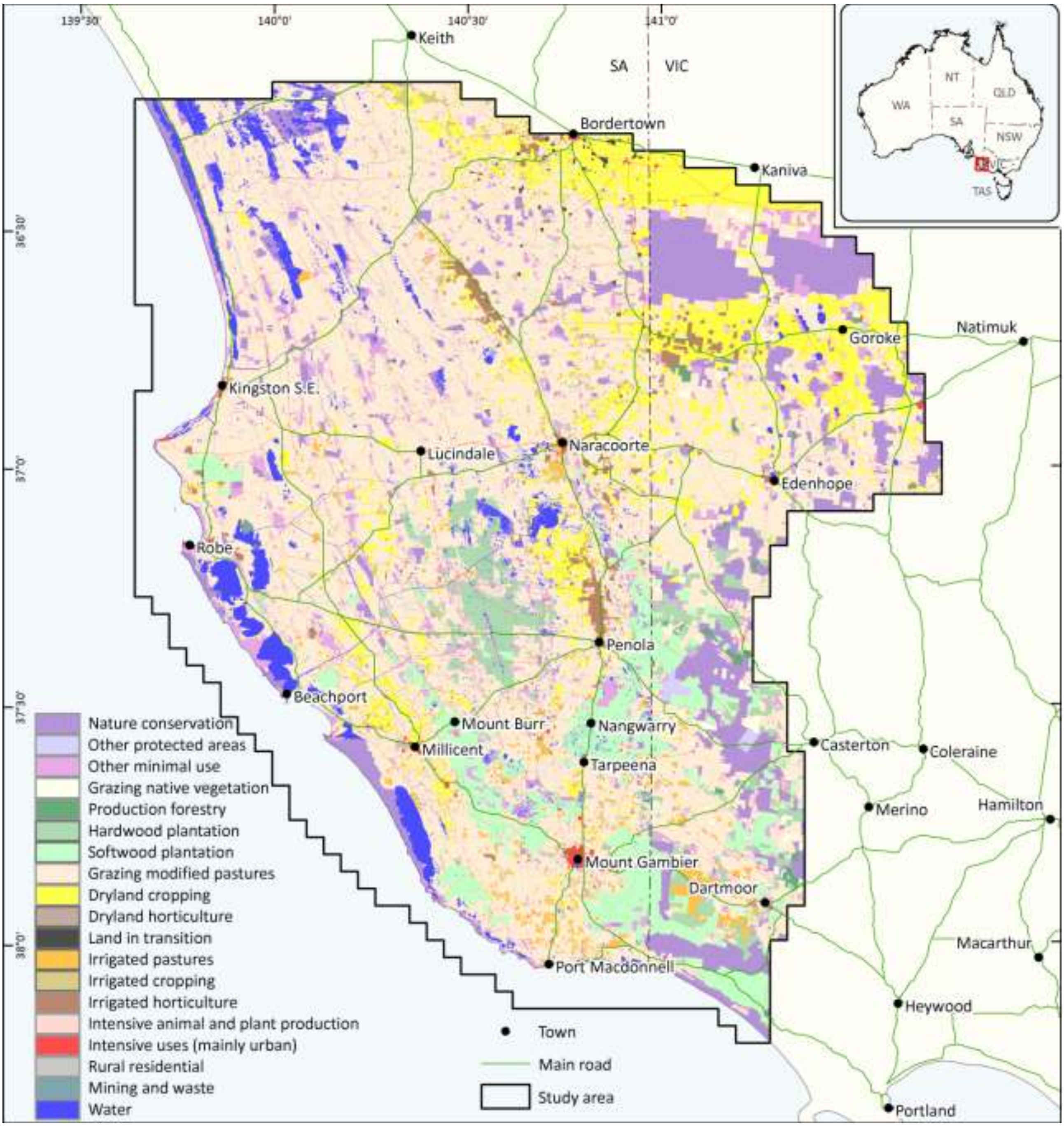


Figure 2.6 Study area land use in 2008.

2.7 Timeline of hydrological and land use-related events in the South East region

The following timeline of relevant milestones in the study area has been compiled during the course of the project. This timeline is maintained in the project archive and will continue to be developed as more information is obtained, as a useful resource for the region.

Table 2.1 Timeline of relevant hydrological and land use-related events in the South East region.

DATE(S)	EVENT(S)
1839	First settlement in the South East.
1864	First drains constructed around Millicent.
1870s	Concerns raised in SA Parliament about over-harvesting of the colony's native forests. Government encourages replanting.
By 1881	Woods and Forests Dept establishes first plantations at Mount Burr and Leg of Mutton Lake (Mount Gambier) due to lack of timber in the region.
1908	Penola plantation established.
1908-onward	Pulses of large-scale forestry established.
1914–1918	World War I
1926	Auspine – Gunns (Newforest) developments established.
1931	Mount Burr sawmill established.
1934	Survey of forests by Swain Royal Commission.
1938	Blue gum plantation established at Tantanoola.
1939	Veneer mill built at Mt Gambier.
1941	First pulp mill in SA opens near Millicent.
1939–1945	World War II – resulting in slowed development of forestry.
1942	Approximately 4,000 acres of scrubland (mainly tea tree and swamp bush) cleared at Eight Mile Creek.
1951	Nangwarry sawmill established.
1957	Mount Gambier sawmill established – then the largest in the southern hemisphere.
late-1950s	Softwood plantations established.
1960s	Expansion of forestry industry financed by Commercial Afforestation Funds, resulting in native vegetation clearance.
1964	Trial vineyard planted at Padthaway and proven successful. (Previous land use was restricted to native vegetation and some improved pasture.) Significant viticultural expansion in Padthaway region followed.
1966	Coonawarra had been established.
1976	Padthaway Prescribed Wells Area proclaimed due to concerns over rising groundwater salinities. Water resource was fully allocated at time of prescription.
1978	Aphid infestations ruined lucerne crops.
1980s	Significant viticultural expansion in Coonawarra region. Vineyards were rain-fed prior to installation of overhead spray and then drip irrigation.
1983	Ash Wednesday bushfires burn vast areas of forests. Replanting is complete by the early 1990s.
1984	Tatiara Prescribed Wells Area proclaimed due to concerns over deteriorating groundwater quality. Prior to prescription, some irrigated areas were increasing in size by 20% per year.
1985	*Groundwater (Border Agreement) Act* proclaimed.

DATE(S)	EVENT(S)
1986	Naracoorte and Comaum Caroline Prescribed Wells Areas proclaimed.
1987–1988	First blue gum (*Eucalyptus globulus*) plantations established.
1990–1995/96	Significant expansion of blue gum forestry plantations financed by taxation concessions and involving organisations such as Apsil, Timbercorp, APT, Great Southern, and Elders.
1992–2002	Significant plantation forestry development in Border Designated Area Zones 1B, 2B and 3B, replaced pasture land.
1992	Establishment of large centre pivots irrigation, particularly in the area south of Mount Gambier. (Previously irrigation was undertaken by flooding and/or travellers (travelling sprinklers)). Expansion of centre pivot irrigation was motivated by local availability of the first mud rotary drill rig, which enabled well completion in the Camelback Formation within 2–3 days. In addition, milk companies were paid premium prices if dairy farmers could supply milk all year-round.
1993	Naracoorte Ranges Prescribed Wells Area expanded to include the Naracoorte Plains area following a two year moratorium.
1997	Lacepede-Kongorong Prescribed Wells Area proclaimed with the intention of introducing structured resource management before problems of over-allocation emerged.
1997–present	Significant development of groundwater resources in the southern part of Border Designated Area Zone 1A.
1997–1998	First report published summarising water allocation and use for an irrigation season following the formation of the South East Water Catchment Management Board.
2003	Prescription of Tintinara-Coonalpyn Prescribed Wells Area completed.
2003–2004	First public reporting of actual groundwater extraction volumes. (Previously, extraction estimates were based on crop water use estimates).
2009	Revised WAP for Padthaway – first rigorous assessment of acceptable extraction limits for groundwater recognising all stakeholders' values.
2011	Completion of REFLOWS floodways, the final engineering stage of the Upper South East Dryland Salinity and Flood Management Program.

2.8 Groundwater use and management

The main source of water for irrigation, stock and domestic, industry, and urban (i.e. town water supply) purposes in the study area is groundwater. Groundwater extraction for irrigation, industry and urban (town water supply) purposes requires a licence. There are approximately 2,300 groundwater extraction licences in the South Australian portion of the study area (both confined and unconfined aquifers), with approximately 4,300 meters accounting for groundwater extraction under these licenses. Total extraction was approximately 355 GL for the 2011/12 year, consisting of 333 GL from the regional unconfined aquifer and 22 GL from the regional confined aquifer. Details of this are provided in Section 8.8. Information on groundwater extraction for the Victorian portion of the study area had not been obtained at the time of preparation of this report, although the data request was being processed.

In South Australia, groundwater extraction levels are managed through a series of Water Allocation Plans for each Prescribed Wells Area shown in Figure 2.1. Within the Prescribed Wells Areas, unconfined groundwater resources in the South Australian portion of the study area are managed through a system of Unconfined Management Areas (Figure 2.7). Confined aquifer groundwater resources are managed through a system of Confined Management Areas (Figure 2.8). Victorian Groundwater Management Units

(GMUs) are also shown on Figure 2.7 and Figure 2.8. These include Groundwater Management Areas (GMAs), of which West Wimmera is one, and Water Supply Protection Areas (WSPAs), of which Glenelg is one.

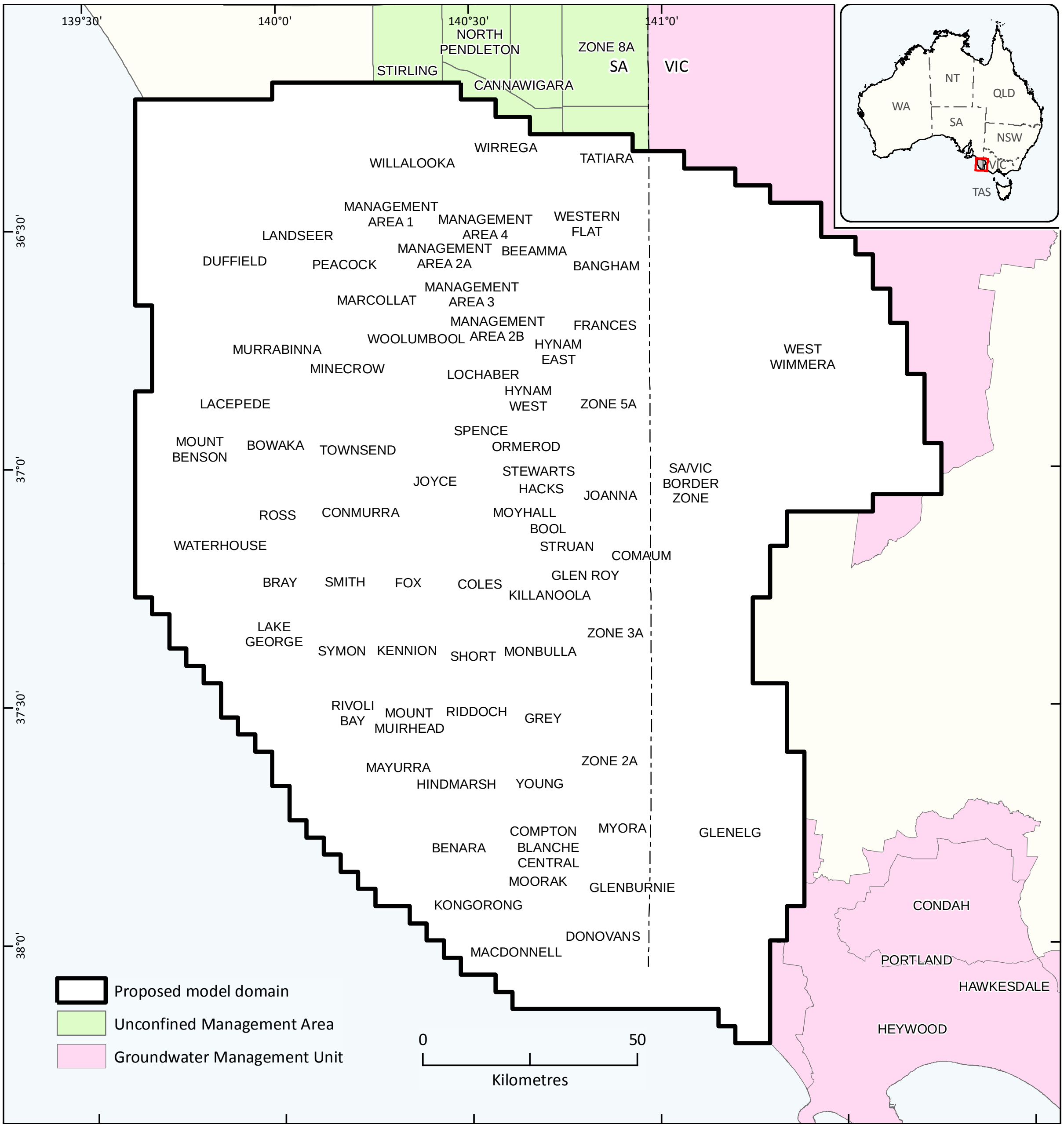


Figure 2.7 Unconfined aquifer Management Areas (South Australia) and Groundwater Management Units (Victoria).

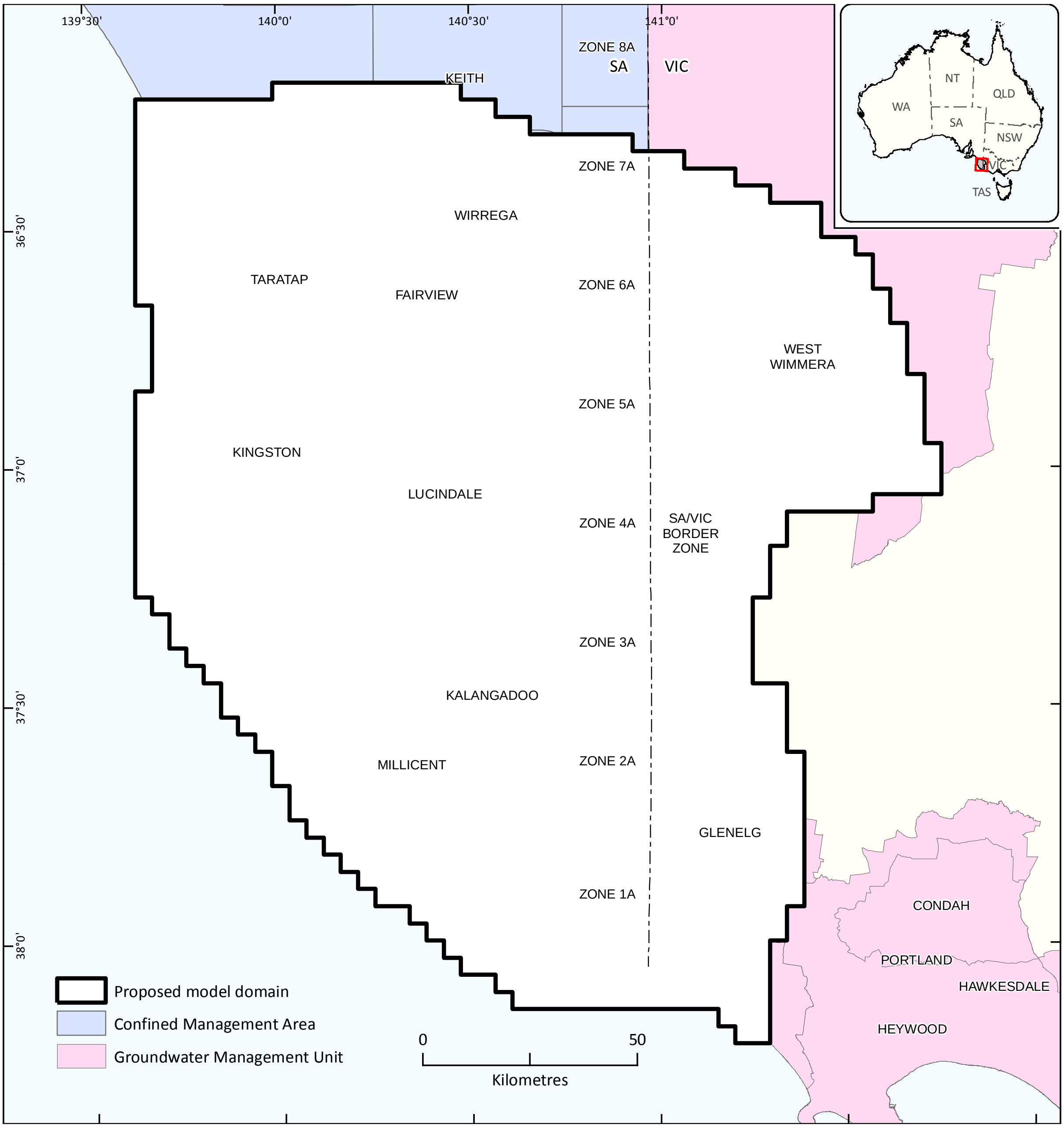


Figure 2.8 Confined aquifer Management Areas (South Australia) and Groundwater Management Units (Victoria).

2.9 Previous estimates of the water balance

The most recent estimate of the water balance for the Lower South East region was undertaken by Wood (2010a). Components of the water balance were estimated for both the Lower Limestone Coast Prescribed Wells Area and the entire South East region. Large uncertainties in these estimates were recognised and error margins of 20% were applied. A number of limitations were recognised, including the use of long-term average data, uncertainties associated with groundwater extraction estimates, and limited characterisation of surface water – groundwater interactions. Wood (2010a) did not attempt to estimate rates of lateral groundwater inflow to, or submarine groundwater discharge from, the water balance study area due to large uncertainties associated with the former and a complete lack of knowledge of the latter.

Table 2.2 Water balance estimates (in GL/year) for the Lower Limestone Coast Prescribed Wells Area and the entire South East region (Wood, 2010a).

PROCESS	LOWER LIMESTONE COAST PRESCRIBED WELLS AREA	ENTIRE SOUTH EAST REGION
Inflows		
Groundwater recharge	1,256	1,378
Surface water inflows	15	18
Drainage from flood irrigation	23	32
Rainfall on surface water bodies	309	397
Total Inflows	**1,603**	**1,825**
Outflows		
Groundwater extraction for irrigation use	268	415
Groundwater extraction for stock and domestic use	17	19
Evaporation from surface water bodies	601	771
Discharge from groundwater springs	97	97
Discharge from surface water drains	99	106
Interception of recharge by plantation forestry	199	199
Direct extraction from plantation forestry	106	106
Total Outflows	**1,387**	**1,713**
Balance (Inflows-Outflows)	**+216**	**+112**

3 Major challenges in water balance modelling of the South East

Juliette Woods and Nikki Harrington

There are a number of specific challenges in developing a water balance model for the study area. These challenges (listed below) can be divided into three categories: data limitations, gaps in the conceptual model and modelling challenges. Many of those in the first two categories were identified and assigned priorities by Harrington et al. (2011), with (1) being high, (2) medium and (3) low priority. The priorities were assigned based on the current level of understanding (i.e. good, moderate or poor) and the impacts of the knowledge gap on the outcomes of regional and local scale models (i.e. high, medium and low impact). The higher priority challenges are listed in Sections 3.1 and 3.2 below, with the suggested priority level listed in brackets. In addition, some specific modelling challenges relevant to the development of a regional numerical model of the study area are also discussed in Section 3.3.

Some of these challenges are being addressed by the current project as described below. Others are still outstanding and should be prioritised for future technical studies.

3.1 Data limitations

The accuracy of a numerical model depends on the type and quality of the datasets which inform it. The datasets are used in three main ways. Firstly, they are analysed to develop the conceptual model. Secondly, they provide the basis for model inputs, whether used directly or in summarised or processed form. Thirdly, they are used for calibration, as model results are compared to observations. Where significant data gaps exist, the model will have limitations. The importance of the limitations depends on the importance of the processes the data describe.

3.1.1 HISTORICAL LAND USE (2)

Historical land use is a critical dataset for the South East. Most of the South East has experienced extensive changes in land use in recent decades. Assessing the impact of future changes in land use on the water balance is expected to be one of the primary uses of the completed regional model.

Recharge, which is one of the main components of the regional groundwater budget, depends greatly on land use. Historical recharge can be estimated from field data (Chapter 5) but estimates of future recharge require some relationship between land use and recharge.

Land use data are also used to estimate groundwater extraction when pumped volumes or allocation data are not available (Section 3.1.2).

Unfortunately, little historical land use data is currently available for the South East. Catchment scale land use maps generally only exist for periods as far back as the mid-1990s, at best. Even coarse national scale land use maps only exist as far back as the late-1980s (ABARES, 2013).

There is, however, a wealth of information available to support the development of historical land use maps. This is a time-consuming and costly exercise, but the product would be of immense value to a range of applications, including regional-scale groundwater modelling. Land use mapping has proved extremely useful in other SA regions, such as the Riverland (Yan et al., 2012). Chapter 4 provides the details of some work carried out as part of this project to assess two methodologies for creating historical land use maps for the study area and some preliminary maps created as part of this.

3.1.2 HISTORICAL GROUNDWATER EXTRACTION (2)

Groundwater extraction data are used to develop model inputs. In areas where extraction is a significant part of the water budget, model calibration and accuracy will depend on this data.

The lack of historical groundwater extraction data for the South East region of South Australia has been identified as a major limitation of model outcomes (Harrington et al., 2011). Again, this problem is common to many areas that require groundwater models where groundwater extraction has occurred in the past. For the South East region, metered groundwater extraction data is available for the past three years (i.e. 2009/10, 2010/11 and 2011/12). Prior to this, groundwater extraction data are available, at a management area scale at best, until as early as 1998; the quality control of this early data is described as 'informal'. Prior to 1998 groundwater extraction data are unavailable. The data available are presented in Section 8.8 and some approaches for creating historical groundwater extraction datasets for input into the regional groundwater model are suggested in Section 9.7.7.

3.1.3 EVAPOTRANSPIRATION (1)

Under natural conditions (i.e. before European settlement), much of the study area had a shallow watertable. This includes most of the Gambier coastal plain west of the Kanawinka Escarpment. Extensive drain networks have since lowered the watertable, but the watertable remains shallow. Critical features such as the groundwater-dependent ecosystems of swamps, wetlands and springs rely on the shallow watertable.

Where the watertable is shallow, groundwater evapotranspiration may be a significant proportion of the water balance. Evapotranspiration is a complex series of processes, dependent on e.g. climate, vegetation type, soil type and groundwater salinity.

Regional groundwater flow models must simplify this complexity or they become too computationally demanding. Assumptions must be made about the relationship between evapotranspiration (ET) and depth to watertable. The most-commonly used numerical code for groundwater flow simulation, MODFLOW (Harbaugh et al., 2000), has a standard module which simulates ET in terms of a linear relationship between ET flux and depth to water; the model input file specifies the maximum ET rate and the extinction depth, below which no ET occurs. Other MODFLOW modules exist which assume a non-linear relationship between ET and depth to water.

It is difficult to determine *a priori* the model input parameters for ET. Bureau of Meteorology records of ET provide an upper limit for the maximum rate. They will vary seasonally and spatially. Estimates of groundwater ET rates derived from site studies are likely to be extremely spatially variable in practice and may not be readily extrapolated regionally. ET rates derived from remote sensing studies are a more promising method of making regional-scale comparisons with model results, improving model input parameters and hence calibration. Chapter 5 provides spatial coverages of estimated net recharge to the groundwater system, derived from remote sensing of evapotranspiration across the study area.

3.2 Gaps in the conceptual model

3.2.1 THE INFLUENCE OF GEOLOGICAL FAULTS (1)

From potentiometric surface maps of the Tertiary Limestone Aquifer (TLA) and the Tertiary Confined Sand Aquifer (TCSA), it is apparent that groundwater flow is affected by the Kanawinka and Tartwaup regional fault zones. This may be observed in localised hydraulic gradients around the fault zones that are much steeper than the regional slope. However, it is uncertain what physical processes are impeding flow across these regions, how these processes vary along the strike of the fault, and how faulting may affect the regional water balance, including inter-aquifer leakage. It is possible that faulting has caused significant stratigraphic offsets resulting in the abutment of permeable formations against lower permeability formations, and thereby restricting lateral groundwater flow. It is also possible that mineralisation within the fault zones is the primary cause of the flow restrictions. While the occurrence of faulting has been extensively mapped in this area, the resulting hydrological effects have not been studied quantitatively. Chapter 7 provides details of some preliminary work carried out as part of Phase 1 to investigate the influence of regional faults on lateral and vertical groundwater flow and recommendations for expansion of this work in Phase 2.

3.2.2 INTERAQUIFER LEAKAGE (1)

Considering the extensive faulting present throughout the study area, potential exists for significant groundwater flow between various aquifers, including the TLA and the TCSA. The geometry of the faults, the presence or absence of mineralisation, and vertical hydraulic gradients between adjacent formations all affect the potential for inter-aquifer leakage. Using environmental tracers along two regional transects, Love et al. (1993) concluded that recharge into the Dilwyn Formation occurs downgradient of the Kanawinka fault zone and along the Gambier Axis in the Nangwarry region. This was later investigated by Harrington et al. (1999), resulting in a conceptual model of preferential interaquifer leakage between the Kanawinka Fault and the ZHD (the line along which the head difference between the TLA and the TCSA changes from being positive to negative; described in Section 8.3).

Inter-aquifer leakage also depends on the presence or absence of an intervening aquitard, and the aquitard's properties. The extent of the aquitard between the unconfined and confined aquifer systems has been mapped but its accuracy at any location depends on the spatial distribution of borehole information. The vertical hydraulic conductivity of the aquitard has been measured at only a few sites. The direction of leakage between the aquifer depends on the difference in potentiometric heads, which can be estimated from observations, but the flux is not known. Again, Chapter 7 provides details of some preliminary work carried out as part of Phase 1 to investigate the influence of regional faults on vertical groundwater flow and recommendations for expansion of this work in Phase 2.

3.2.3 SPATIAL AND TEMPORAL VARIABILITY IN GROUNDWATER RECHARGE (2)

Recharge is a large component of the groundwater balance of the South East. It is also a component that is greatly influenced by land and water management practices, particularly land use (Section 2.6). Recharge varies spatially and temporally as it depends on climate, season, topography, soil type, vegetation and depth to water.

In some regions, it is possible to back-calculate (inversely model) the recharge over time using a groundwater flow model. This assumes that aquifer parameters are reasonably well-known and that there is detailed historical data on potentiometric heads. This is unlikely to be an appropriate method for the South East due to limited data on aquifer properties.

Historical recharge can also be estimated from field data (Chapter 5) but to make future predictions, a relationship must be derived for recharge, which depends on land use (vegetative cover, irrigation practices), soil type, water table depth and climate. Prior estimates of recharge based on land use have considered whether the vegetation is native or agricultural (Bradley et al., 1995) or whether the irrigation method is drip, pivot or flood (Harrington et al., 2006) but the general applicability of these estimates across the South East has not been tested. Chapter 5 considers recharge by crop type based on more extensive datasets. The accuracy to which this is developed for the South East will impact the capability of the regional model to make water balance predictions.

3.2.4 PROCESSES OCCURRING AT THE COASTAL BOUNDARY (1-2)

Determining appropriate model boundary conditions to represent submarine groundwater discharge (SGD) to the ocean is a common challenge in the development of coastal groundwater models as SGD can occur via various pathways and measurement remains difficult (Burnett et al., 2003; Stieglitz, 2005). Several modes of SGD can be considered, including: 1) point discharge along the coastline (e.g. at springs); 2) diffuse discharge along the coastline; 3) offshore discharge through preferential features such as faults and karst conduits (Bayari and Kurttas, 2002); 4) offshore discharge via exposed sections of confined aquifers ('Wonky holes'; Stieglitz, 2005); and, 5) offshore discharge via aquifer outcrops along the continental shelf. In an homogeneous unconfined aquifer, the presence of a subsurface saltwater wedge will tend to focus groundwater discharge at the coastline and inland, thereby simplifying the characterisation of SGD.

How SGD occurs along the coastline of the South East is unclear. The presence of springs along this coastline is well-documented (e.g. Herpich (2010)). However, the significance of diffuse discharge along the coastline and of offshore discharge is not known. In a recent study, Herpich (2010) found some evidence for the locations of offshore springs using remote sensing. Locations at which the Tertiary Limestone Aquifer and Tertiary Confined Sand Aquifer outcrop at sea are currently unclear. Only the upper TLA is exposed along the coastline of the LLC PWA.

At the regional scale, groundwater discharge processes at the coastline may be different between the western (i.e. Robe to Port MacDonnell) and southern (i.e. Port MacDonnell to eastern boundary of study area) sections of the LLC PWA coastline. The key difference is that large coastal lakes (such as Lake George) are present along the western edge and could potentially intercept regional groundwater flow, especially when the standing water level in these lakes is low. The role of these coastal lakes in the regional groundwater flow system is thus unclear at present. Chapter 6 presents the results of a preliminary study to investigate the applicability of environmental tracers to identifying and quantifying SGD in the study area. However, it has been determined that the characterisation and quantification of SGD for the study area will require a large amount of future work.

The position of the seawater-freshwater interface

Knowledge of the position of the seawater – freshwater interface is important in selecting the model boundary conditions used to represent the coastal boundary of the regional groundwater flow model and the resulting simulated groundwater outflows at the coast. The only investigations of the position and dynamics of the seawater – freshwater interface in the study area have focused on the coastline from a point roughly south of Millicent to the South Australian-Victorian border. In this region, decreases in discharge at some coastal springs have led to concerns about the risk of seawater intrusion. King and Dodds (2002) used surface geophysical methods to identify the location of the saltwater wedge along five 5 km-long transects oriented perpendicular to the coastline. In many cases, what appeared to be seawater or a mixture of seawater and fresher groundwater could be clearly identified within the Tertiary Limestone Aquifer at various depths and distances inland, although this required subsequent confirmed by drilling and groundwater sampling. The authors inferred that the saltwater wedge was located near to the ground surface along the coastline but potentially as deep as ~ 200 m further inland. Mustafa et al. (2012) installed monitoring wells to investigate seawater intrusion and collected groundwater salinity data. These data helped to confirm the position of the seawater – freshwater interface and provide a solid basis for local-scale seawater intrusion models. The results of these studies are summarised in Section 8.9. However, such information does not exist for the majority of the coastline in the study area and, as described above, due to differences in physical characteristics along the coastline this information cannot be readily up-scaled.

3.2.5 SURFACE WATER – GROUNDWATER INTERACTIONS AROUND AN ARTIFICIAL DRAINAGE NETWORK (1)

The question of how the influence of the extensive constructed South East drainage network on water movement around the landscape may be represented in a regional water balance model is complex. It is believed that the drainage network has a significant impact on groundwater flow in the unconfined aquifer, but whether this impact is relevant at the regional scale, or is very local, is largely unknown. Limited data relating to water movement through the drainage network exists to support detailed modelling of the drainage system. Additionally, a large number of operational control points exist at which water can be diverted through the system, and there is currently little information on how these are operated, i.e. when regulators are opened and closed. There are also very limited datasets on flows along the drains. Hence this item also represents a data gap for the region. It is believed that the first issue will be overcome through the future development and implementation of a decision support system, which implicitly will record the use of operational controls to move water. However, the lack of drain flow data remains a serious limitation.

A small number of modelling studies have focused on localised sections of the drains to quantify groundwater – surface water interactions (e.g. the Bald Hill drain; Cox et al. (2005)). A small number of focused technical projects are beginning to investigate this issue (e.g. Noorduijn et al. (in prep-a; in prep-b) but it currently represents a significant knowledge gap in understanding surface water movement within the study area. This is not being addressed through the current project.

3.2.6 THE NATURE OF WETLAND – GROUNDWATER INTERACTIONS (2)

Wetland – groundwater interactions are generally local-scale processes and hence are not expected to have a significant impact on the outcomes of a regional-scale flow model. However, representation of these processes is likely to be important in the development of future smaller-scale 'hotspot ' models of areas including lakes or wetlands, whether designed to investigate the impacts of changes to groundwater regime on wetland hydrology or not. Once again, this is a developing area of research for the South East region of South Australia and there currently exists limited data to support detailed modelling of these interactions. Investigation and modelling of 'wetland types' for the South East to investigate the various surface water – groundwater interactions that occur around these systems and how they react to regional and local scale changes in groundwater levels is a proposed activity for Phase 2 of this project.

3.3 Modelling challenges

3.3.1 RECONCILING DATA FROM MULTIPLE JURISDICTIONS

One of the challenges in developing a water balance model for the study area is that it incorporates multiple jurisdictions, i.e. South Australia and Victoria. Although the data flow has been good between the two states for this project, there are always challenges in reconciling datasets that have been created under different frameworks and hence are presented in different formats. Where this was particularly apparent for this project was in the creation of the preliminary hydrostratigraphic model.

3.3.2 REPRESENTING THE INFLUENCE OF THE MAN-MADE DRAINAGE SYSTEM

Drains have transformed the Lower South East over the past 150 years, lowering watertables across much of the study area. The location, development over time, and depth of the drains is known, but as described above in Section 3.2.5, little information is available on flow rates or on the routing of surface water through the drainage network.

The drains are long but narrow when compared to the grid size of a regional-scale numerical groundwater flow model. However, the impact of a drain on a single regional-scale grid cell is simply to remove some of the groundwater; it is a sink term. This can be simulated using MODFLOW's DRN package, where the groundwater flow to the drain is the difference between the watertable level in the cell and the base of the drain, multiplied by a conductance term. The difficulty is that the conductance is not known: if there were historical estimates of groundwater flux to the drains, it would be possible to estimate the conductance during calibration (i.e. through inverse modelling). Estimates of flux derived from field studies, or less ideally small-scale models, would be useful in this regard. The approach will be to start simply, representing the major drains as drain boundary conditions through the MODFLOW DRN package. Comparison of water balance results with gauging station data will be critical to identify how applicable this approach is and whether a more complex approach is required. Another issue would be if it is found that routing of drained water needs to be taken into account, which will add another dimension to the modelling.

3.3.3 INCORPORATING GROUNDWATER USE BY PLANTATION FORESTRY AND NATIVE VEGETATION (1-2)

As the depth to watertable can be shallow in some part of the model domain, the effects of forest plantations on the groundwater resources of the unconfined Tertiary Limestone Aquifer can be significant. Forest plantations, mainly blue gum (hardwood) and pine (softwood) plantations in the study area, can impact upon the groundwater resources through the reduction of groundwater recharge and through direct uptake of groundwater. Based upon recent estimates, direct extraction of groundwater and recharge interception by forest plantations represent an outflow from the Lower Limestone Coast Prescribed Wells Area that is greater than groundwater extraction from pumping wells (Wood, 2010a).

However, despite this apparent significance, a large amount of uncertainty still remains around quantifying the impacts of forest plantations on the groundwater balance. A number of point-scale studies have been undertaken to quantify direct extraction of groundwater and recharge interception by forest plantations and these are reviewed in Section 8.7.2. However, the spatial variability of these processes and the applicability of up-scaling point scale measurements in order to represent entire plantations or regions has yet to be investigated. In one respect, this represents a gap in the conceptual model for the region and belongs in the previous section. However, this knowledge gap is broader than this as the best modelling approach for implementing forestry impacts, should they be well-characterised, is also currently unclear.

Evapotranspiration (ET), a combination of evaporation and vegetation transpiration, is conventionally simulated in groundwater flow models by the MODFLOW Evapotranspiration (EVT) package (McDonald and Harbaugh, 1988). The inputs required for this approach include a maximum ET rate, which is the ET rate that would occur at the ET surface (generally this is the ground surface), and an extinction depth, below which there is no ET. The package assumes a linear decline in ET rate from the ET surface to the extinction depth. A regional extinction depth of 6 m has been adopted for the plantation forestry in the South East (Harvey, 2010) for regional scale resource management and accounting purposes, recognising the regional variability in soils and other factors (N. Power, DEWNR, *personal communication*, 18 November 2013). Benyon et al. (2006) have observed groundwater uptake by tree plantations for a water table depth as deep as 8-9 m. In some settings, the results of the recharge estimation study carried out as part of this project (Chapter 5) suggest that this extinction depth can extend below 20 m.

Two studies that have attempted to model the effects of forest plantations are summarised below.

Wattle Range 2010 Model

The Wattle Range 2010 MODFLOW model (WR2010) was developed to estimate the effects of forest plantations on the water balance and groundwater levels of the Wattle Range region and to undertake selected scenario modelling to inform future management of the forestry areas in the South East . Most forest plantations in the model domain are blue gums, but some small areas of pine are included. Data regarding planting area dates and locations, recharge interception rates and forest uptake rates were provided by the former Department of Water, Land and Biodiversity Conservation (DWLBC).

The study approximated the effects of forestry plantations through two primary processes, both of which were represented by the MODFLOW Recharge package:

Recharge Interception

- Recharge rates were set to the rates reported by Brown et al. (2006) for individual groundwater management areas in the model domain. In the forested areas, the forestry impact on recharge was represented as time-varying percentages of the management area recharge rates according to the forest rotation.
- Recharge interception was only applied in winter in the model.

Groundwater Uptake

- Groundwater uptake by forests was simulated as negative recharge. This means the forestry uptake is not depth-dependent in this model. The time-varying negative recharge rates are based on the forest rotation.
- Groundwater uptake by forestry was only applied in summer in the model.

An Alternative Approach

An alternative approach to simulating groundwater uptake by forestry was investigated in two of the modelling scenarios, using the MODFLOW Evapotranspiration Segments (ETS) package (Banta, 2000). Here, ET extinction depths of 6 m and 9 m were tried, based upon the fact that, for regional scale resource management and water accounting purposes, an extinction depth of 6 m for the forestry plantations in the South East has been adopted (Harvey, 2010) and that Benyon et al. (2006) have observed groundwater uptakes by tree plantations from watertables as deep as 8 – 9 m. A better match to the observed heads with a 9 m extinction depth in this study indicates that the 6 m extinction depth for forestry extraction may be a conservative estimate in the study region (Aquaterra, 2010b).

Coupling a WAVES Model with MODFLOW

Treijs (2011) investigated the use of a detailed surface-process based model, WAVES (Zhang and Dawes, 1998b) coupled with a three-dimensional finite difference groundwater flow model, MODFLOW-2005 (Harbaugh, 2005) in order to represent the effects of forest plantations on groundwater levels.

WAVES is a one-dimensional daily-time step model that aims to represent the interactions between plants, soil and the atmosphere based on detailed understanding of the individual physical and biological processes and the applied knowledge of the interdependencies and links between them. The groundwater uptake component of the WAVES water budget output was used to define the nature of the decline in evapotranspiration with depth. The ET profile developed formed the input for the ETS package in the MODFLOW simulations.

The study concluded that the methodology resulted in an acceptable model fit to field data. It also recommended that any further development of the methodology evaluate the capacity of the ETS package as well as investigating the level of sensitivity of the ETS package to ET profiles provided.

Current Understanding

While the Wattle Range 2010 model was considered to provide an acceptable representation of forestry impacts, a significant limitation identified was that the representation of forestry impacts was assumed to be correct and that other model parameters were calibrated around this assumption. Additionally, rates of groundwater recharge and extraction in the region surrounding the forest plantations were assumed to be constant in time. With the exception of two alternative model scenarios, sensitivity of the model to variations in representation of forestry impacts was not investigated. Assessment of whether forestry impacts were adequately implemented would require improved characterisation of other hydrogeological processes, which would then serve to reduce the range of possible model configurations that match observed data. For these reasons, and although an existing methodology appears to match observed groundwater drawdown levels and time series, it must be recognised that there still remains a great deal of uncertainty associated with the best method to represent forestry plantation impacts in the South East region.

3.4 Summary of major challenges

Table 3.1 summarises the major challenges in water balance modelling of the South East, where they have been addressed in this report and their status.

Table 3.1 Summary of major challenges in water balance modelling of the South East, where they have been addressed in this report and their status.

Challenge	Type of challenge	Priority	Chapter/Section in which it is addressed	Status
Historical land use	Data	2	4	Preliminary assessment of methods.
Historical groundwater extraction	Data	2	8.8	All available data collated. Crude methods described for extrapolating this back in time to generate earlier historical datasets.
Evapotranspiration	Data	1	5	Evapotranspiration derived from remote sensing data to create spatial estimates of net recharge. Requires calibration.
The influence of geological faults on groundwater flow	Conceptual	1	7	Preliminary assessment carried out. Recommendations for further work in Phase 2.
Interaquifer leakage	Conceptual	1	7	Preliminary assessment carried out. Recommendations for further work in Phase 2.
Spatial and temporal variability in groundwater recharge	Conceptual	2	5	Spatial datasets derived from water balance using remotely sensed ET data. Required calibration and validation in Phase 2.

Processes occurring at the coastal boundary	Conceptual	1-2	6 and 8.9	Lots of work required to characterize and quantify SGD. Information on the position of the seawater interface available for small region but not necessarily possible to up-scale this. The influence of the numerous coastal lakes on processes occurring at the coastal boundary is currently unknown.
Surface water-groundwater interactions around an artificial drainage network	Conceptual/Data	1	NA	Remains a large knowledge gap.
The nature of wetland-groundwater interactions	Conceptual/Data	1	NA	Proposed for Phase 2.
Reconciling data from multiple jurisdictions	Modelling		8	Presented minor challenges but this has not been a great issue
Representing the influence of the man-made drainage system in a numerical model.	Modelling		NA	Not considered to be a major issue in a regional scale model but difficulties may be identified through comparison of model water balance data with gauging station data.
Incorporating groundwater use by plantation forestry and native vegetation	Modelling/Conceptual	1-2	NA Water balance results from Chapter 5 provide some insight.	Remains a large modeling and conceptual challenge.

4 Methods for developing historical land use datasets

Andrew Millington, Stephen Fildes, David Hocking, Robert Keane, Chris Li, and Nikki Harrington

4.1 Background and introduction

The relationships between land use and hydrological processes are well known. They are based on measurements of hydrological stores and fluxes under a wide range of contemporary land uses globally and through numerical modelling land use-hydrology interactions. A consequence of this is that research into the hydrological outcomes of land use change has generally been based on relatively short-term experimental observations (e.g., experimental watersheds where hydrological processes are monitored before and after land use manipulations) or modelling past and future changes through backcasting and forecasting. Whilst this has provided good insights into contemporary fluxes and stores it omits the growing interest among a range of scientists that natural or physical environments are conditioned by historical contingency, in addition to their location, geology, soil, climate and contemporary land use and vegetation (e.g., Antrop (2005), Foster et al. (2003), Phillips (2007)). The historical contingencies of most likely of concern to hydrologists are medium-term to recent climate change, and past human-induced land use changes.

Antrop (2005), Foster et al. (2003) and Phillips (2007) argued for the importance of historical contingency in the contexts of landscape ecology, biogeography and geomorphology respectively. There has been a general lack of attention to land use-change driven historical contingency in hydrology, perhaps this is because many fluxes are relatively rapid and stores short term compared to the time frames of historical land use change. However, the time frames of many groundwater-related fluxes and stores suggest land use change history may provide historical context that may aid the understanding of some hydrogeological systems. Moreover, land use change often leads to a legacy effect in vegetation and soils, which modulates hydrological fluxes and stores long after the land use change has occurred.

In the South East of South Australia, published land use maps exist from 1998 onwards. We have investigated the possibility of extending the land use record, and by extension the land use change record, back to the mid-1800s when the area was first colonised by Europeans, by investigating the potential to use satellite imagery back to the 1970s, and historical land use and land tenure census data, which exists from the mid-1970s back to the late 1850s. Time constraints mean that some of our conclusions are provisional, but in general this project has recognised the immense value of historical land use information for hydrological modelling and other natural resource and ecosystem services applications. In particular it was recognised that, since there is currently no comprehensive dataset on historical land use for the study area, any improved understanding, even at broad scales, would be beneficial for understanding historical changes to recharge and, perhaps groundwater extraction, in the regional water balance model.

This chapter focuses on data sources and investigates key techniques that will be needed to develop comprehensive historical land use datasets for the study area. An inherent problem is that ground verification of historical land use is generally not possible through standard methods applied to contemporary aerial photography and satellite imagery. But studies have shown that verification is possible by drawing upon a range of data sources to help to improve and provide confidence in the accuracy of the final product. These include cross verification of data sources that were collected simultaneously in the past, archival and documentary sources, and obtaining oral histories from land managers.

4.2 1975 to 1998: satellite-derived land use mapping method

4.2.1 BACKGROUND AND OBJECTIVES

Satellite images provide the ability to spectrally differentiate between earth surface features and thus facilitate in the production of land use land cover (LULC) maps. Broad-scale land cover mapping derived from satellite images play a key role in regional and global LULC studies, such as those undertaken by the United States Geological Survey (USGS)(Cihlar, 2000).

Landsat MSS, TM and ETM+ satellite imagery is the most widely used data type for land use and cover mapping due to its relatively high spatial resolution and its 40-year (largely free) data archive. Importantly, the Landsat data Continuity Mission (NASA, 2013) ensures continued access to the Landsat image product into the future.

The applicability of Landsat image data to developing historical land use maps was identified early in the project. Reasonable data and coverage for the study area exists for as far back as 1975. Initial study of the literature, discussions with land use mapping experts and attempts to create broad land use classes from the images using the ERDAS IMAGINE image processing software (Intergraph, 2013) indicated that creating historical land use maps from Landsat images would not be a trivial exercise. Several constraints have been identified, including the inability to ground verify mapping results derived from historic Landsat image data in the same way as for contemporary images; though Bradley and Millington (2008) is one of a number of recent studies that have developed other ways to verify maps derived from historical imagery. Moreover, LULC mapping is often derived using a single scene classification method. Single scenes lack the information contained in a temporal profile extracted from a sequence of images, which is often necessary to map seasonal and phenological vegetation changes that help define land use classes. It was, however, considered possible to create a broad-scale land use product using two stacked Landsat scenes (one month apart) as detailed in Chapter 4.2.2 using this method with a moderate level of effort and the cost involved in further refining the accuracy of this and extending it to other points in time (within the bounds of Landsat data availability). This was done to allow an assessment of the accuracy of the method applied to the 1995 imagery to map land use map to be compared to detailed land use map produced in 1998 by the South Australian Department of Industry and Primary Resources (PIRSA).

The objective of this section for Phase 1 of the project was to create a historical land use map from Landsat data, using image classification software, for a time when a historical land use map is available (i.e., the time for which the earliest land use map is available). This would allow an assessment of the accuracy of the method and hence a 1995 land use map was attempted, with the 1998 land use map as a calibration tool.

4.2.2 METHOD

The 1995 land use map derived for this study was produced using Landsat 5 TM image data. Two image dates were stacked together (one month apart) to create a 14 band image stack that provides better spectral separation between invariant and variant land cover types (e.g., native vegetation versus irrigated agriculture). A mosaic of two adjacent scenes were also joined together to cover the majority of the study area (four scenes would be required to cover the entire study area). A 100-class ISODATA unsupervised classification was performed on the image stack and each category investigated and was labelled according to its likely land use type. A spatial filter was used to eliminate classification noise from the final product.

The sequential procedure followed was:

1. Image selection; ordered and download from USGS
2. Import all bands from TIFF to IMG
3. Stack image layers to create a single image
4. Remove cloud covered areas

5. Reproject each image to MGA54
6. Mosaic adjacent images
7. Subset to study area using a shape file
8. Overlay images (from two dates) to create a 14 band image stack
9. Unsupervised classification – 100 classes (convergence = 0.975)
10. Investigate and label/colour land use classes
11. Produce maps, export to EPS format

4.2.3 PRELIMINARY PRODUCT: ASSESSMENT OF ACCURACY

When compared with the 'official' 1998 land use map developed by PIRSA (1998) the 1995 image-derived land use map developed for this study has successfully mapped broad-scale primary land use categories across the study area, but is not without error. The inset maps in Figure 4.1 show a comparison between the two land use maps:

1. Notably, as displayed inset map 2, the 1995 land use map incorrectly shows significant areas of surface water in and around the southern coastal native vegetated areas, an error caused by the presence of cloud in the imagery.
2. Areas of irrigated agriculture in the 1995 land use map are not present in the PIRSA (1998) land use map. This is due to the presence of marsh/wetland grasses in the dry period satellite image that has similar/same spectral characteristics as irrigated agriculture.
3. Dominant areas of non-irrigated cereal cropping shown in the PIRSA (1998) land use map are not present in the 1995 land use map (primarily mapped as grazing modified pasture) due to the necessary use of a dry period (summer scene) image, when non-irrigated cereal crops are not present, to separate irrigated agriculture from non-irrigated grazing areas responding to seasonal winter rainfall.
4. Inset map 1 in Figure 4.1 shows significantly different patterns of non-irrigated cereal crop allotments between the 1995 land use map and the PIRSA (1998) land use map. This is primarily due to annual crop rotation practices, including rotation between cereal cropping and grazing. These land use rotation practices make it particularly difficult to quantify the accuracy of the historic 1995 image-derived land use map product using traditional ground-based verification methods.

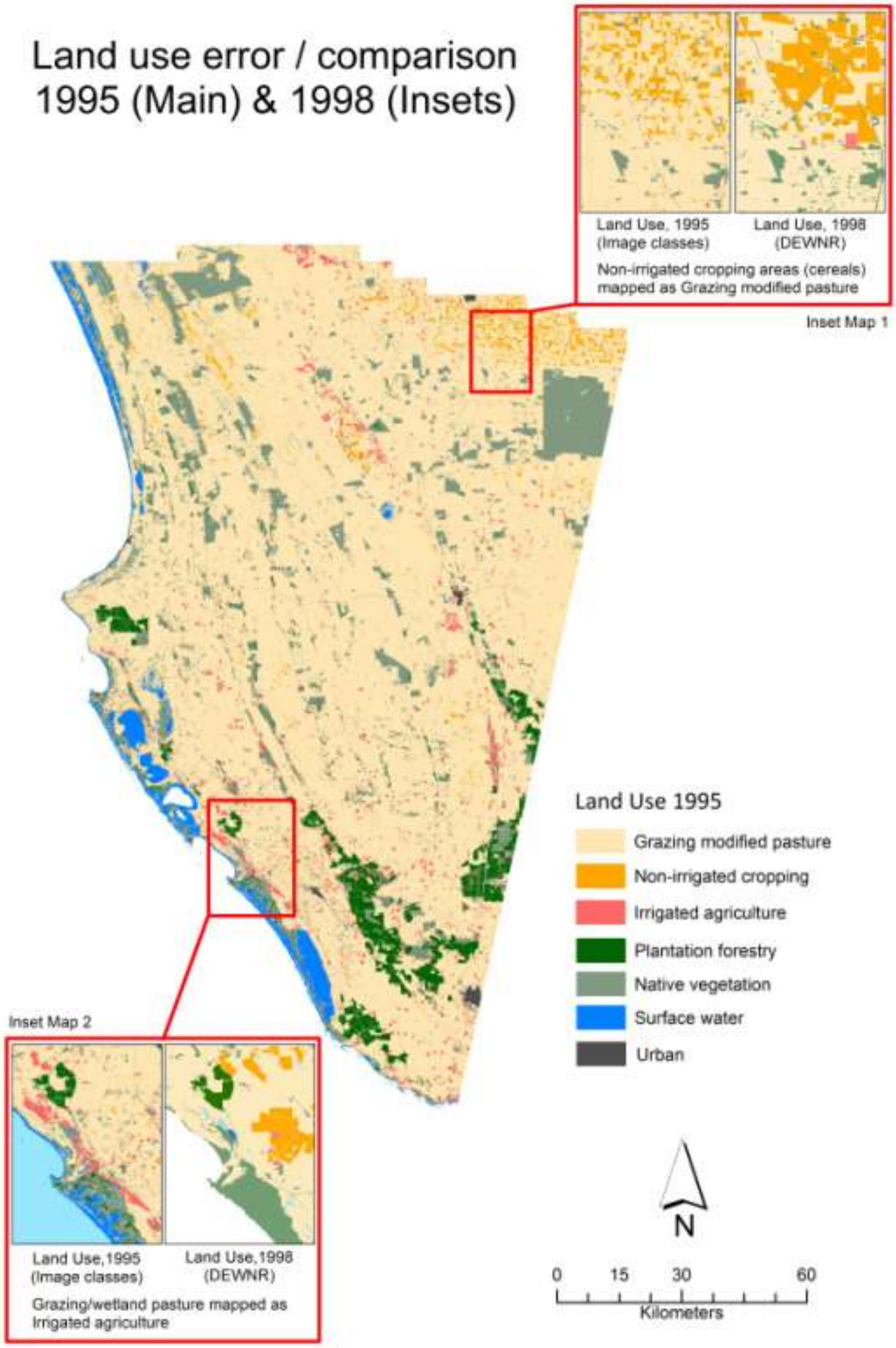


Figure 4.1 Preliminary land use map for 1995 derived from Landsat 5 TM imagery, compared with existing PIRSA 1998 land use map to demonstrate some of the limitations of the method employed.

4.2.4 OPTIONS FOR IMPROVING THE CURRENT LAND USE MAP ACCURACY

Option A

Initial improvements can be made to the current 1995 image-derived land use map through a more detailed evaluation and comparison with that of the PIRSA (1998) derived land use products and comparisons with aerial photography available at the time. The PIRSA (1998) land use products, while not produced at time intervals suitable to meet the objectives of this study, are nonetheless helpful in refining historic land use mapping; as is the case in this project.

Moreover, the current 1995 image-derived land use map requires a further two eastern image scenes to cover the full extent of the study area. This would involve a repeat of the approach undertaken to derive the current 1995 land use map (detailed in Chapter 4.2.2).

While this option is likely to improve the mapping of broad-scale primary land use categories, it is unlikely to help map descriptive sub-classes of land use, and thus has a lower likelihood of meeting project objectives.

This method could also be applied to older Landsat imagery to map land cover from the mid-1970s (Landsat MSS imagery was acquired from 1973) to 1995, if data are available.

Option B

It is recommended that considerable improvements can be made in separating primary broad-scale and descriptive sub-classes of land use to better meet the objectives of the study through the use of high temporal image stacks of Landsat image data. There are a number of temporal approaches using a range of land cover parameters that can be used to do this, each of which may need to be tested to determine the best outcome for the study area and project objectives.

Landsat 5 image TM data is acquired on a regular 16 day cycle (subject to cloud cover and maintenance/technical issues) that date back to 1984 and is available free of charge. Landsat 3 and 4 image data is available for earlier years, while the Landsat Data Continuity Mission (Landsat 8) is now fully operational and will provide imagery into the future.

Improvements in the accuracy of broad-scale land use mapping and the identification of descriptive sub-classes can be achieved through tracking land cover parameters (e.g., vegetation indices) and their trajectories over time using multiple Landsat image stacks. Land cover parameter trajectories assist in separating spectrally similar land cover types under different land use scenarios – for example, separating areas of 'green' vegetation, responding to seasonal rainfall in non-irrigated agricultural areas, from areas under different types of artificial irrigation; or the separation of different vegetation types from irrigation regimes by identifying their specific phenological cycles (growing seasons) (Figure 4.2). This has been done successfully to differentiate irrigated from rainfed cropping and grazing in somewhat similar landscapes in South America using coarser resolution MODIS data (Redo and Millington, 2011), the recent release of significant Landsat archives to Australian researchers would enable similar mapping to be achieved in the south east at a finer spatial resolution. However, the archives need to be searched to see exactly what data is available from 1973 (the earliest date Landsat 1 MSS imagery was acquired).

Temporal trajectories not only assist in refining land use mapping categories but for selected parcels of land (down to the pixel level), but they can reveal landscape dynamics important to hydrologists and land managers, including land use change (LUC) and its 'land use state' at any point in time.

This option will require more resources to accomplish but would provide an adaptive model upon which land use dynamics can be monitored into the future and at a scale where hydrological processes and land management activities occur. The cost to achieve the improved land use map using this option method will depend on the data requirements of the hydrological model – but should be noted that any hydrological model should be adaptive in its ability to use frequently updated land use data as land use is dynamic and improvements to land use mapping accuracy is ongoing.

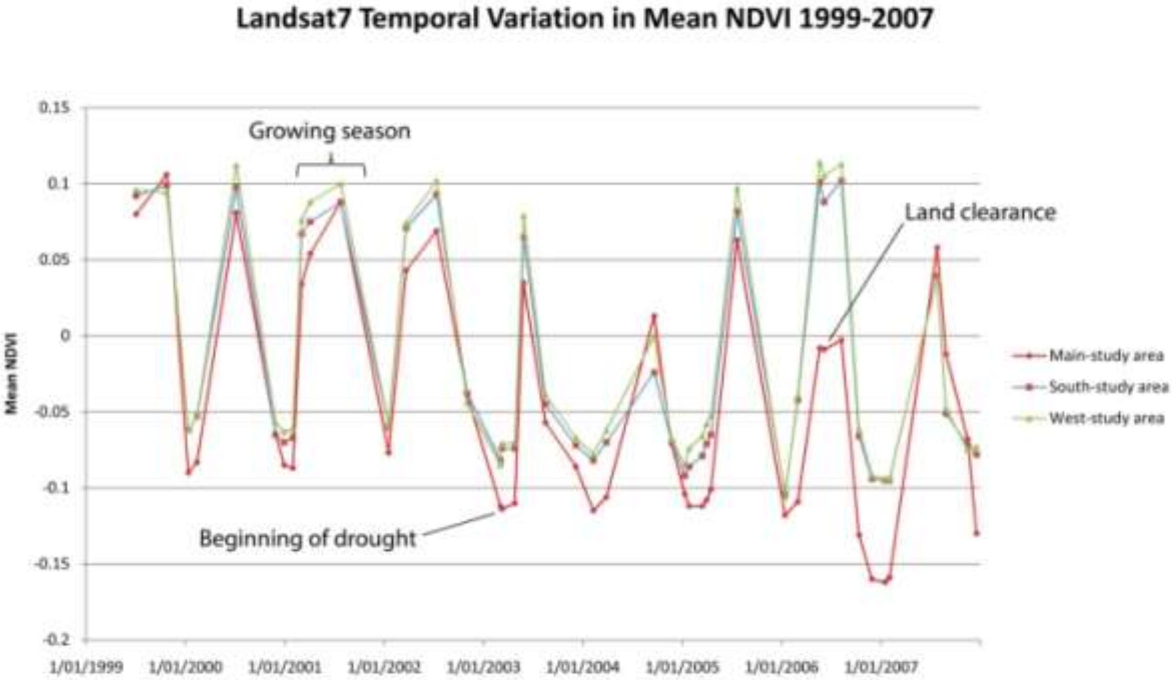


Figure 4.2 A temporal profile based on a Normalised Difference Vegetation Index (NDVI) calculated for three study areas in South Australia showing land use land cover dynamics.

4.3 Historical land use and land cover reconstruction for hydrological investigations, 1857 to 1974.

4.3.1 BACKGROUND

This part of the chapter provides an evaluation of the potential of historical land data extracted from the South Australian Parliamentary Papers for hydrological analyses in the South East of South Australia specifically, as well a providing a more general opinion about the use of these data in the state and how they can be 'stitched' together with aerial photography and satellite imagery to produce a seamless long-term record of land use and land cover (LULC).

South Australia has a very rich archived land data set that can be used for historical LULC reconstruction in the form of the agricultural production and land tenure returns that were reported in the South Australian Government Parliamentary Papers between 1857 and 1974. These records are unusual in their high spatial and temporal resolutions compared to similar information that exists for other political units around the world that experienced colonization and agricultural expansion during the 19th and 20th centuries. With the exception of 1885 to 1888 and 1893 to 1895 the data were collected and presented annually. The primary spatial reporting unit was the hundred (an area of approximately 30,000 ha that is generally rectangular in shape). In other political units where comparable data exist, reporting was less frequent or data were only reported for coarser spatial units.

Hundreds are the spatial unit of the South Australian cadastre below the county level. In total there are 51 counties and 501 hundreds in the state, which are concentrated in the wetter inland and coastal areas where cultivation is possible. They are based on the traditional land administration unit used in Great Britain and some Scandinavian countries, which is also known as a hundred. These are based on a 100 square mile (approximately 26,000 ha) area. They were adopted in South Australia, but not elsewhere in Australia, and this probably relates to the highly planned nature of the Colony of South Australia. The mean area of hundreds in the South East is 30,783.4 ha (range = 19,083– 56,588 ha). Hundreds were established (declared) as a response to pressures for land to cultivate from colonists. Therefore the hundreds dealt with in this study (in what is now the South East Division of the state, Figure 4.3) were not all declared at the same time. Counties were established (declared) and then 'filled up' with hundreds over time. The earliest hundreds were created in the 1850s in the two counties – Grey and Robe -- that were proclaimed first in the South East; and the last almost eight decades later in 1939 in Buckingham County. The counties and hundreds used in this study are included in Appendix A with their dates of declaration and areas.

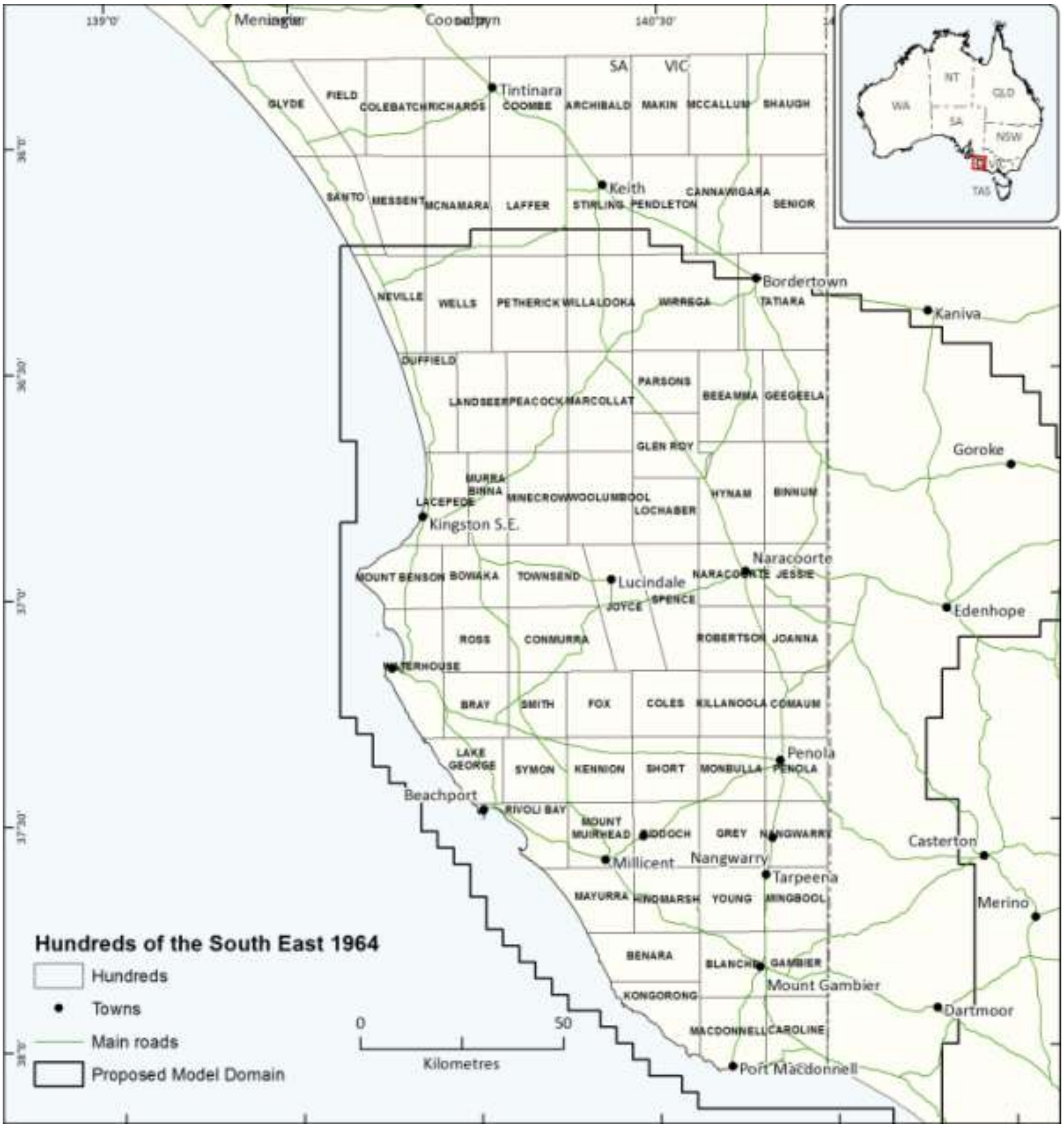


Figure 4.3 Hundreds in the South East Division of South Australia

Land use and land cover reconstructions using archived historical data or maps are relatively uncommon compared to those using aerial photography or satellite imagery, but where they have been used they extend the LULC change record into the period before the earliest aerial photography is available they have not focussed on hydrological applications. Rather these studies have either been methodological (e.g., Petit and Lambin (2002)), or have focused on vegetation ecology (e.g., Foster et al. (2003), Lunt (1998)) and, more straightforwardly, land use (Aspinall, 2004; Brown et al., 2005; Liu and Tian, 2010).

4.3.2 EXTRACTING LAND USE AND LAND-COVER INFORMATION

Annual volumes of papers dealt with by the South Australian Government are available as bound volumes in the State Library and at the three university libraries in the state. The information relevant to this research is contained in various tables in the Statistical Reports (Table 4.1). This information varies from year-to-year, not simply in terms of the reports, which are often numbered differently, but also in the following ways:

1. The particular land use categories reported on varies over time. This occurs, in part, because land use changed in south east South Australia. When colonisation started in the mid 1800s the rural production system was mainly based on wheat and sheep. Vineyards and forestry, two important contemporary land uses in region, were not present or not considered important by the colonial government. For example, vineyards were not reported on in the 1890 register (John Riddoch planted the first vines in the south east at Yallem in 1890), but they were in the 1925 records.
2. The land tenure information reported on also changes over time. Again this is due to the changing nature of the land tenure information requirements of the early colonial government compared to those of the state after Federation. For example, the tenure category 'Land dedicated for forest purposes' was recorded in 1925 but not in 1890.
3. Government policy requirements affected what was collected and, likely, how it was collected. The information reported changed accordingly.

As a consequence the information is non-stationary, but it is nevertheless reasonably comprehensive over time.

The relevant tables from the Statistical Registers that report on 1890, 1925, 1935, 1955 and 1964 were used to obtain data to provide a preliminary evaluation of its utility for groundwater-related studies in the South East (Table 4.2).

All relevant LULC and land tenure information was extracted from the tables and manually entered into a series of Excel worksheets. The information in these worksheets falls into the following categories:

1. Basic information: county and hundred names and areas (all areas are reported in acres in the Parliamentary Papers, acre values were converted to hectares)
2. Areas in each hundred under different crops or groups of crops (all areas are reported in acres, acre values were converted to hectares)
3. Production data for the land uses under category (2), in this category the units of production vary and include bushels (e.g., grain crops), tonnes (e.g., potatoes and hay) and hundredweights (e.g., grapes and raisins). All units were converted to metric equivalents.
4. Land tenure information, as acreages under different tenure categories. These were converted to hectares.
5. Information on land dynamics, i.e., the area of native vegetation cleared in the previous year, and the area that reverted from cultivation to fallow between years.

Table 4.1 Parliamentary reports used in the preparation historical South East land use change

REPORT
South Australia Proceedings of Parliament Papers 1891 Vol (I), Part V Production pp. 1
South Australia Proceedings of Parliament Papers 1927 Vol (III), Part V Production pp. 1
Proceedings of the Parliament of South Australia 1937 Vol (I), Part V Production pp. 1
Proceedings of the Parliament of South Australia 1947 Vol (I), Part V Production pp. 1
Proceedings of the Parliament of South Australia 1957 Vol (III), Part V Production pp. 1
Proceedings of the Parliament of South Australia 1967 Vol (I), Part V(a) Production pp. 1
South Australia Proceedings of Parliament Papers 1891 Vol (I), Part V Production pp. 1

Table 4.2 Summary table showing the availability of County and Hundred level data used in the study. The numbers in parentheses refer to the corresponding table reference in the Statistical Registers. Blue areas indicate a parameter not reported in the Statistical Register.

	TA	S	GPP	IPoA-	IPoA-UAP	IPoA-SDP	IPoA-AWC	IPoA-AL31Dec	PL	OL	LLT	UnO	DFP
1964	C(2)	C(2)	C(2)		C(2)				C(2)	C(2)	C(2)		C(2)
1955	C(2)	C(2)	C(2)			C(2)			C(2)	C(2)	C(2)	Can be derived (not recorded)	C(2)
1945	C(2)	C(2)	C(2)			C(2)			C(2)	C(2)	C(2)		C(2)
1935	C(2)	C(2)	C(2)			C(2)			C(2)	C(2)	C(2)		C(2)
1925	C(1)	C(2)	C(2)			C(2)	C(1)		C(2)	C(2)	C(2)	C(1)	C(2)
1890	C(1/2)			C(1)				C(2)					

	TO	TAUC	UPASG	PCLLI	NGCS	LF	BH	TAH	PO	CLC/L	ELHF	LE	LENC
1964	C(2)	C/H(6&18)						C(6)					
1955	C(2)	C/H(6&18)					C(6)	C(6)					
1945	C(2)	C/H(7&16)				C(7)		C(7)					
1935	C(2)	C/H(6&7)	C/H(6&7)	C/H(6&7)	C/H(6&7)	C/H((6&7)	C(6)	C/H(6&7)	C/H(6&7)	C/H(6&7)			
1925	C(1)	C/H(6&7)	C/H(6&7)	C/H((6&7)	C/H(6&7)	C/H(6&7)	C(6)	C/H(6&7)	C/H(6&7)	C/H(6&7)			
1890		C/H(2/15)						H(15)			C(2)	C(2)	C(2)

C	County level data
H	Hundred level data
C/H	County/Hundred level data
(2) or (14) etc	Table Ref No.

TA	Total Area	TAUC	Total Area Under Crop
S	Sold	UPASG	Under Permanent Artificia
GPP	Granted for Public Purpose	PCLLI	Previous Crop Land Lying I
IPoA-	In process of Alienation-	NGCS	New Ground Cleared Duri
IPoA-UAP	In Process of Alienation-Under Agreement to Purchase	LF	Land in Fallow
IPoA-SDP	In Process of Alienation-Under System of Deferred Payments	BH	Balance of Holdings
IPoA-AWC	In Process of Alienation-Alienated Wholly or Conditionally	TAH	Total Area of Holdings
IPoA-AL31Dec	In Process of Alienation-Alienated Land to 31 December 1890	PO	Privately Owned
PL	Pastoral Lease	CLC/L	Crown Land Cleared or Lic
OL	Other Lease	ELHF	Extent of Land Held by Fre
LLT	Land Leased Total	LE	Land Enclosed
UnO	Unoccupied	LENC	Land Enclosed but not Cul
DFP	Dedicated for Forest Purposes	TO	Total in Occupation

The data are usually reported by hundred. However, there are a number of reporting issues that arise regularly in the archives. Methods were developed to address these issues as follow:

1. In the early phases of colonisation, when counties did not have their full complements of hundreds declared, data from farms and stations outside the proclaimed hundreds are aggregated under a 'Remainder of County' category. These are almost always small areas compared to those in the declared hundreds in the county. Areas in this category were distributed amongst the named hundreds in proportion to amounts cultivated. For example. one hectare of orchards was recorded in the remainder of the County of Buckingham in 1925, this was divided between the following hundreds in proportion to their reported areas, Beeamma, Binnum, Geegeela, Hyman, Lacepede and Lochaber (1 ha each) and Glen Roy (9 ha). Thereby adjusting the area for Glen Roy to 9.6 ha and the

other hundreds to 1.07 ha. It is recognised that this in an assumption, which needs be verified if possible against detailed records in PIRSA if they still exist.

2. Crop area and production data were sometimes reported for a group of two to four hundreds. In these instances the area and production data were simply divided by the number of hundreds. To illustrate, in the County of Robe, the data for 'all crops under production' in Coles and Fox hundreds were recorded as a single entry in the statistical register for 1925, so the total are under crops (49 acres) of area was divided evenly and 24.5 acres of area under crop was entered for each hundred of Coles and Fox in spreadsheet for 1925 and the same was done for the individual crops that were reported.
3. Crop area and production data for a hundred were sometimes split and reported as separate individual entries or separated parts of a hundred were combined with the data from other hundreds. Again to illustrate an example from the 1925 register is used. The area under 'all kinds of hay' for the hundred of Benara in Grey County appeared as part of the hundreds of Benara (114 acres) and Tantanoola (857 acres). In such cases, the area under the crop reported was combined and recorded as a single entry for that hundred (in this case 399.7 acres for the hundred of Benara).

The key parameters from categories 2 to 4 were used to evaluate the utility of this information in the context of the groundwater issues in the South East.

4.3.3 Displaying land use land-cover and land tenure information

We have not made an exhaustive evaluation of the best ways to present the information at the present, partly because of time constraints but also because we only used six years of data for the test. We are aware that the presentation issues would be different for the full set of data.

Therefore we have focussed on ways to visualize the summary information, rather than present the results of in-depth analyses (which have not yet been performed). The summary information was visualised on maps of hundreds for each county for each year studied for individual counties. We provide the following examples; maps of area in Grey County under different land use groups according to similar hydrological properties for each year studied (Figures 4.4 to 4.8), and maps of areas under different land use groups according to similar hydrological properties for all counties for 1925 (Figures 4.5, and 4.9 to 4.12). Maps of native vegetation are provided for all hundreds in the region for each year studied (Figures 4.13 to 4.17).

A number of visualization tools were examined in ArcGIS. The most clear and visually revealing method of displaying areas under area under different land use groups according to similar hydrological properties was to provide proportional pie charts of these groups located in the relevant hundred in a grid frame of hundreds (e.g., Figures 4.4 to 4.12). In these maps the area of the circles is proportional to the total area under cultivation in each hundred, and the size of circles is consistent between the maps for different years. For the case of a single variable simple choropleth mapping was feasible, and this was used for the proportion of native vegetation remaining in hundreds (Figures 4.13 to 4.17).

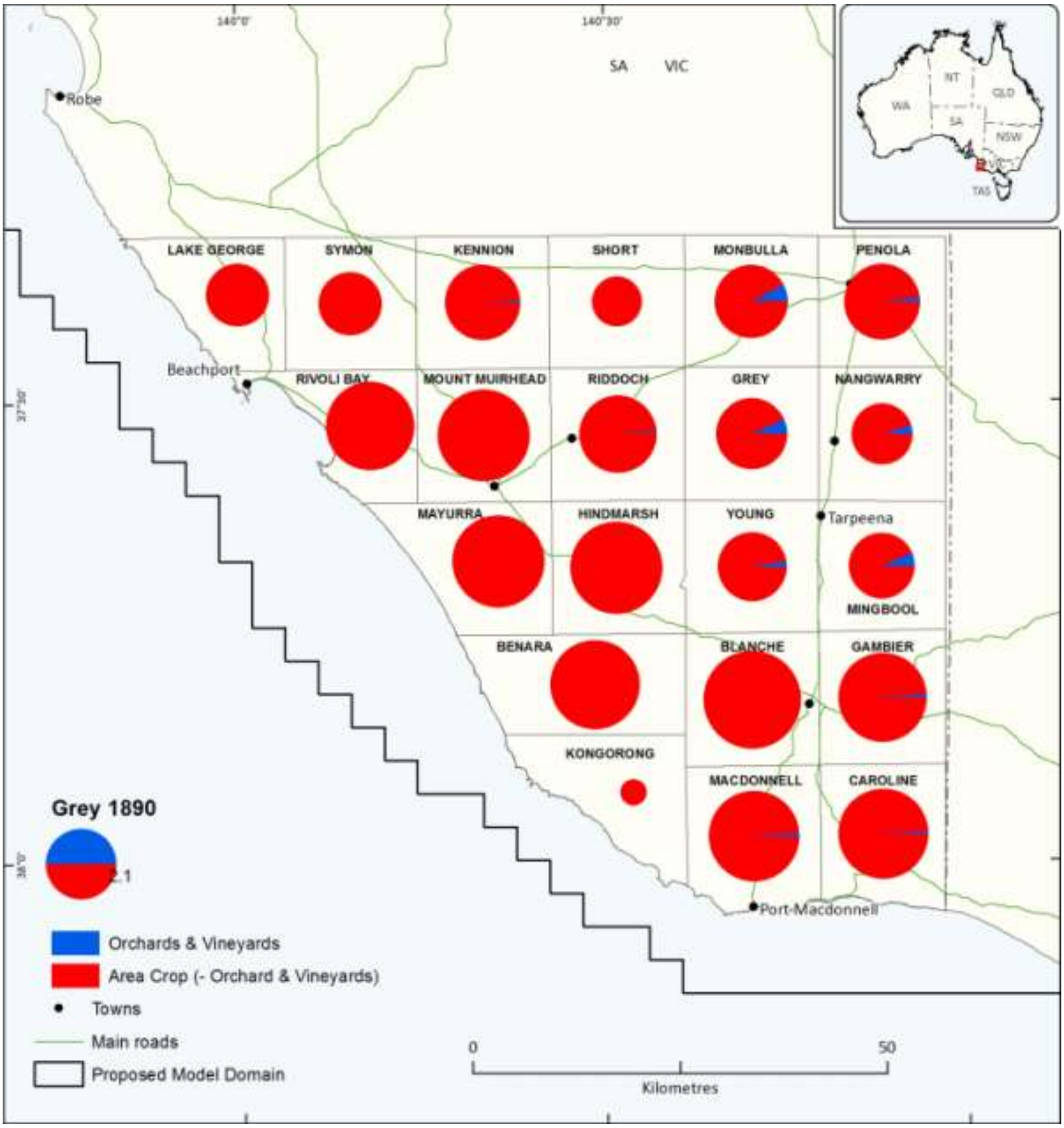


Figure 4.4 Percentages of farmed areas under different hydrologically-meaningful classes by hundred, Grey County 1890. The size of the pie chart in each hundred is proportional the area cultivated.

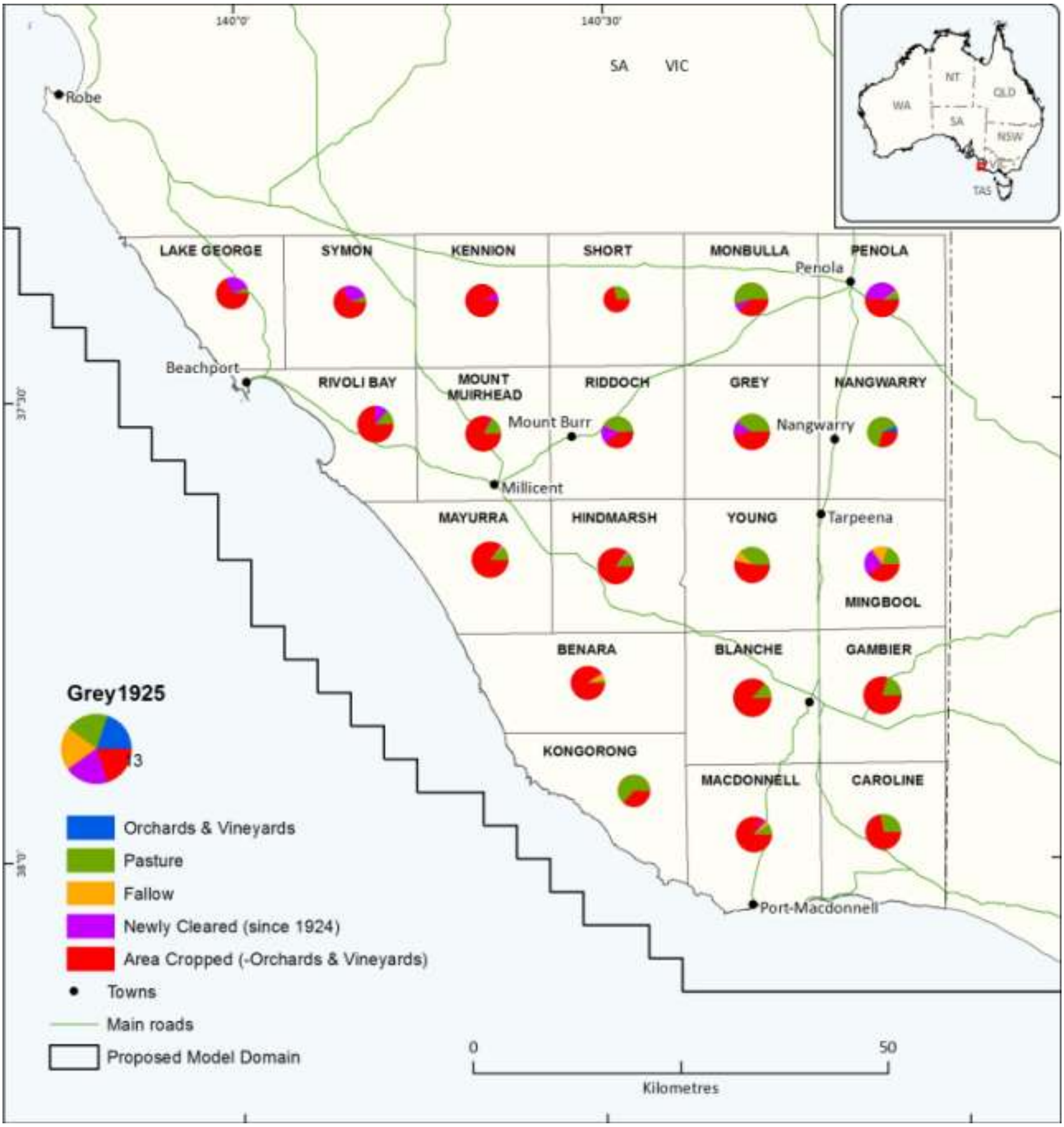


Figure 4.5 Percentages of farmed areas under different hydrologically-meaningful classes by hundred, Grey County 1925. The size of the pie chart in each hundred is proportional the area cultivated.

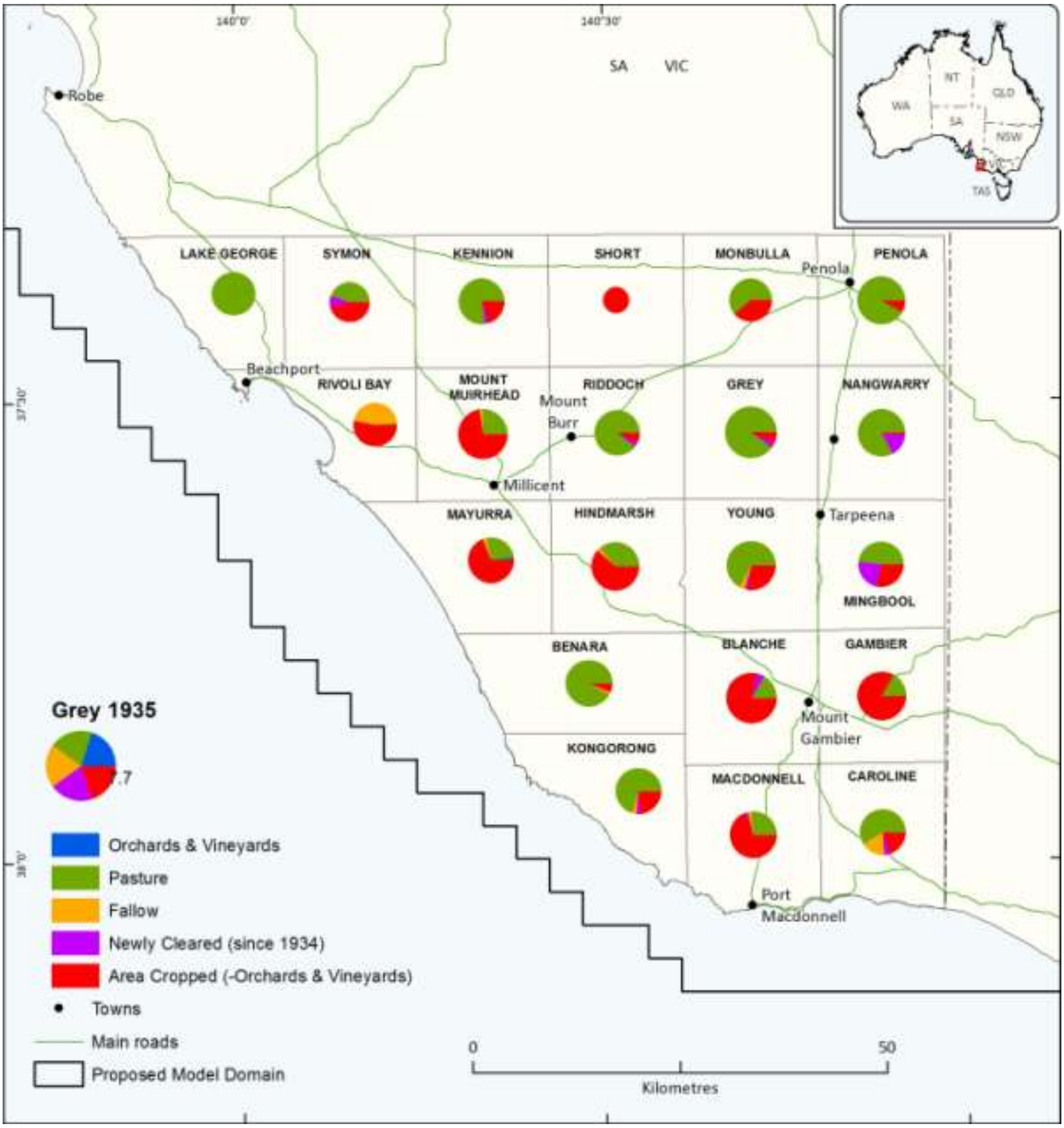


Figure 4.6 Percentages of farmed areas under different hydrologically-meaningful classes by hundred, Grey County 1935. The size of the pie chart in each hundred is proportional the area cultivated.

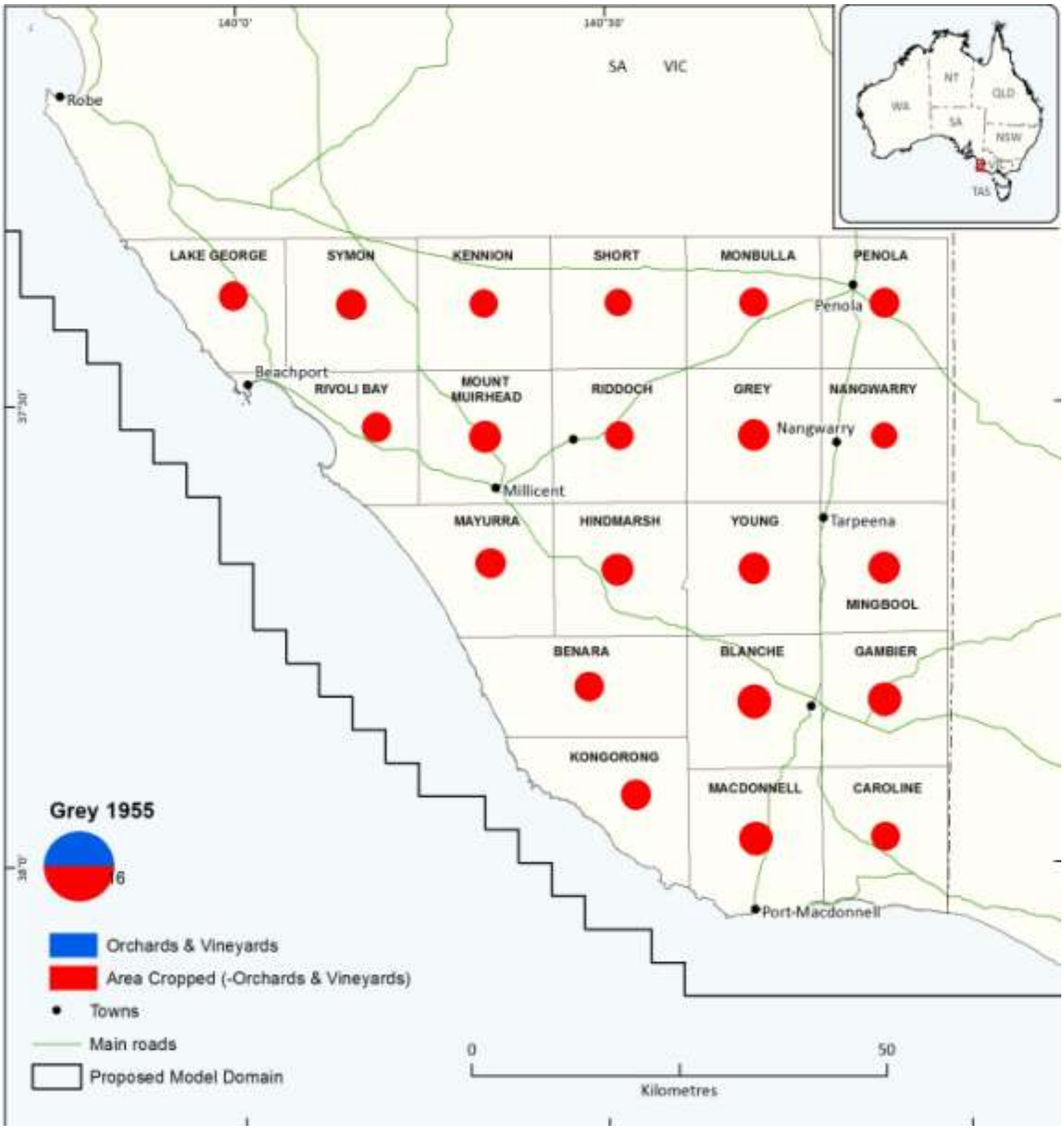


Figure 4.7 Percentages of farmed areas under different hydrologically-meaningful classes by hundred, Grey County 1955. The size of the pie chart in each hundred is proportional the area cultivated.

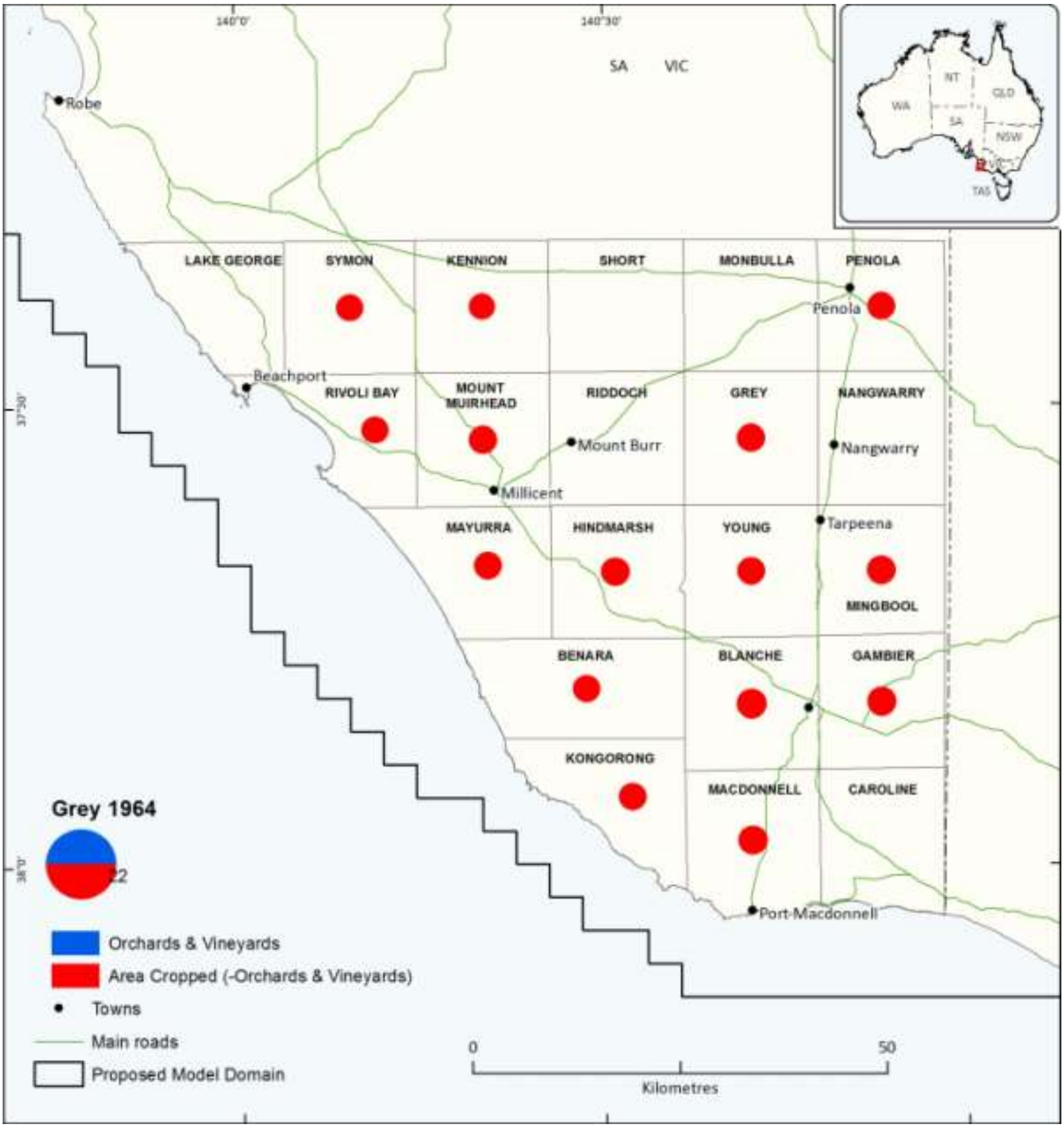


Figure 4.8 Percentages of farmed areas under different hydrologically-meaningful classes by hundred, Grey County 1964. The size of the pie chart in each hundred is proportional the area cultivated.

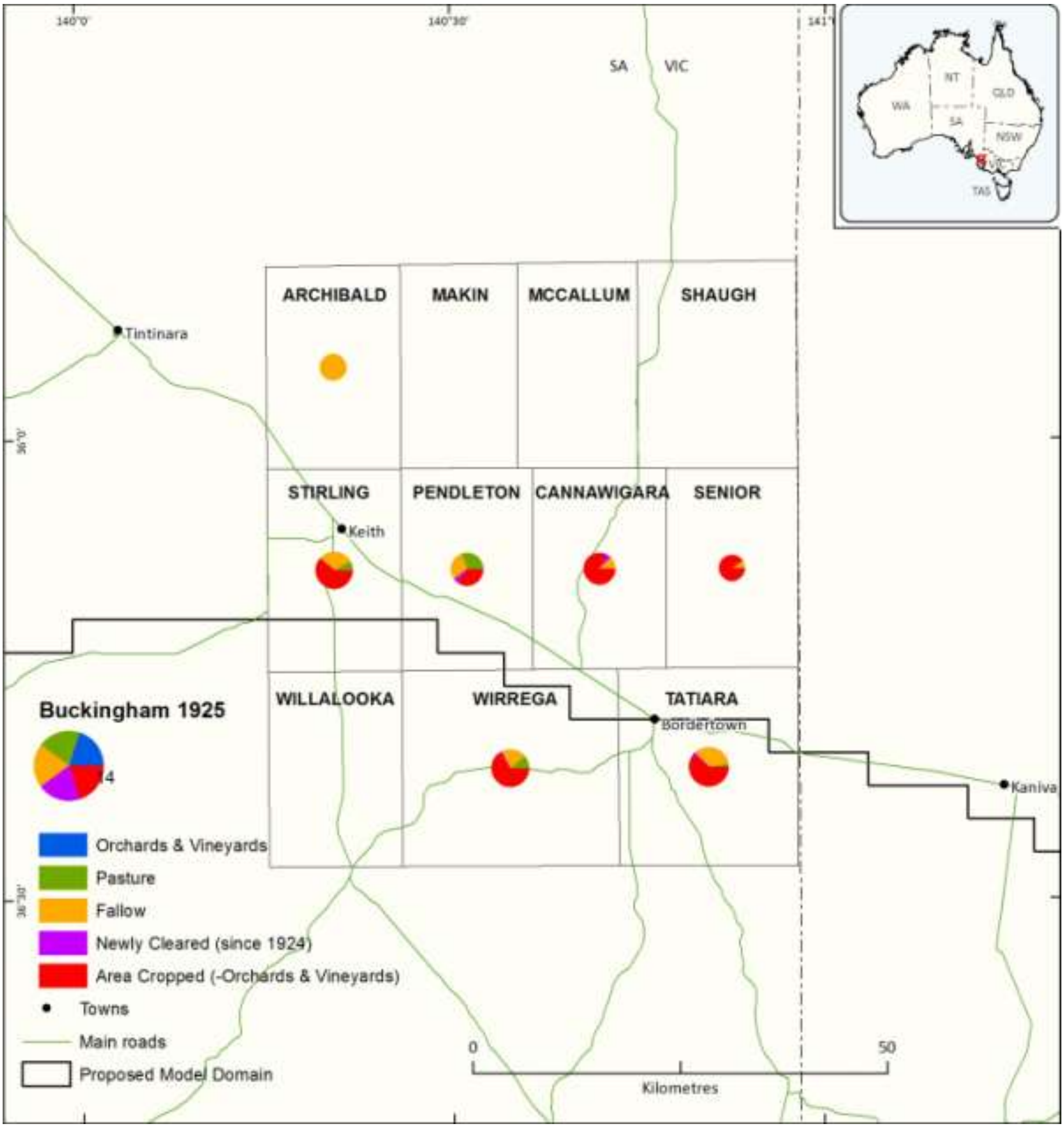


Figure 4.9 Percentages of farmed areas under different hydrologically-meaningful classes by county, Buckingham County 1925. The size of the pie chart in each hundred is proportional the area cultivated.

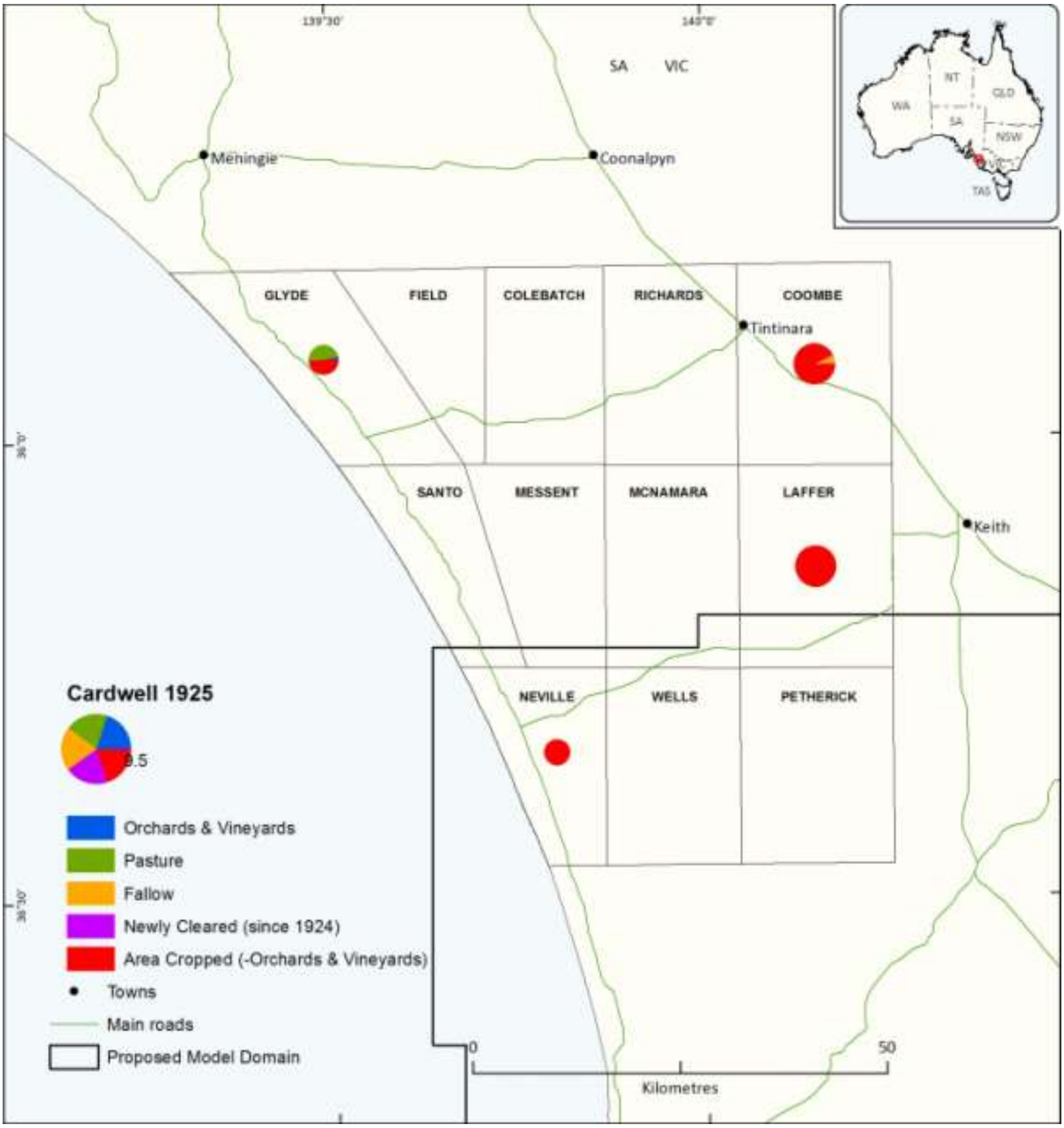


Figure 4.10 Percentages of farmed areas under different hydrologically-meaningful classes by county, Caldwell County 1925. The size of the pie chart in each hundred is proportional the area cultivated.

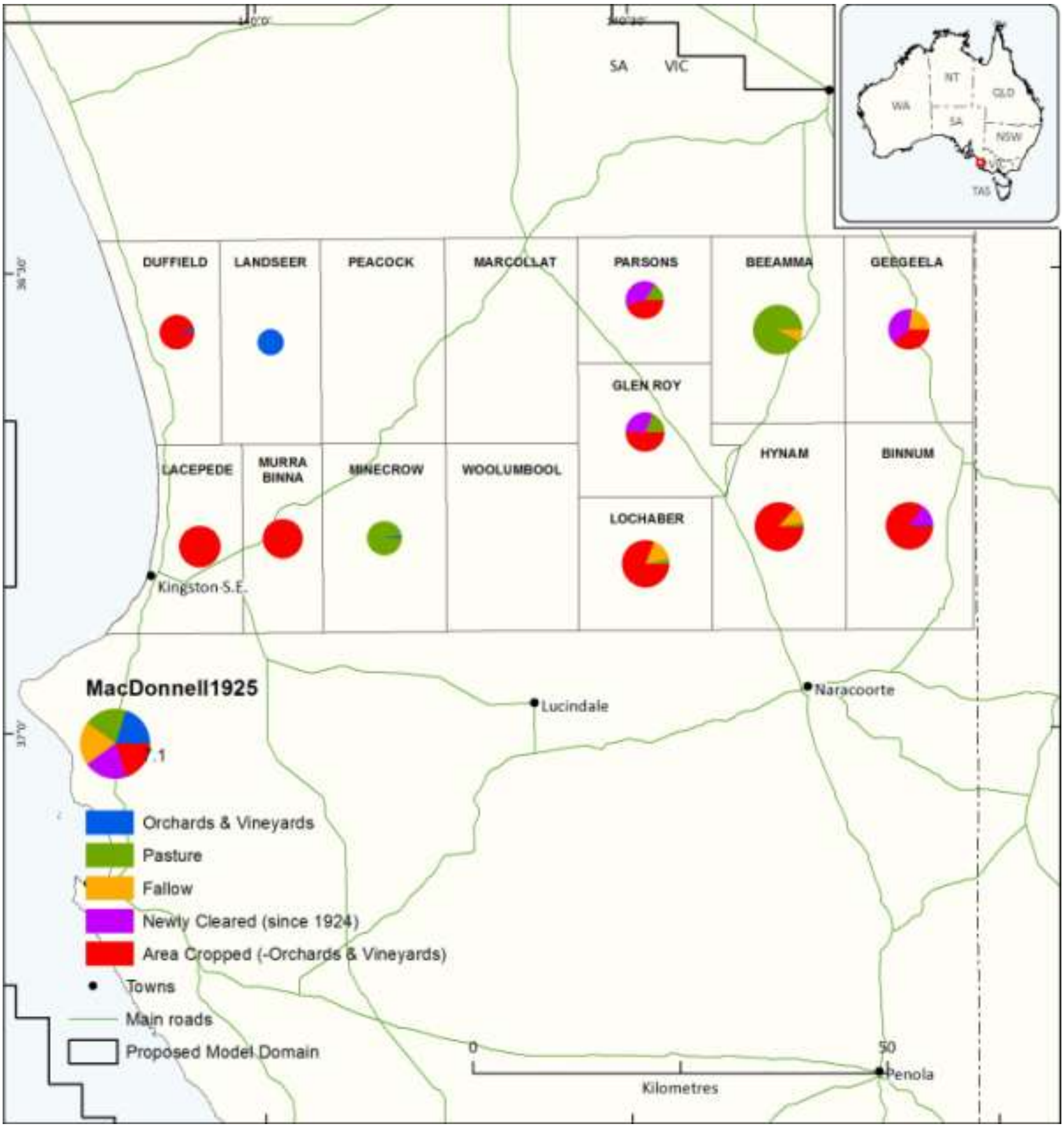


Figure 4.11 Percentages of farmed areas under different hydrologically-meaningful classes by county, MacDonnell County 1925. The size of the pie chart in each hundred is proportional the area cultivated.

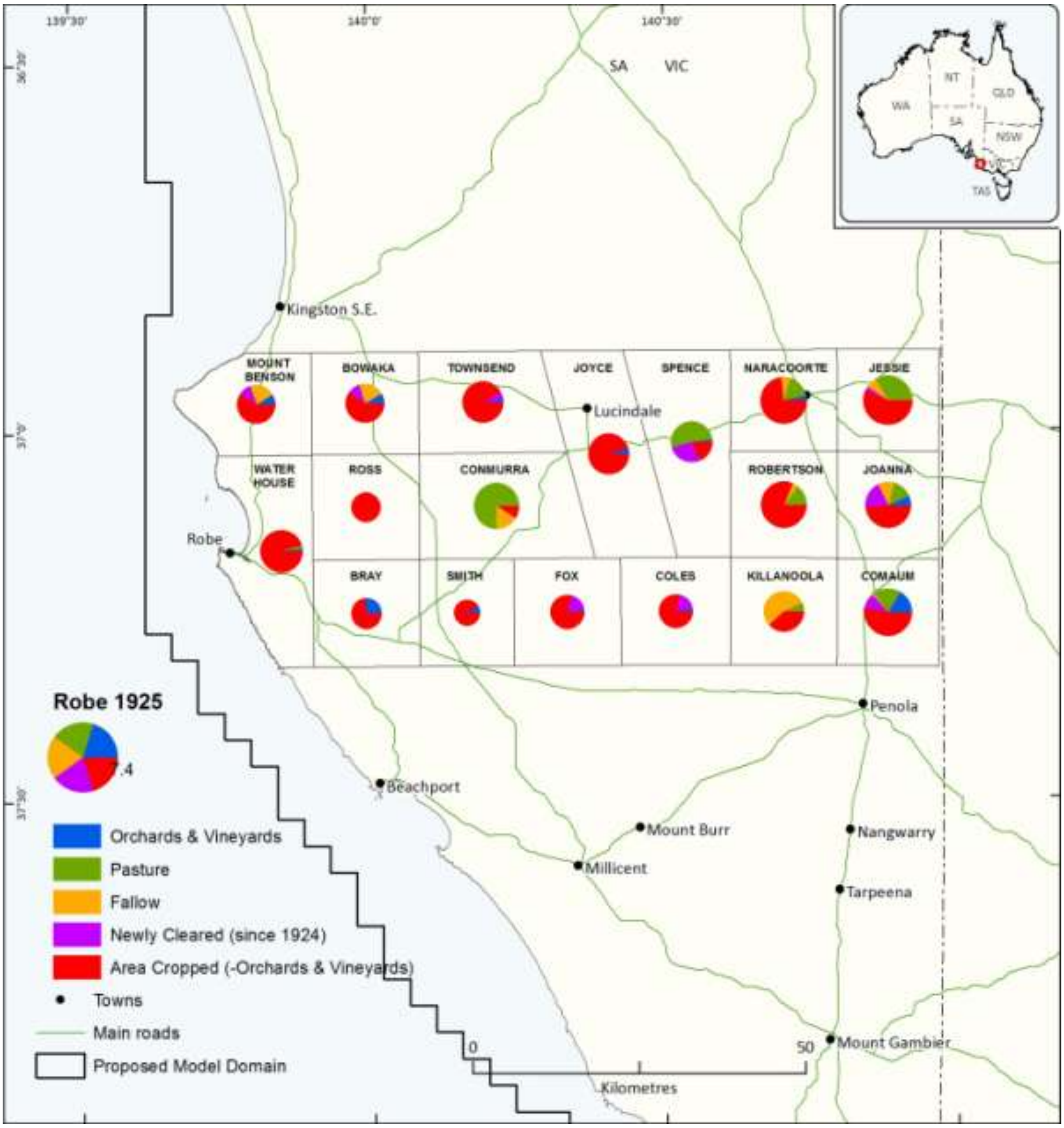


Figure 4.12 Percentages of farmed areas under different hydrologically-meaningful classes by county, Robe County 1925. The size of the pie chart in each hundred is proportional the area cultivated.

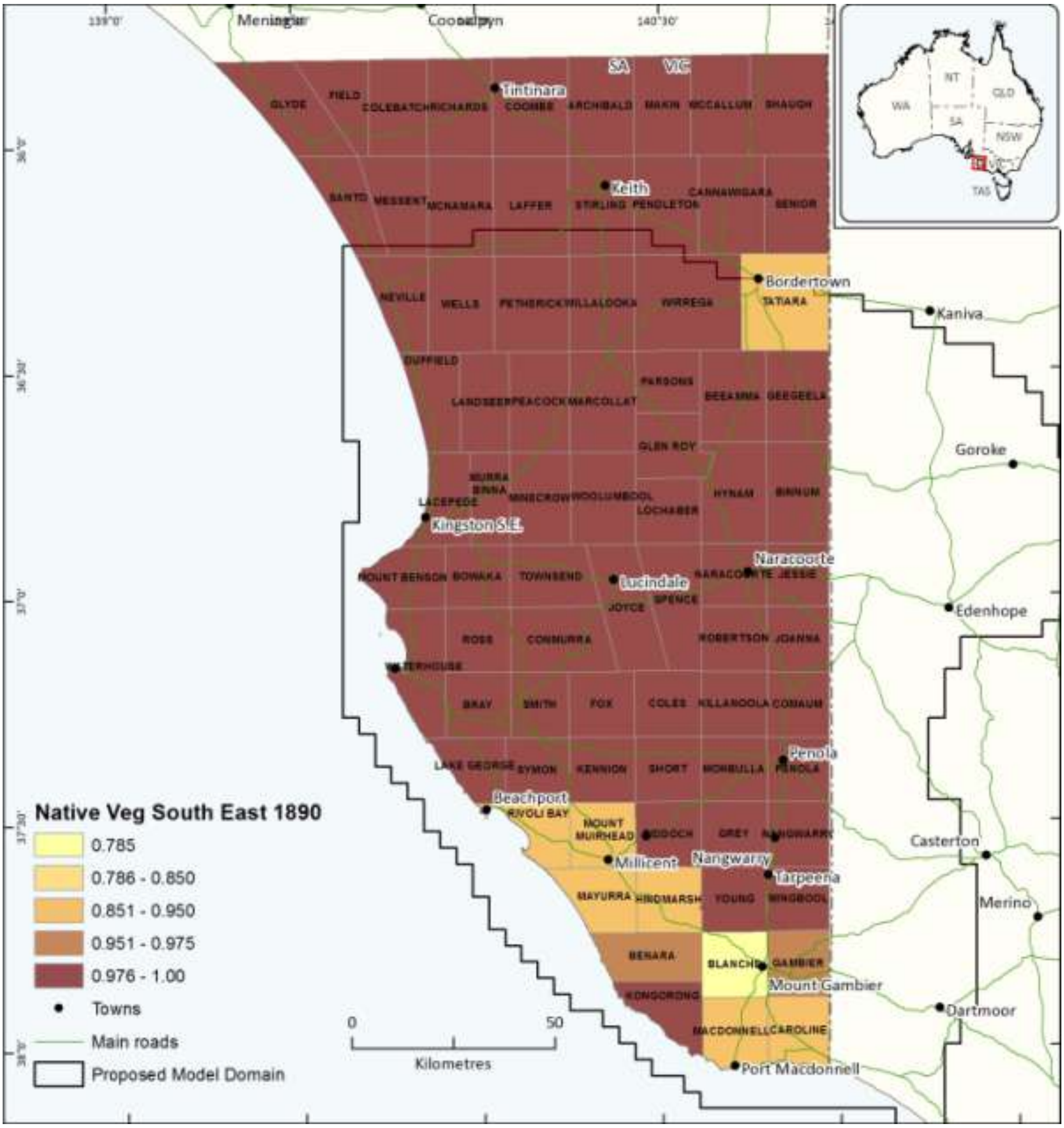


Figure 4.13 Proportions of native vegetation remaining in hundred in the South East of South Australia, 1890.

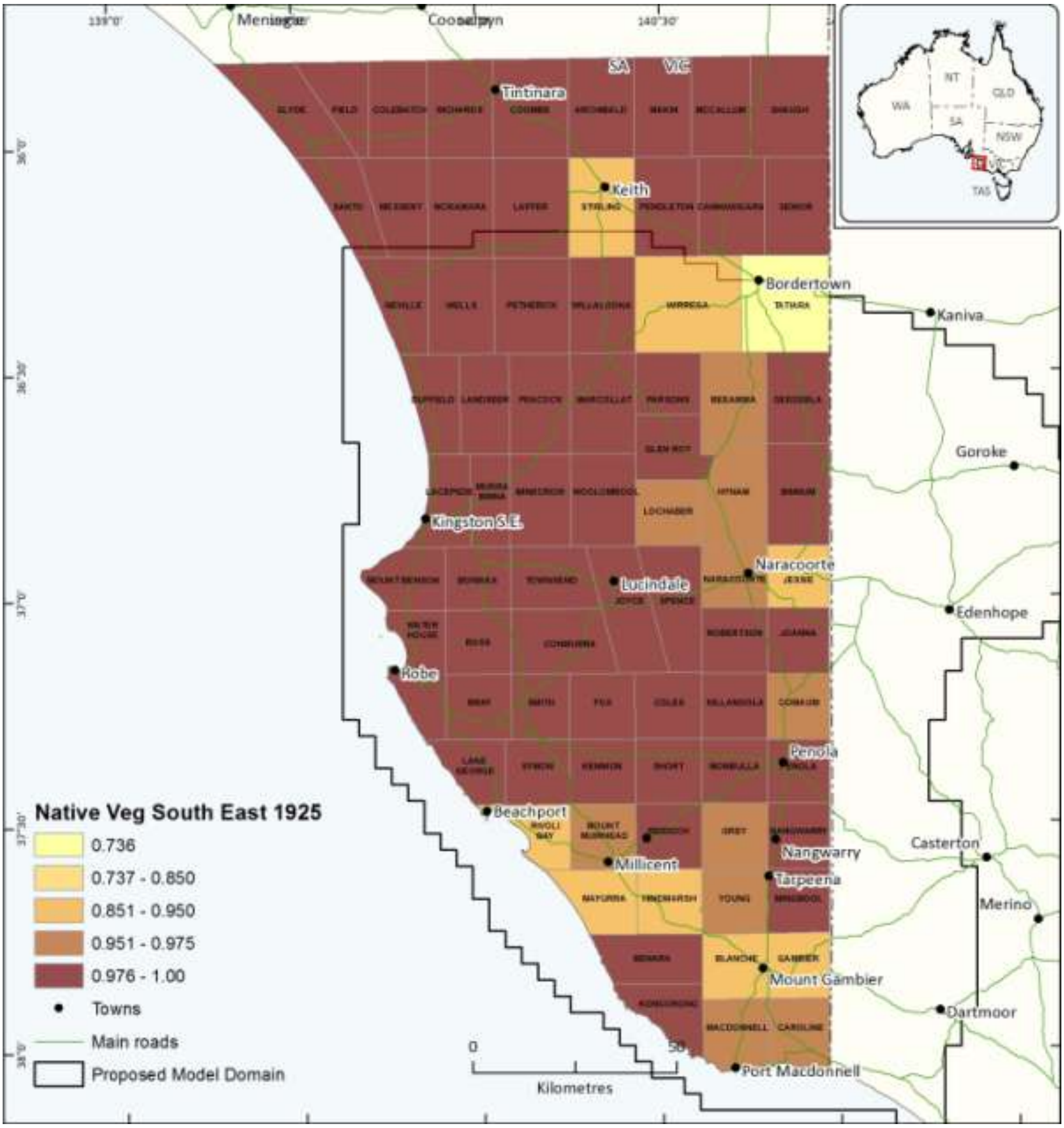


Figure 4.14 Proportions of native vegetation remaining in hundred in the South East of South Australia, 1925.

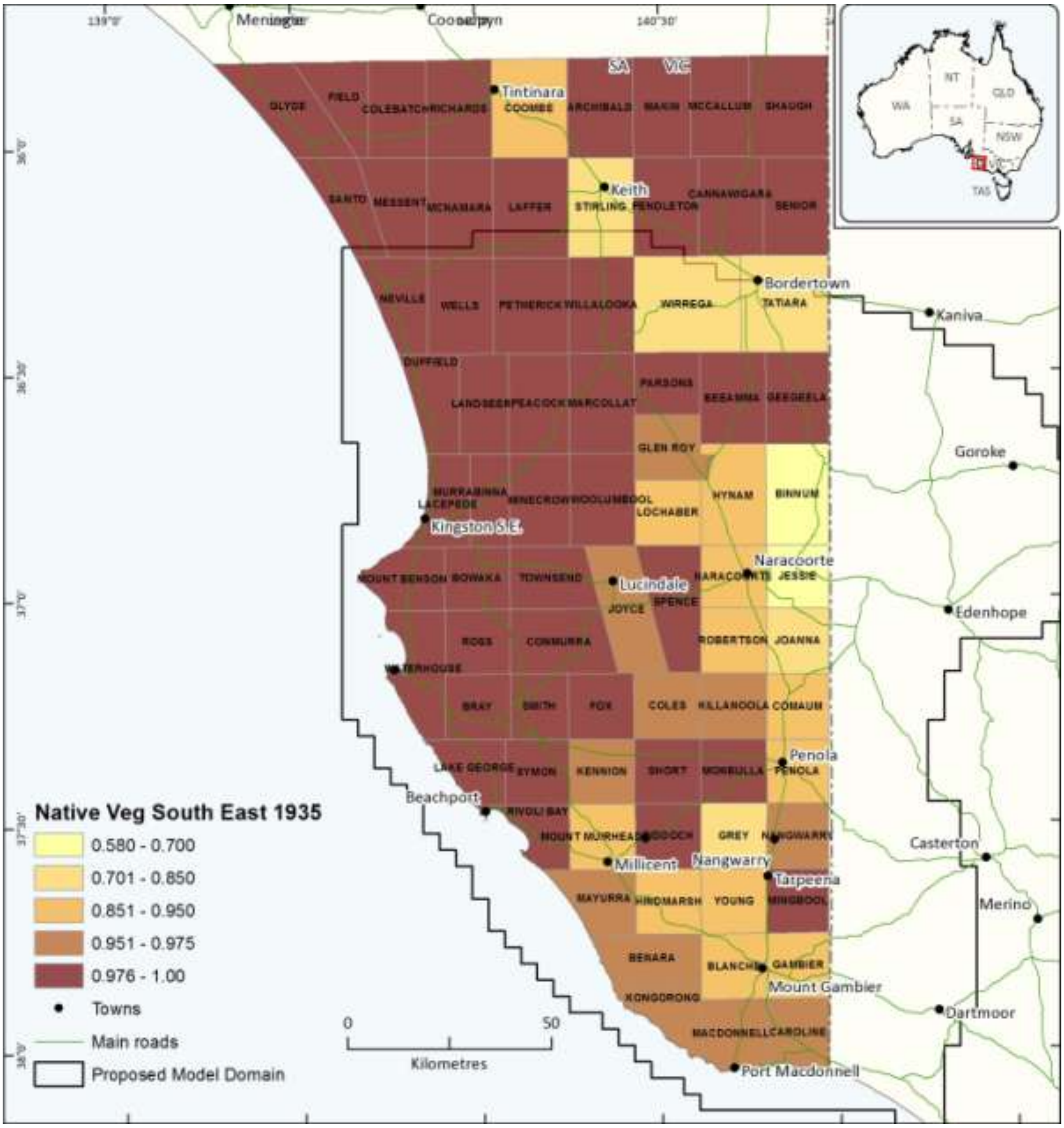


Figure 4.15 Proportions of native vegetation remaining in hundred in the South East of South Australia, 1935.

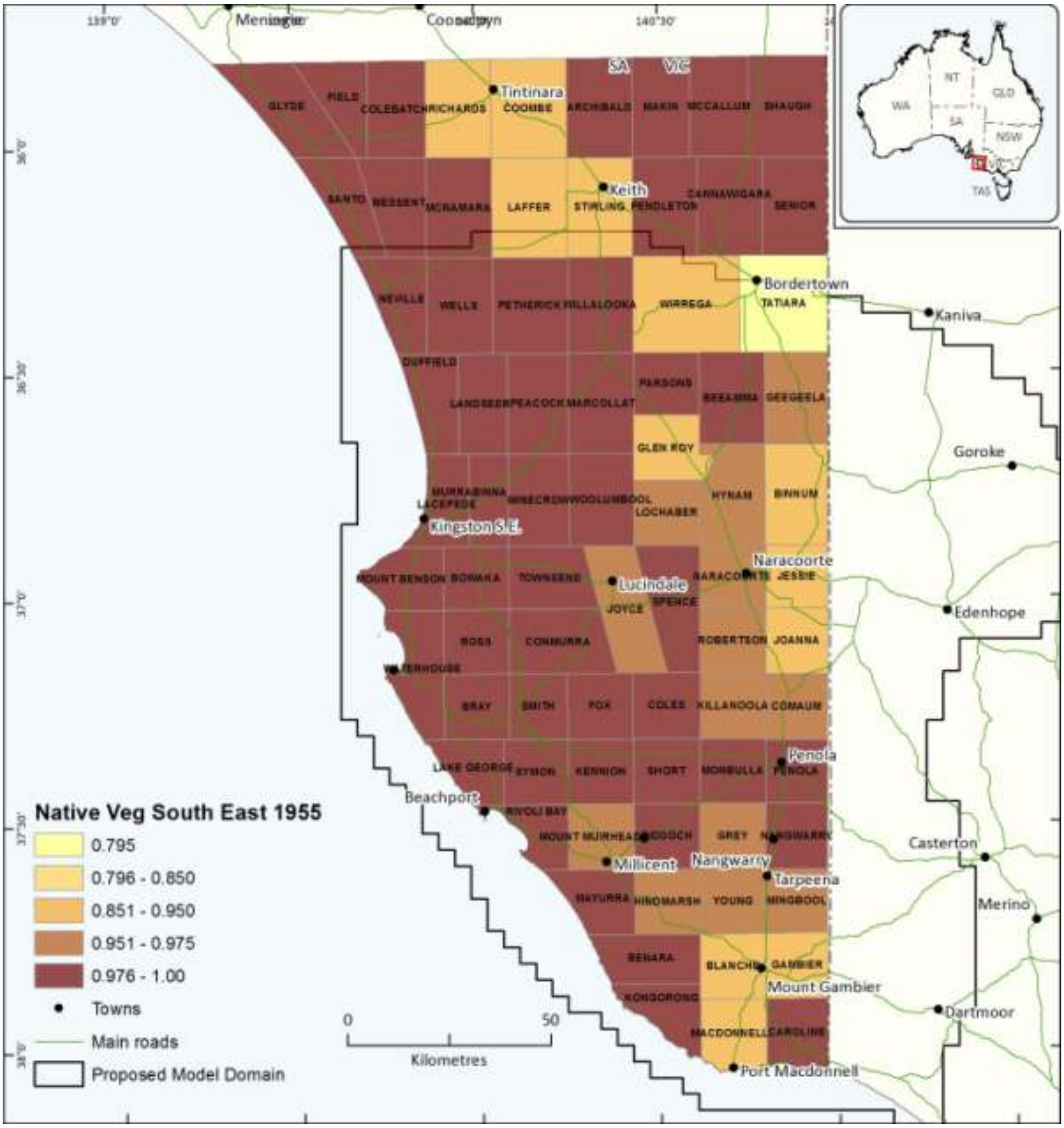


Figure 4.16 Proportions of native vegetation remaining in hundred in the South Eastof South Australia, 1955.

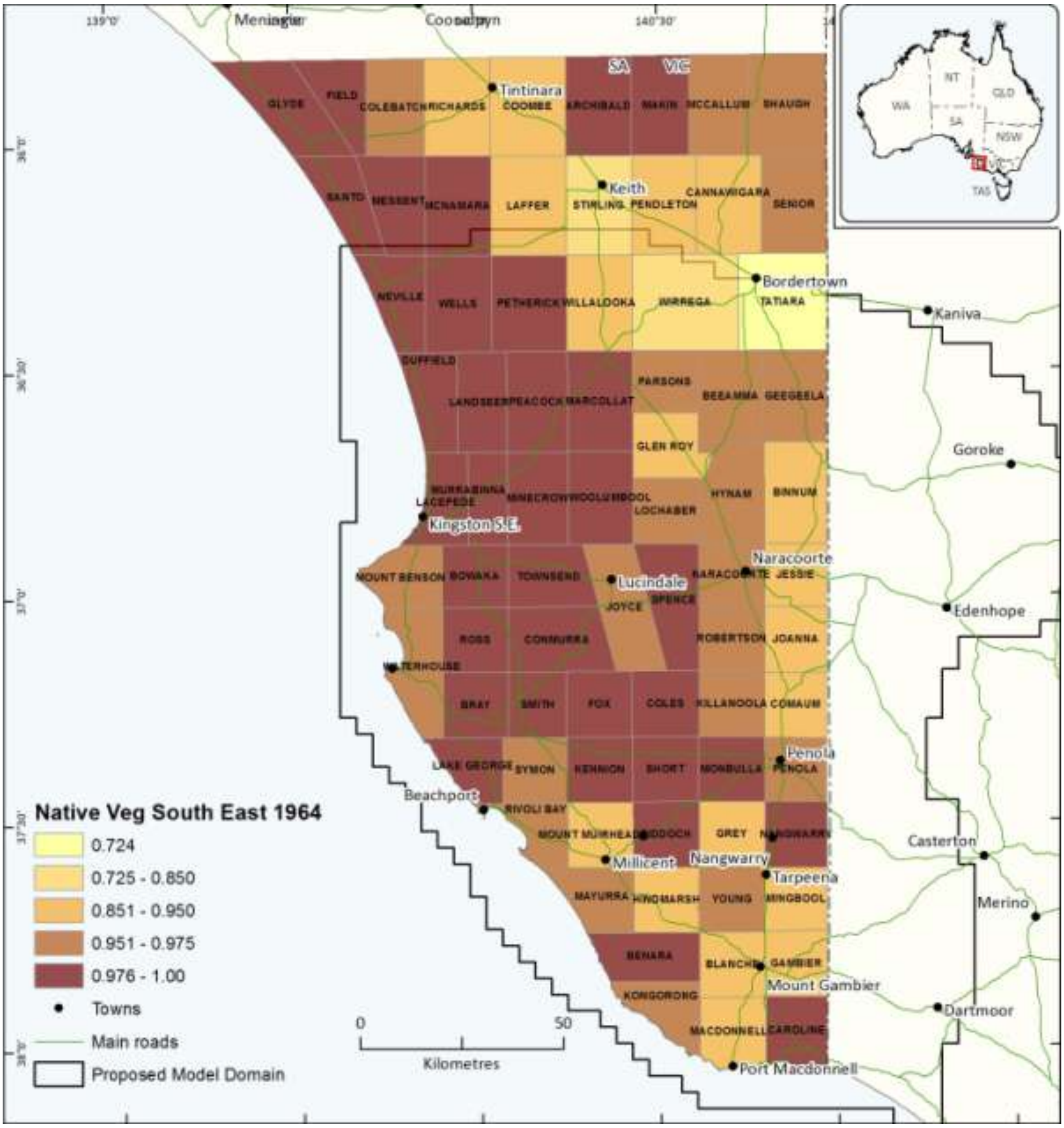


Figure 4.17 Proportions of native vegetation remaining in hundred in the South East of South Australia, 1964.

4.3.4 BROAD PATTERNS OF LAND USE CHANGE, 1890 TO 1964

Three sequences of maps are described in this section in a preliminary format to illustrate their potential in this kind of research.

Grey was one of the first two counties proclaimed in the South East in 1846 and therefore land use in the county would have been more advanced in 1890 (the first year of the five years analysed) in comparison to counties proclaimed later (i.e., Buckingham proclaimed in 1869; Cardwell, 1864; and MacDonnell , 1857). Therefore it was chosen to illustrate change in land use in one county over time through a sequence of maps for each of the test years (Figures 4.4 to 4.8). The initial rural production systems used by the first colonists in South Australia were mainly based on a wheat cultivation-sheep grazing farming system. These were rain fed systems and relatively extensive in area compared to later production systems. Each of the 21 hundreds in the county was dominated by wheat acreages in 1890 (Figure 4.4). A comparison of Figures 4.4 and 4.5 shows that the areas under cultivation are greater in most hundreds in 1890 than those in 1925; the exception being Kongorong hundred. By 1925, and again in 1935, the areas cultivated are not only smaller than those in 1890 but are more diverse in terms of the number of hydrologically-meaningful land classes. In most hundreds at least four of five possible land classes are present, compared to only one class in most hundreds in 1890. By 1955 the areas under cultivation had reduced significantly compared to 1935, but had also become less diverse again. The pattern in 1964 is similar to that in 1955. Even though only five years have been evaluated, it is likely that these records are characterised by periods when the data is likely stationary (i.e., 1925 and 1935, and 1955 and 1964). These stationary periods are separated by changes in the way the data were collected and/or reported for reasons outlined in Chapter 4.3.2.

Figures 4.5 and 4.9 to 4.12 show the proportions of hydrologically-meaningful land classes for the 77 hundreds in all five counties in 1925. These illustrate a number of salient features:

1. The relatively high diversity of land classes throughout the region at that time, with only eight hundreds (Archibald in Buckingham County; Laffer and Neville in Cardwell; Lacepede, Landseer, and Murrabinna in MacDonnell; and Ross in Robe County) having land in one hydrologically-meaningful land class. This was normally 'Areas cropped (- Orchards and Vineyards)', but exceptions were Archibald (fallow) and Landseer (orchards and vineyards).
2. A number of hundreds without any cultivated areas 'appear' to be reported at this time. However, most of those in the north of the division had not been declared by 1925. Of those that had, Willalooka in Buckingham County was only declared four years earlier in 1921, while four others were declared much earlier: Santo (Cardwell) in 1864 and Marcollat, Peacock and Wollumbool in MacDonnell in 1888. A future action would to either leave the hundreds in the grid frame but delete the names of undeclared hundreds, or merge the undeclared hundreds with the 'larger' hundreds they were part of before they were declared. The latter option would require a detailed analysis of the history hundreds in each county.
3. The diversity of hydrologically-meaningful land classes was highest in the hundreds in the older counties (Grey, Robe and MacDonnell) and least in the north – where broadacre crops and fallow dominated the more recently cleared mallee along the Victorian border.

The sequences of maps for 1925 and those for Grey County can be interpreted in conjunction with the maps showing the proportions of remaining native vegetation in each hundred for the five years studied (Figures 4.13 to 4.17). Early clearance for agriculture in the southern parts of the region, simultaneous with the establishments of early settlements, is clear in the hundreds of Hindmarsh, Mayurra, Mount Muirhead and Rivoli Bay (around the towns of Beachport, 1878, and Millicent, 1870), and Blanche, Caroline and Macdonnell (Mount Gambier, 1854, and Port Macdonnell, 1860). There was also significant clearance in Tatiara hundred centered on Bordertown, which had been founded in 1852. By 1925 clearance had consolidated around the two foci in the south (Beachport/Millicent and Mount Gambier/Port Macdonell) and expanded along the road and rail corridor between Bordertown to Keith (Stirling, Tatiara and Wiregga hundreds). Additionally, a new area of clearance had emerged immediately east of Naracoorte (which had been established in 1845) with significant amounts of native vegetation having been removed in Jessie hundred. By 1935 noticeable inroads into the stock of native vegetation extended inwards from the state border with Victoria by about three hundreds all the way from the south coast to north of Naracoorte. The hundreds most affected by this clearance were, from north to south, Binnum, Hynam and Lochaber; Jessie and Naracoorte; Joanna and Robertson; Comaum; Penola; Grey; Young and Hindmarsh; and Gambier and Blanche. However, it is noticeable that the hundreds bordering Victoria to the north of Bordertown still had most of their native vegetation intact. There were strong similarities in the patterns of native vegetation between 1935 and 1955. Only along the main road and rail routes to Adelaide had there been any significant reduction in native vegetation in the two decades up to 1955, this was mainly in Coombe, Laffer and Richards hundreds. However, a decade later clearance had progressed significantly, hundreds adjacent to those along the road and rail route in Buckingham and Cardwell counties had witnessed much clearance (Colebatch, Cannawigara, Pendleton and Willalooka hundreds in particular). There had been further clearance in the south, but mostly in the hundreds where it had been most advanced in 1955.

4.3.5 MAJOR LIMITATIONS AND CHALLENGES IDENTIFIED

A number of challenges have been identified with the data in the Statistical Registers that require further research.

First, the data is non-stationary, i.e., the same full set of land use and land tenure information is not available for each of the years analysed (Table 4.2). The main reasons for this have been outlined in Chapter 4.3.2, and illustrated in Chapter 4.3.4. The non-stationary nature of the data is highlighted in this study because only five, widely spaced years were examined. Using early findings from ongoing research with these data from the mid North and Yorke Peninsula by the Geospatial Information Group at Flinders University, it is clear that if the full set of data (i.e., each year) were to be used, there would be relatively long periods of time when the same data would have been collected and reported. These periods are separated by shifts in the actual data that were recorded and reported because of the reasons outlined above (Chapter 4.3.2). Analyses of periods of stationary continuous sets would reveal temporal and spatial trends in a far better manner than the test data have done in this initial evaluation for the South East. For example, highly relevant hydrological analyses could be accomplished by examining the clearance of native vegetation and new ground being cultivated through analysis of the 'New Ground Cleared in Previous Year' parameter, which was collected annually.

A key omission in the information presented in this chapter is that related to forest production. The areas under production forestry for each hundred are not recorded in the Statistical Registers. The closest entry is 'land dedicated to forest purposes' which is reported as a land tenure category in Post World War I years (e.g., 1925, 1935, 1955 and 1964), which was reported on at the county level. Despite only being available at the country level, this is a tenure class and is does not mean that production forests were being grown on these lands. Further investigation into forest statistics for the South East is needed before these areas can unambiguously be included as forest, either wholly or partially, at the hundred level.

Pasture is an important land use class in the South East because of the importance of the dairy industry. Grazing, in the context of the wheat-sheep production system was important before pasture for dairying. In the maps presented pasture is a best estimate based solely on the class 'Land Under Artificially Sown Permanent Grass' from the land tenure tables. However, this does not include any grazing on native vegetation, which may have been important earlier in the history of the region. In addition there are two related categories – lucerne for forage, and hay (which is reported as 'Hay all kinds' and 'Hay Wheaten', the latter class being a sub-set of the first). Whilst hay was likely harvested and fed to stock, forage lucerne could either be grazed in the field or harvested as a green off take. Further research is needed before making a decision on merging these classes and we have simply used the area for each hundred categorised as 'Land Under Artificially Sown Permanent Grass'.

Native vegetation is overestimated at the present time, though the maps presented in Figures 4.13 to 4.17 are probably a reasonable reflection of the spatial patterns of where clearance was most advanced in any particular year. This is because native vegetation is not recorded as a specific class in land census data, and it was calculated as the area of a hundred minus all of the land use classes and land tenure classes that were umambiguously interpreted as a land use.

4.3.6 NEXT STEPS

There is a very high potential for creating a 'seamless' record of land use in the South East from the later 1850s through to the present day at the hundred and, later, at finer spatial resolutions if required for a regional water balance model. This 'seamless' record would be based on the agricultural census data up to the 1970s, and satellite imagery from the 1970s onwards. Of course these two information sources are not the same and, as a consequence the land use classes would not be the same. Nevertheless the importance including long runs of multi-source data in improving our understanding of land change science has been argued by Jepson and Millington (2008).

Methods could be developed where periods of overlap between different data sources are analysed in detail to derive conversions between land uses derived from different sources. The initial overlaps would be in the 1950s between land uses derived from the census data and aerial photography; a second period would be in the 1970s between the census data, aerial photography and early Landsat imagery; later overlaps would be between aerial photography and Landsat imagery. There is also the potential to use old maps. This type of record has been developed in Belgium and China by Petit and Lambin (2002) and Liu and Tian (2010) respectively; but the product we propose for the South East would be more comprehensive in data inputs than either of these studies and provide a high profile research output for the international land change community, as well as serving the needs of hydrological modelling in the South East and ecosystem services research in the area more generally.

There are a number of issues that need to be addressed by land change scientists and hydrologists together, the most important of which is converting LULC classes to hydrologically-meaningful 'land classes' in terms of groundwater-related studies is important. There are a number of ways in which this can be done, and if this were to be a component in any further research a sound theoretical basis drawing on what the LULC classes mean in terms of water recharge would need to be developed and articulated. For the purposes of this preliminary evaluation certain land use classes were grouped on the basis of their rooting depths and periods of dormancy as a 'first cut' at converting LULC classes to hydrologically-meaningful 'land classes' (Table 4.3). In a similar vein, converting land tenure classes to hydrologically-meaningful 'land classes' is more difficult and we have not paid much attention to this in the preliminary study. There are some opportunities in this area in the dynamic between native vegetation clearance, cultivation, and land reverting to fallow. However, to do this in a meaningful way, annual series would be needed because the clearance and reverting to fallow categories are annual measurements at the hundred level. In addition, we would need to use the pre-European map of vegetation to understand what type of native vegetation was in the hundred before clearance so we can assign a hydrological meaning to the land conversion.

The need to incorporate layers of ancillary information and the potential complexity of spatio-temporal patterns of land-use land-cover change leads to the essential need for analysis of these data in a GIS, especially if long, continuous data sets are to be analysed. A further advantage of this would be that any outputs of the land-use and land-change analyses could be integrated with other spatially-explicit hydrological and hydrologically-relevant data, e.g., geology layers, soil layers and well records, and modelled as has been done by, for example, Aspinall (2004). GIS-based analysis is also essential in analysing the periods of overlaps between census products and spatial products (i.e., those derived from aerial photography and satellite imagery). With the satellite imagery, the high temporal image stacks of land cover parameters, derived using Landsat imagery (Option B outlined in Chapter 4.2.5), would not only provide an improved land use map product for this groundwater modelling project) but using this approach would enhance the historic temporal profile of landscape processes important to researchers and land managers. This information is most valuable to groundwater researchers by highlighting the spatial and temporal variability that exists within homogeneously mapped land use classes – for example, vegetation indices and surface temperature values may correlate with transpiration and evaporation rates from different vegetated and non-vegetated areas to better understand water recharge potential.

Land use change (LUC) is a major driver in the decline of ecosystem services, of which water recharge is a key regulating service. In this broader context, long-term sets of land use and land cover such as those that could be derived for the South East are critical to understanding the stocks of natural capital and ecosystem services that they generate. Such information will help land managers in general to better understand natural landscape process and help facilitate improved production of their land while enhancing ecosystems and supporting long-term sustainable management across natural and cultivated landscapes.

Table 4.3 Construction of hydrologically-meaningful classes

HYDROLOGCIALLY-MEANINGFUL LAND CLASS	LAND USE AND LAND TENURE CLASSES IN STATISTICAL REGISTERS INCLUDED IN CLASS
Orchards and Vineyards	Orchards, Vineyards
Pasture	Area under sown grass
Fallow	Land in fallow
Newly cleared land	Newly cleared ground in previous year
Area cropped (-Orchards and Vineyards)	Wheat, Maize, Barley, Oats, Lucerne, Other green forage, Potato, Peas and Beans,
Native vegetation	Area of hundred – (total area cropped + land in fallow)

5 Recharge estimation

Russell Crosbie and Phil Davies

The goal of this chapter is to determine what the current recharge is to the model domain which forms an input into the numerical groundwater model. This will be achieved firstly through a literature review of previous recharge investigations in the region and then by building upon this understanding using observational data collected over the past few decades. The methods used to estimate recharge from observational data are:

1. Watertable fluctuation method
2. Chloride mass balance of the groundwater
3. A water balance using satellite derived estimates of actual evapotranspiration

These three methods give complementary information on the groundwater recharge which will be used to guide the modelling.

5.1 Previous recharge investigations in the South East

The South East of South Australia has had a long history of investigations into groundwater recharge from both a scientific methods development point of view (Allison and Hughes, 1978; Anderson, 1945) and an operational water resources management perspective (Brown et al., 2006; Wohling, 2008; Wood, 2010b). A recent review of recharge studies in Australia (Crosbie et al., 2010a) identified 220 recharge estimates within the model domain extent from 19 studies (Figure 5.1) (the details are listed in an appendix to Crosbie et al. (2010b)). These recharge estimates range from 0 to 375 mm/year with an average of 49 mm/year (a median of 22 mm/yr and a geometric mean of 16 mm/yr). [There are also another 90 recharge estimates that were not identified within that literature review (Brown et al., 2006)].

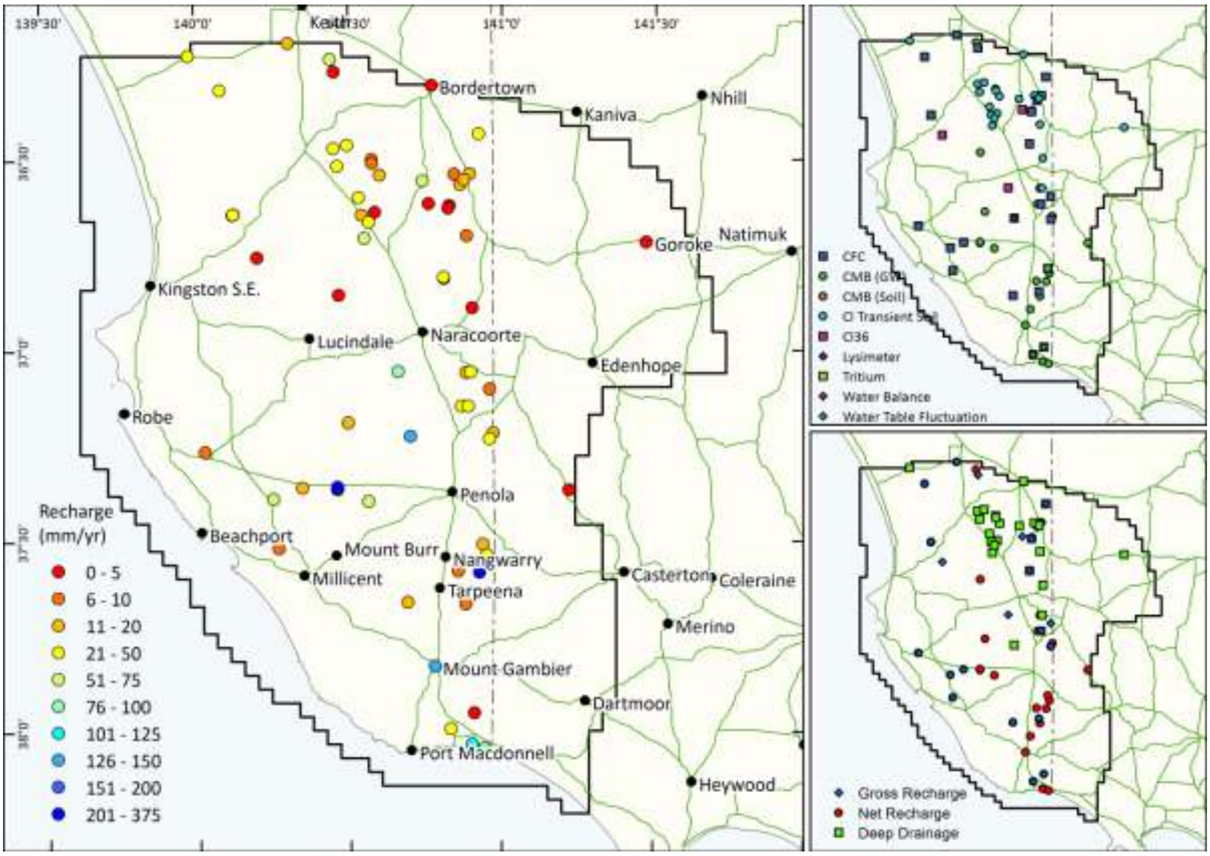


Figure 5.1 Previous recharge estimates located within in the model domain extent as identified during a recent literature review (Crosbie et al., 2010a). Also shown are the techniques used for estimating recharge and the type of recharge being estimated.

From the previous recharge studies we have ascertained that recharge is greater under agricultural land uses than native vegetation [e.g. Kennett-Smith *et al.* (1994)], that recharge is greater under sandy soils than heavier textured soils [e.g. Wohling et al. (2012)] and that recharge decreases with increasing depth to the watertable (Brown et al., 2006).

Directly comparing recharge rates estimated from previous studies is confounded by the myriad of techniques used and the different definitions of recharge used by these techniques (Figure 5.1). Techniques such as lysimeters and chloride techniques in the unsaturated zone estimate deep drainage, which is defined as water flow below a given depth that is then assumed to become recharge upon reaching the watertable. Other techniques, such as the watertable fluctuation method estimate gross recharge, i.e. water that has reached the watertable. The last category of techniques, which includes the chloride mass balance method, estimate net recharge, which accounts for losses due to evapotranspiration from the watertable. Further complicating the comparison between studies are the varying spatial and temporal scales of the measurements.

5.2 Recharge derived from observational data

The three techniques for estimating recharge that are used here are applied consistently at the spatial scale of the model domain using as much temporal data as is possible. This will ensure that the spatial patterns in recharge from each of the three techniques are directly comparable across the model domain. Each of the three techniques uses a different definition of recharge, so will provide complimentary information; however this also means that magnitudes of recharge estimates between methods are not directly comparable.

5.2.1 WATERTABLE FLUCTUATIONS

The watertable fluctuation (WTF) method of recharge estimation was first proposed by Meinzer and Stearns (1929) and remains well-used due to its simplicity (Healy and Cook, 2002). The method assumes that watertable rises are caused by recharge. If the specific yield of the unconfined aquifer in question is known, then recharge (R) can be calculated as the change in water level (Δh) multiplied by the specific yield (S_y):

$$R = \Delta h \times S_y \tag{5.1}$$

Recharge calculated using the WTF method is usually estimated on an event basis. If the watertable is shallow and responds quickly to rainfall, the method provides an estimate of gross recharge. If the recharge is calculated over longer time periods (such as annually) then the recharge will be underestimated, since groundwater discharge during the time of measurements is not accounted for. As a method of gross recharge the WTF method cannot produce negative recharge estimates.

Since a large amount of monitoring data is available for the model domain, analysis of the observations required automation. Previous approaches to automate the watertable fluctuation method have relied on high frequency monitoring data (Crosbie et al., 2005). In the present application a more flexible approach was necessary due to irregular measurement frequencies. The method used is modelled on that previously used in the South East by Brown et al. (2006), this uses seasonal (i.e. quarterly) measurements of groundwater level and a specific yield value of 0.1. To automate the process the change in groundwater level was calculated as the difference between (a) the minimum groundwater level recorded before July 1 of each calendar year and (b) the subsequent maximum groundwater level occurring before the end of the calendar year. This was used on a subset of observation bores that were less than 50 m deep, featured a depth to watertable less than 10 m, and featured at least five years of data during the period 1970 to 2012. The use of a maximum observation of depth to water of 10 m is following on from the analysis of Brown et al. (2006) that showed that at depths greater than this the WTF method gave low results due to attenuation of the recharge signal. The results of this analysis are shown in Figure 5.2.

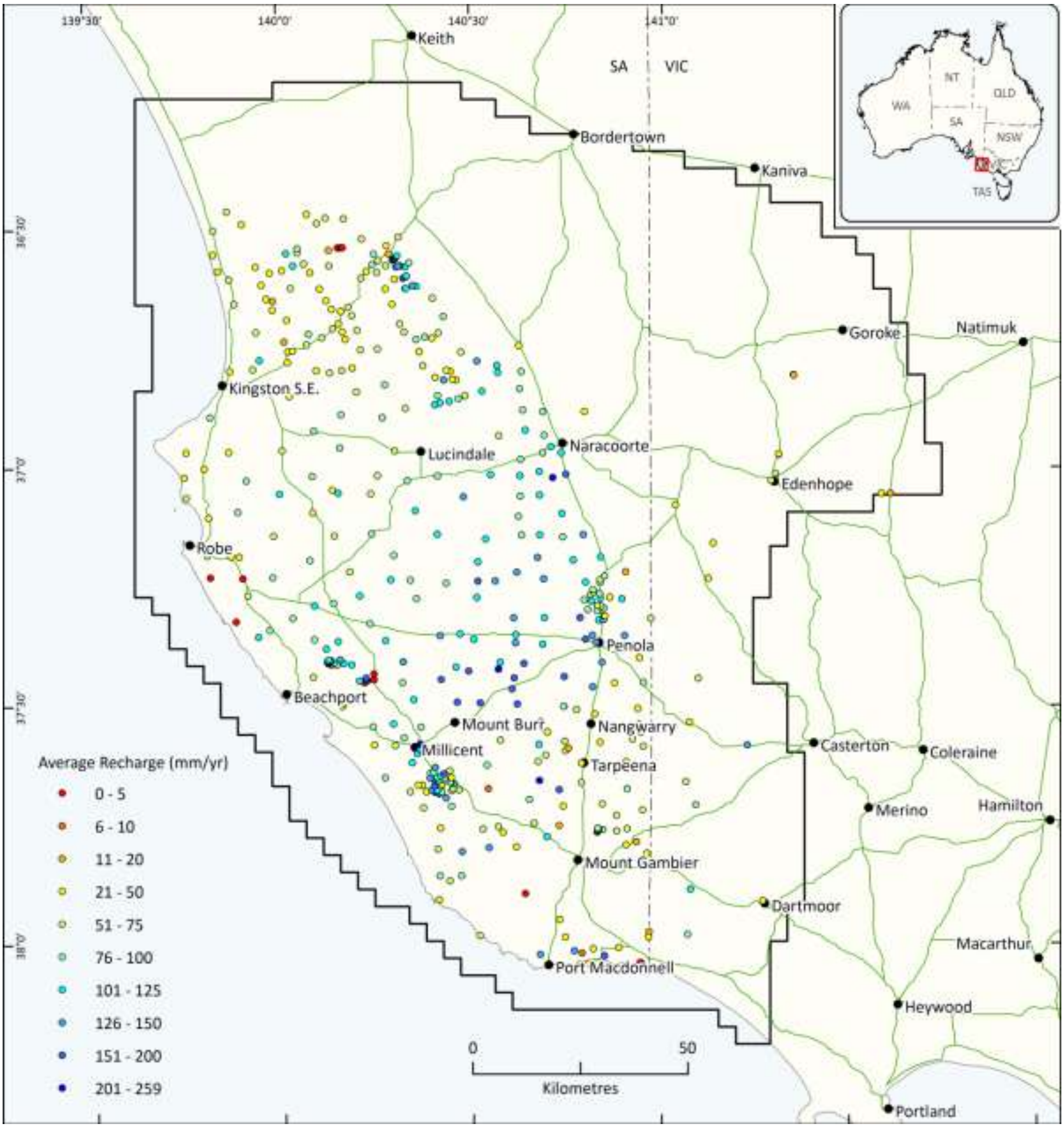


Figure 5.2 Estimates of recharge using the watertable fluctuation method for 464 locations across the model domain.

Recharge calculated using the watertable fluctuation method ranged from 2–259 mm/year with an average of 85 mm/year (a median of 83 mm/yr and a geometric mean of 73 mm/yr). This average is not representative of the model domain as a whole because of the bias due to the sampling of bores with shallow depth to watertable. Significant interannual variability in estimated recharge also exists, with an average coefficient of variation across all sites of 0.53.

These results were subsequently analysed further by grouping the recharge estimates by soil (Figure 2.5), vegetation (Figure 2.6) and depth to watertable (Figure 8.7) and then normalising the results by rainfall. The resulting relationship between soil clay content and recharge (Figure 5.3) was not consistent with expectation. Previous research has shown a strong negative correlation between the average clay content of the soil and recharge (Wohling et al., 2012), whereas what is seen here is a weak positive correlation. The reason for this is not yet known but could be due to a relationship between the soil clay content and depth to watertable, or a dependency may exist between soil clay content and the specific yield.

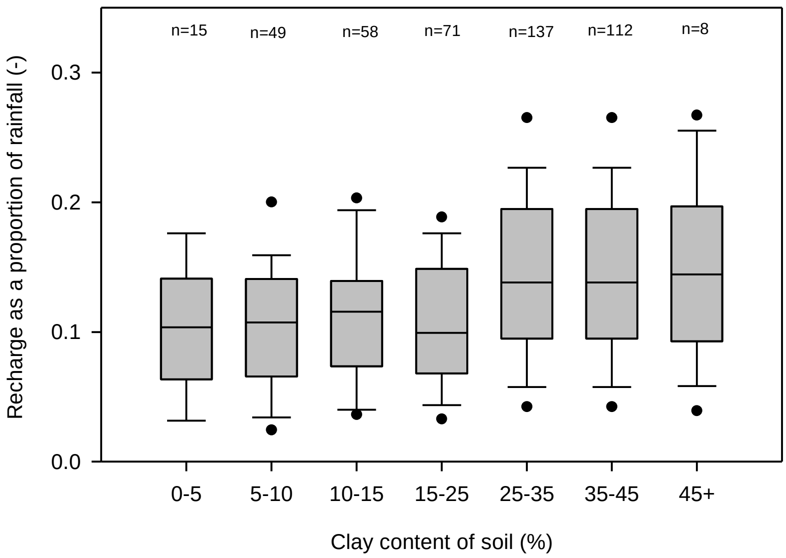


Figure 5.3 Relationship between recharge estimated by the watertable fluctuation method and the clay content of soil. The recharge (R) estimates have been normalised by rainfall (P).

The relationship between vegetation type and recharge estimated using the watertable fluctuation method is consistent with expectations with the exception of the hardwoods (Figure 5.4). This may be because the land use is close to current but hardwood plantations did not exist at the start of the analysis (1970) so they have been excluded from further consideration (including Figure 5.4). Irrigated vegetation is associated with the highest recharge due to the extra source of water in addition to precipitation. However, if irrigation water is sourced from groundwater this will not result in an addition to groundwater storage, since evapotranspiration would be increased above dryland agricultural uses. The next highest recharge estimates are associated with cropping and pasture land use types. The lowest recharge estimates are associated with native vegetation and softwood forestry.

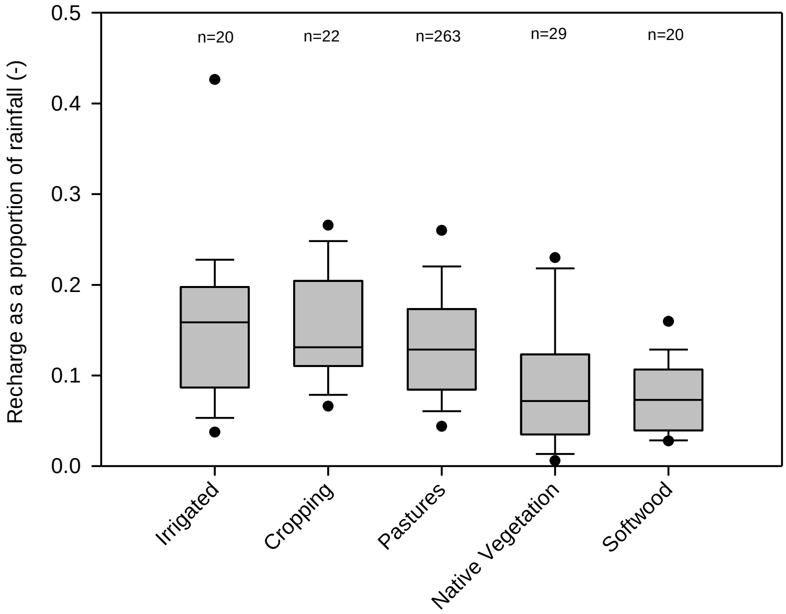


Figure 5.4 Relationship between recharge estimated by the watertable fluctuation method and the vegetation type. The recharge (R) estimates have been normalised by rainfall (P).

The relationship between depth to watertable and recharge estimated using the watertable fluctuation method is consistent with expectation (Figure 5.5). Lower recharge is associated with shallow depths to watertable, as limited space exists in the unsaturated zone for additional storage when rainfall recharge occurs. Maximum estimated recharge is associated with a depth to watertable of 1–2 m. This is likely due to rainfall infiltrating quickly with minimal losses to evapotranspiration or soil moisture storage. Recharge estimates decrease with increasing depth to watertable above 1–2 m in accordance with increasing travel time from the surface to the watertable. Greater travel time in the unsaturated zone increases the likelihood of plant water uptake. Also, a greater soil moisture deficit may need to be overcome before recharge can occur. These relationships between recharge and depth to watertable are consistent with those observed previously in Tomago, NSW (Crosbie, 2003).

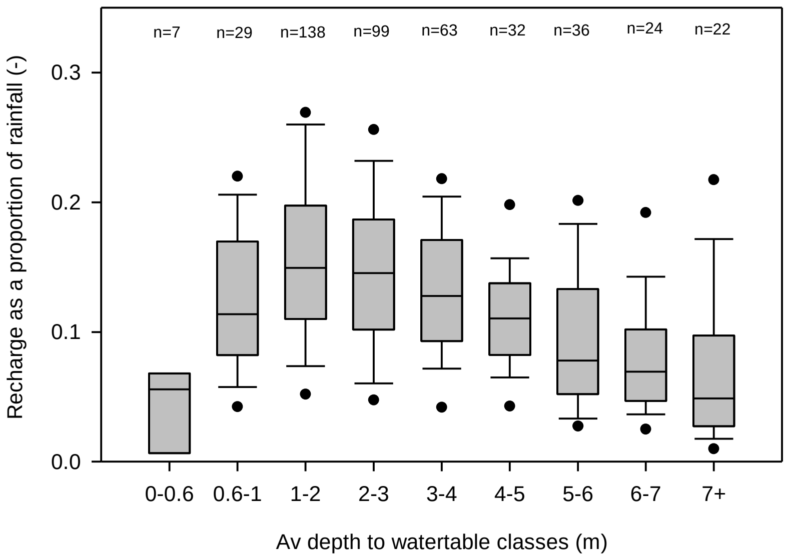


Figure 5.5 Relationship between recharge estimated by the watertable fluctuation method and the average depth to the watertable. The recharge (R) estimates have been normalised by rainfall (P).

The watertable fluctuation method of estimating recharge can give us a time series of recharge for as far back as we have monitoring records. The analysis undertaken here started with data collected in 1970 until the end of 2012 giving potentially a 43 year annual series, however the average length of time series from the individual bores is 21 years. To investigate the changes in recharge through time, the average recharge from all bores with a recharge estimate for a particular year were collated into an annual series (Figure 5.6). (This anlaysis is a superposition in time and space and assumes that the sample size of bores is large enough that the trends are not biased.) It can be seen that along with inter-annual fluctuations in recharge there is a long term decreasing trend of almost 1 mm/year. When the recharge time series was investigated at the six individual bores with the longest time series, it can be seen that the decreasing trend is still evident (Figure 5.7). However, only two (HIN005 and SYM002) of the six bores has a statistically significant ($p<0.05$) decreasing trend in recharge (MAY002 has $p=0.07$). This apparent decreasing trend in recharge warrants further investigation.

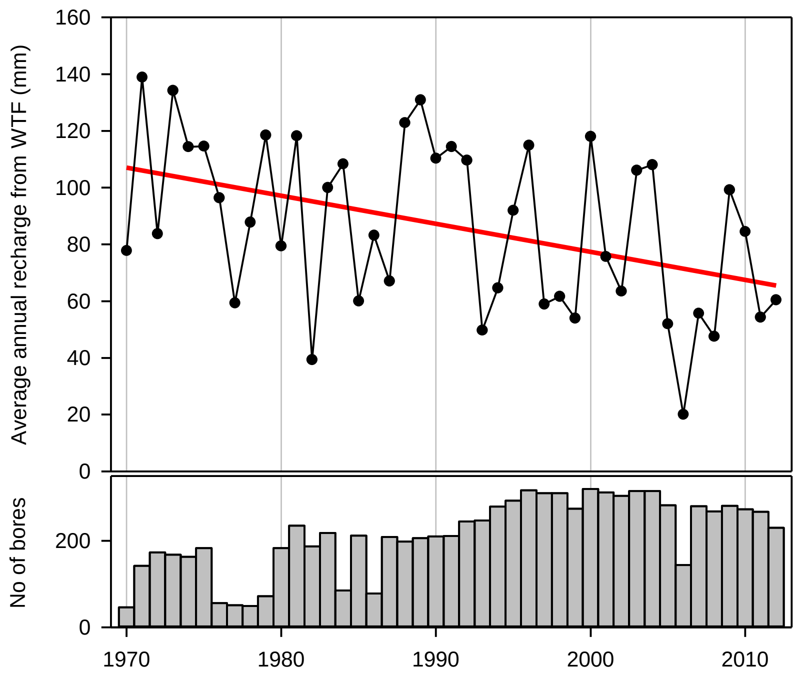


Figure 5.6 Annual series of average recharge estimated across all bores using the watertable fluctuation (WTF) method and the number of bore that contributed to the average.

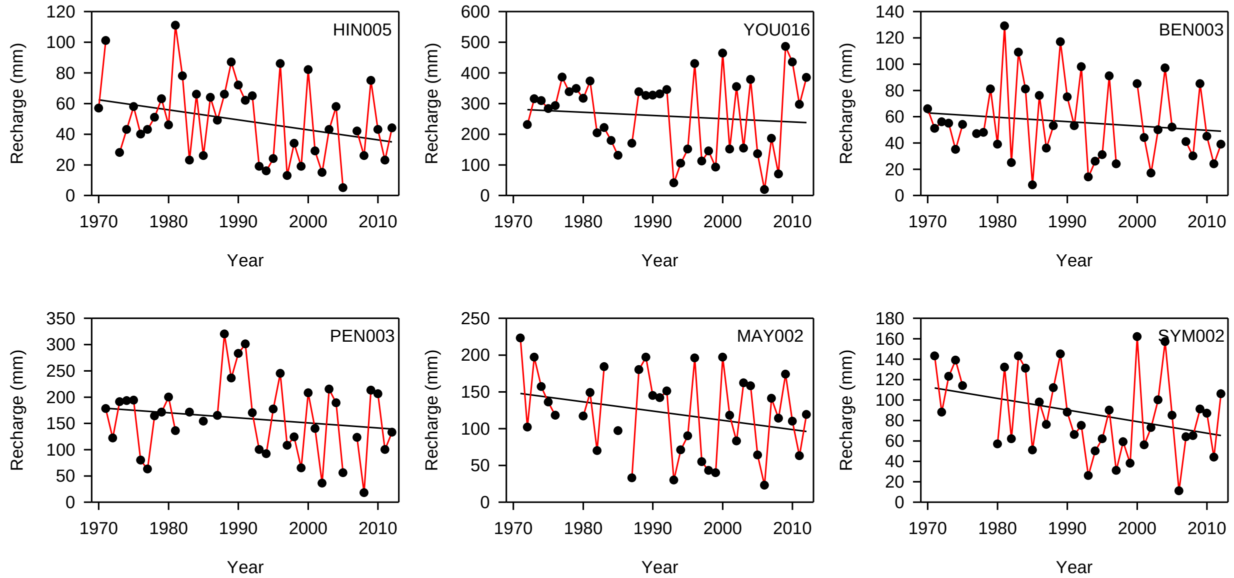


Figure 5.7 Annual series of recharge estimated for the six bores with the longest time series using the watertable fluctuation (WTF) method.

5.2.2 CHLORIDE MASS BALANCE

The chloride mass balance (CMB) method of estimating recharge was used for the first time in the world in the South East region in 1945 (Anderson, 1945). It has since become the most widely used method of estimating recharge in Australia (Crosbie et al., 2010a). The CMB method is very simple and the cost of obtaining the data required is comparatively cheap. Chloride deposited by rainfall is not removed by evaporation or transpiration, resulting in accumulation in the unsaturated and saturated zones. Using an estimate of chloride deposition rate at ground surface and groundwater chloride concentration, recharge is estimated as:

$$R_n = 100 \times D / C_{gw}, \qquad (5.2)$$

where R_n is net recharge (mm/year), D is chloride deposition rate (kg/ha/year) and C_{gw} is the concentration of chloride in the groundwater (mg/L).

The assumptions inherent in the method are that:

1. Chloride present in the groundwater originates solely from precipitation (not rock weathering or halite dissolution).
2. Chloride imported or exported via runoff or run-on can be accounted for.
3. Chloride is conservative in the system.
4. The rate of chloride deposition has not changed over time.

The chloride mass balance method produces an estimate of net recharge averaged over the residence time of the groundwater in the aquifer. This confounds results in systems where land use change has resulted in a change in recharge rate. In most situations, land use change results in an increase in recharge; for example, when native vegetation is cleared for agricultural development. In the South East region the opposite result has also occurred where plantation forestry has replaced agricultural land use. In summary, due to land use changes in this region, the chloride mass balance method may not provide an estimate of current recharge.

Also, the way the CMB has been applied here is not applicable to discharge areas and so cannot produce negative estimates of net recharge.

The chloride deposition rate used in the present study was derived from a national surface described in Leaney et al. (2011), who developed a national coverage of chloride deposition from 291 field observations of chloride deposition over the past 60 years throughout Australia. This was achieved using a four parameter function previously derived by Keywood et al. (1997) and based upon distance from the coast. Surfaces were interpolated for each of the four parameters using a pilot point regularisation approach within PEST (Doherty et al., 2000). The uncertainty in the chloride deposition rate surface was quantified using the mean, standard deviation and skewness of the derived from null-space Monte Carlo analysis (Tonkin and Doherty, 2009) of 791 equally well-calibrated models. For the present application, the national coverages were resampled from 0.05–0.005 degrees (Figure 5.8).

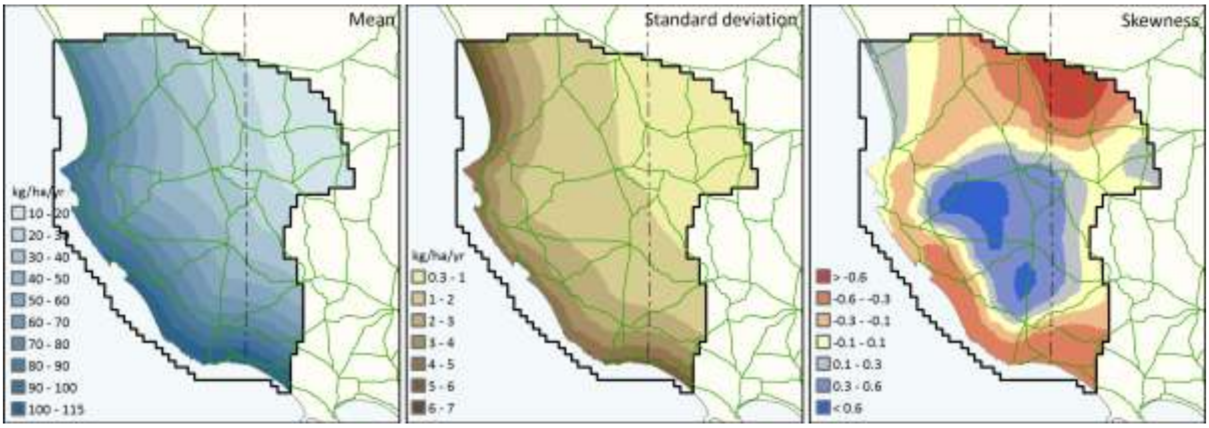


Figure 5.8 The mean, standard deviation and skewness of the chloride deposition rate surface derived from 791 equally well-calibrated models.

The chloride in groundwater data was obtained from the databases held by DEWNR in South Australia and DSE in Victoria. There are 3901 point locations with measurements of chloride in groundwater (Figure 5.9). In locations where multiple observations were found to exist, the geometric mean was used. Ordinary kriging was used to interpolate point measurements to a gridded surface. The 0.005 degrees grid used by Leaney et al. (2011) to create the chloride deposition rate surface was used to create the interpolated surface in the present study. This interpolated surface and its associated standard error are shown in Figure 5.9.

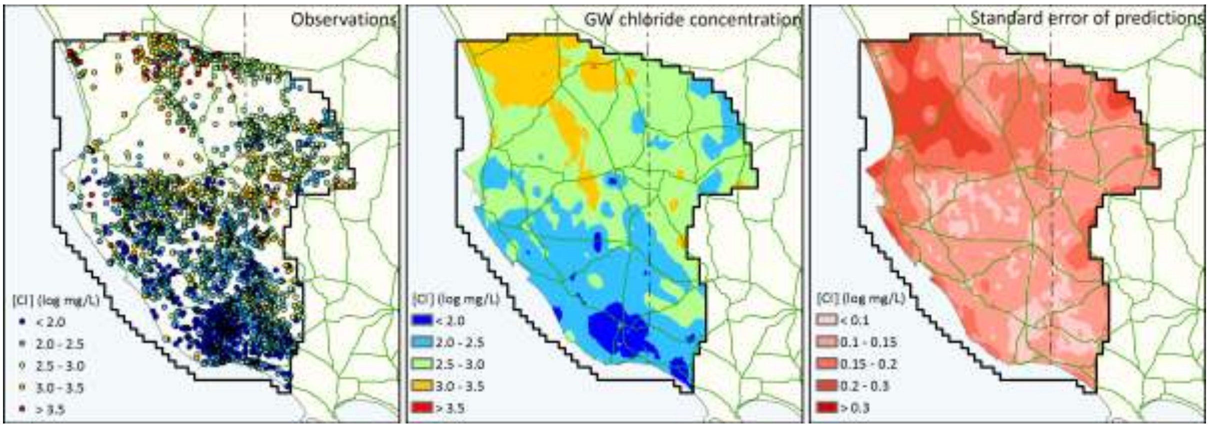


Figure 5.9 The chloride concentration of the groundwater ([Cl^-]) plotted on a logarithmic scale (i.e. 2 = 100 mg/L, 3 = 1000 mg/L etc.). Left plot shows the raw data (n=3901), the centre plot shows an interpolated surface and the right plot shows the standard error in the interpolated surface.

While the chloride mass balance method has been widely used to estimate spatial distributions of recharge (Eriksson and Khunakasem, 1969; Scanlon et al., 2012), the uncertainty associated with both chloride deposition rates and groundwater chloride concentrations are rarely propagated to quantify the uncertainty associated with estimated rates of recharge. In practice, stochastic methods can be used to generate many replicates of an estimated recharge surface through random sampling of the input probability distribution. In the present study, 10,000 replicates were created through sampling of a Pearson Type III-shaped probability distribution of possible chloride deposition rates and a log-normal-shaped probability distribution of possible groundwater chloride concentrations. The results are reported as the 5th, 50th and 95th percentiles of net recharge at each grid cell from the 10,000 replicates (Figure 5.10). Results indicate that areas of highest recharge are located in the south of the study area (i.e. along the coast). Conversely, areas of lowest recharge are located toward the north of the study area and (i.e. inland). Using the chloride mass balance approach, the average recharge rate across the model domain is estimated at 21 mm/year for the 50th percentile, with a plausible range of 13–34 mm/year based upon the 5th and 95th percentiles.

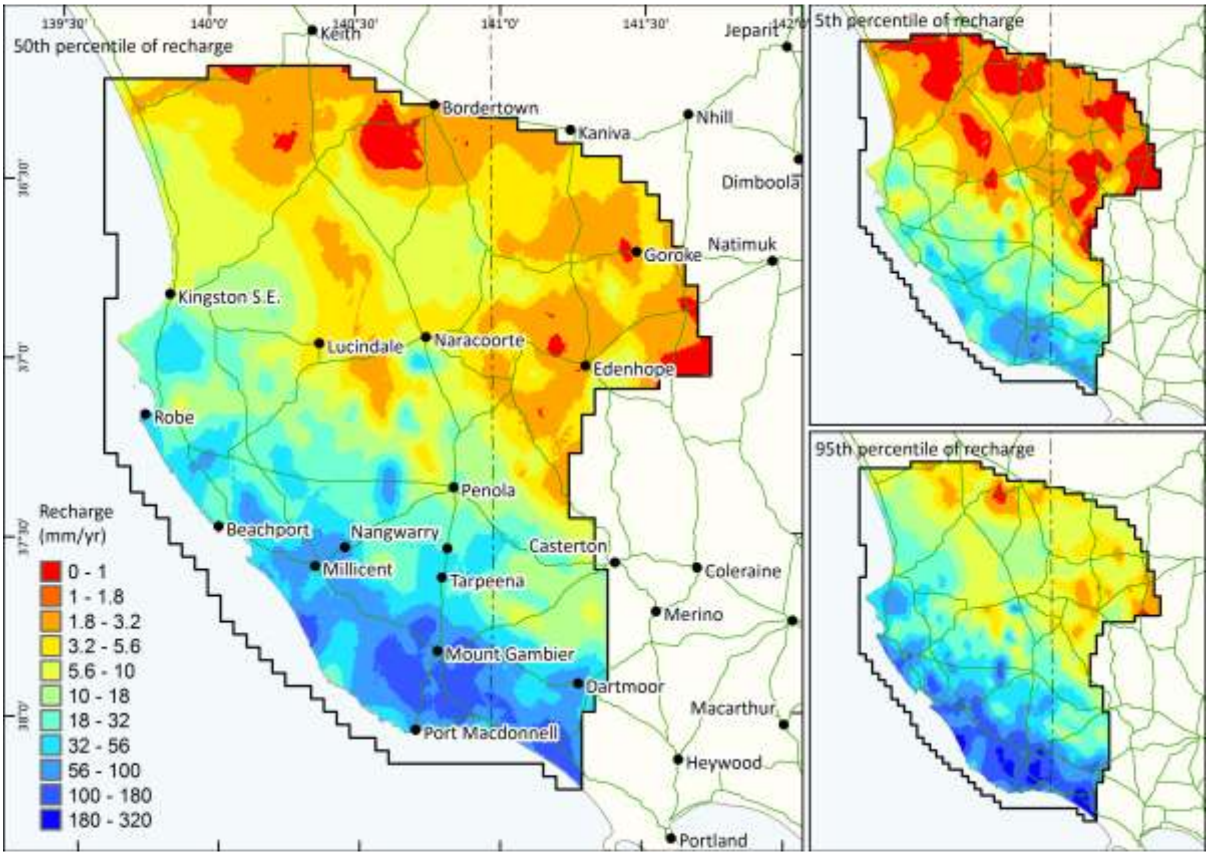


Figure 5.10 Net recharge rate derived using the chloride mass balance method, showing the 5th, 50th and 95th percentiles from 10 000 equally-likely realisations.

The chloride mass balance as applied here assumes that the screen depth in the bore is shallow enough that the chloride concentration as recorded is representative of local recharge. This would be true if the screen was at the water table but as the depth below the water table increases, the sample is averaged over an area upgradient of the measurement location.

The other problem with the method as applied here is that it is not appropriate to use in groundwater discharge locations. As the chloride concentration increases the recharge estimate will tend to 0, in groundwater discharge areas the net recharge is negative and this cannot be accounted for in this method. This will cause unreliable results particularly in the west of the Upper South-East.

5.2.3 WATER BALANCE USING SATELLITE DERIVED ESTIMATES OF EVAPOTRANSPIRATION

Using satellite estimates of evapotranspiration (ET) as a means of estimating net recharge (Szilagyi et al., 2011) is a relatively new method that has had little exposure in Australia. The method relies on a water balance where net recharge can be estimated as the difference between rainfall (P) and ET if runoff and changes in soil moisture storage can be ignored (Equation 5.3). The application of the definition of net recharge is slightly different to that of the chloride mass balance as this method can estimate where groundwater discharge is greater than groundwater recharge resulting in a negative estimate of net recharge; this is expected to be prominent in irrigation areas and forestry areas where the trees are accessing groundwater. The advantage of this method is the spatial and temporal density of the data; however, the uncertainty in the recharge estimates has not been assessed.

$$R = \mathrm{P} - \mathrm{ET} \qquad (5.3)$$

Estimates of evapotranspiration are derived using the CSIRO MODIS Reflectance-based Scaling Evapotranspiration (CMRSET) algorithm (Guerschman et al., 2009). This uses eight-day aggregated MODIS data to produce ET estimates on a 250 m resolution grid. The actual ET estimates are scaled from potential ET using a relationship that uses the Enhanced Vegetation Index (EVI) and the Global Vegetation Moisture Index (GVMI). In a comparative study of various ET-estimation algorithms against a range of metrics, the CMRSET algorithm was determined to provide the most reliable estimates (Glenn et al., 2011; King et al., 2011). The rainfall data used in the present study was obtained from a Bureau of Meteorology product described by Jones et al. (2009) which features a daily temporal resolution and 0.05° spatial resolution .

The spatial distribution of average net recharge over the period 2001 to 2010 (Figure 5.11) appears to be consistent with expectation. The coastal lakes of the Coorong (north of Kingston SE) and areas located between Robe and Beachport feature negative net recharge rates, as would be expected for areas of open water where ET exceeds precipitation in a semi-arid (i.e. water-limited) environment. Irrigation areas (Figure 2.6) located in the north of the study area are identifiable as areas of negative net recharge whereas irrigation areas in the south are less prominent, due to relatively higher rates of rainfall. Other visible areas of high negative net recharge include hardwood plantations located to the west of Penola (Figure 2.6) and softwood plantations located to the east and south of Penola and to the east of Mount Gambier (Figure 2.6). Regions of highest positive net recharge are associated with areas of cropping and pasture located from Kingston through Millicent to Mount Gambier (where rainfall is highest). Locations of limited positive net recharge are distributed throughout the study area and are mainly associated with cropping and pastoral land use.

Using the CMRSET approach, net recharge over the period 2001 to 2010 and averaged over the entire model domain is estimated as -5 mm (i.e. -0.9% of rainfall), which represents an overall net discharge. When this result is partitioned according to vegetation type, the median net recharge is positive for cropping (i.e. +2.8% of rainfall) and pasture (+1.4%) and negative for native vegetation (-3.6%), softwood vegetation (-9.7%), irrigation (-13.4%) and hardwood vegetation (-16.4%). When these results are examined on a per-pixel basis (Figure 5.12), considerable dispersion around the median is apparent for each vegetation class, and for all classes the range of values includes both positive and negative rates of net recharge.

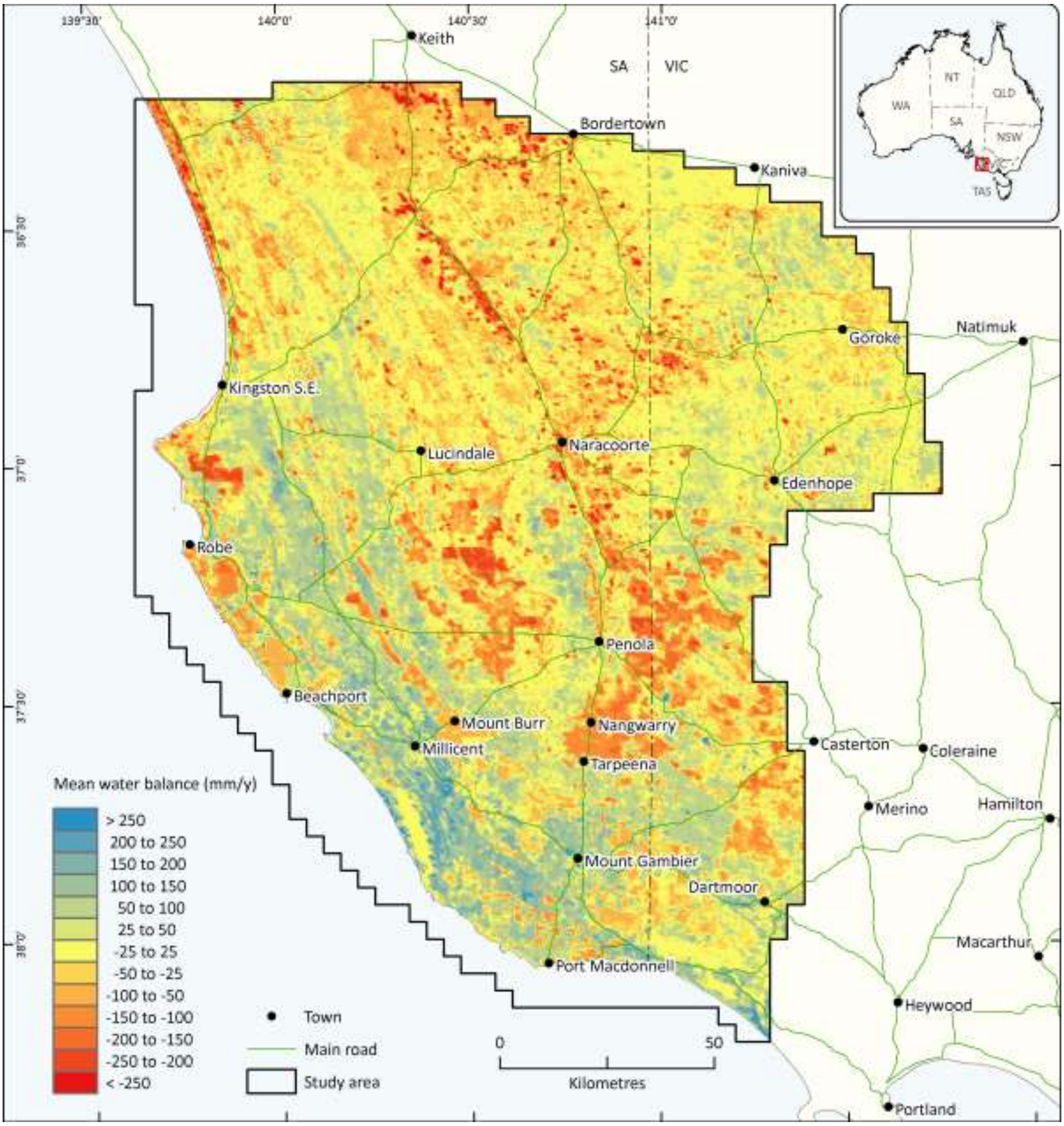


Figure 5.11 Net recharge rate averaged over the period 2001 to 2010 estimated using the CMRSET-water balance approach

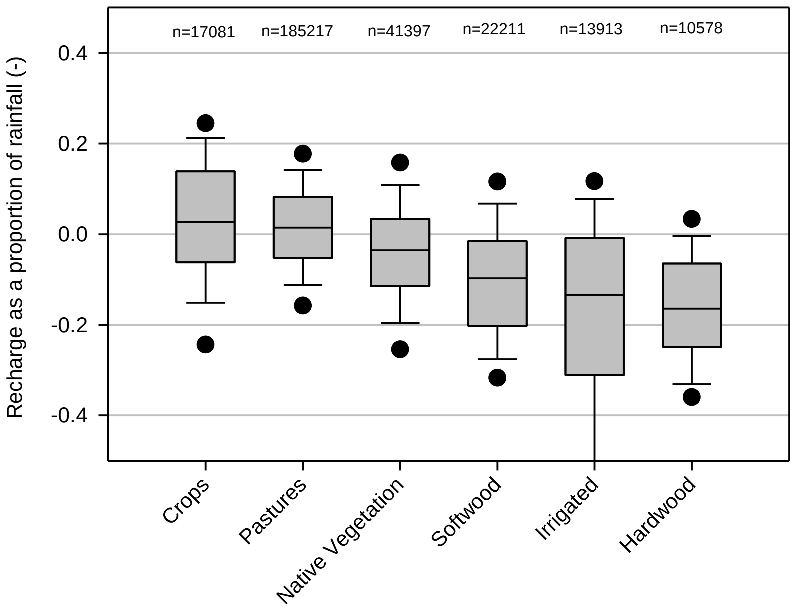


Figure 5.12 Box and whisker plot showing net recharge averaged over the period 2001 to 2010 and normalised by rainfall, for each vegetation class.

When per-pixel CMRSET-water balance-based net recharge estimates are partitioned according to soil clay content and depth to watertable (DTWT), further differences between vegetation types become apparent. Net recharge under pasture does not appear to be correlated with DTWT (Figure 5.13). (Although the positive net recharge at shallow DTWT on heavy textured soils may be indicative of run-off.) This is consistent with expectation, since pasture vegetation is shallow-rooted and typically cannot access groundwater below a depth of one metre. Conversely, net recharge under softwood vegetation does appear to be dependence upon DTWT (Figure 5.14). Previous field studies in the South East region have identified positive correlation between rates of ET and DTWT. Evapotranspiration from hardwood and softwood vegetation is highest when the DTWT is within a few metres of the ground surface and decreases to negligible when the DTWT is approximately 6 m on sandy soils (Benyon et al., 2006). The results of the present study (Figure 5.14) for sandy soils (soil class 1) are consistent with the field results of Benyon, *et al.* (2006); however, this is not the case for heavier-textured soil classes.

For soil classes 2, 3 and 4 (i.e. clay content ranging from 5%–25%) positive net recharge occurs for an average DTWT of less than 1 m. With increasing depth, evapotranspiration increases to a maximum rate at a DTWT of 3–7 m. With further increases in depth, the net recharge rate approaches zero; this represents an extinction depth, at which vegetation can no longer access groundwater. These relationships are also dependent on soil clay content. For soils classes 1 (0–5%), 2 (5–10%), 3 (10–15%) and 4 (15–25%) this extinction depth occurs at approximately 6, 9, 13 and 16 m respectively. For heavier-textured soils (i.e. classes 5, 6 and 7), at a DTWT of 20 m (the extent of the present analysis) the net recharge rate does not approach zero. This suggests that softwood and hardwood vegetation types are capable of accessing groundwater when the DTWT is in excess of 20 m.

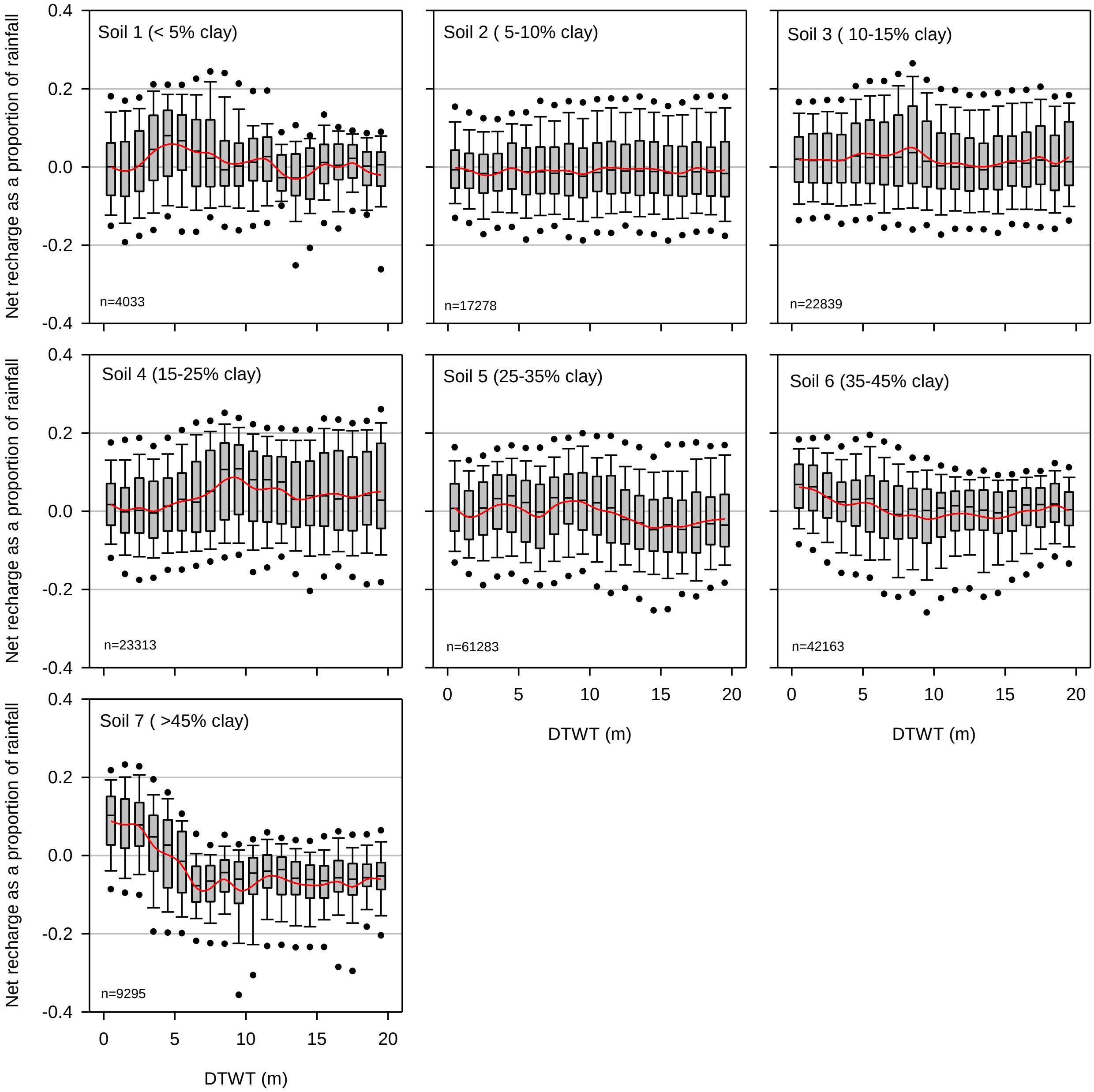


Figure 5.13 Boxplots of average net recharge normalised by rainfall over the period 2001 to 2010 for pastures with data separated by depth to watertable (DTWT) and soils class based upon clay content (Class 1: 0–5% clay, 2: 5–10%, 3: 10–15%, 4: 15–25%, 5: 25–35%, 6: 35–45%, 7: 45+%). The red line represents the mean of the depth classes.

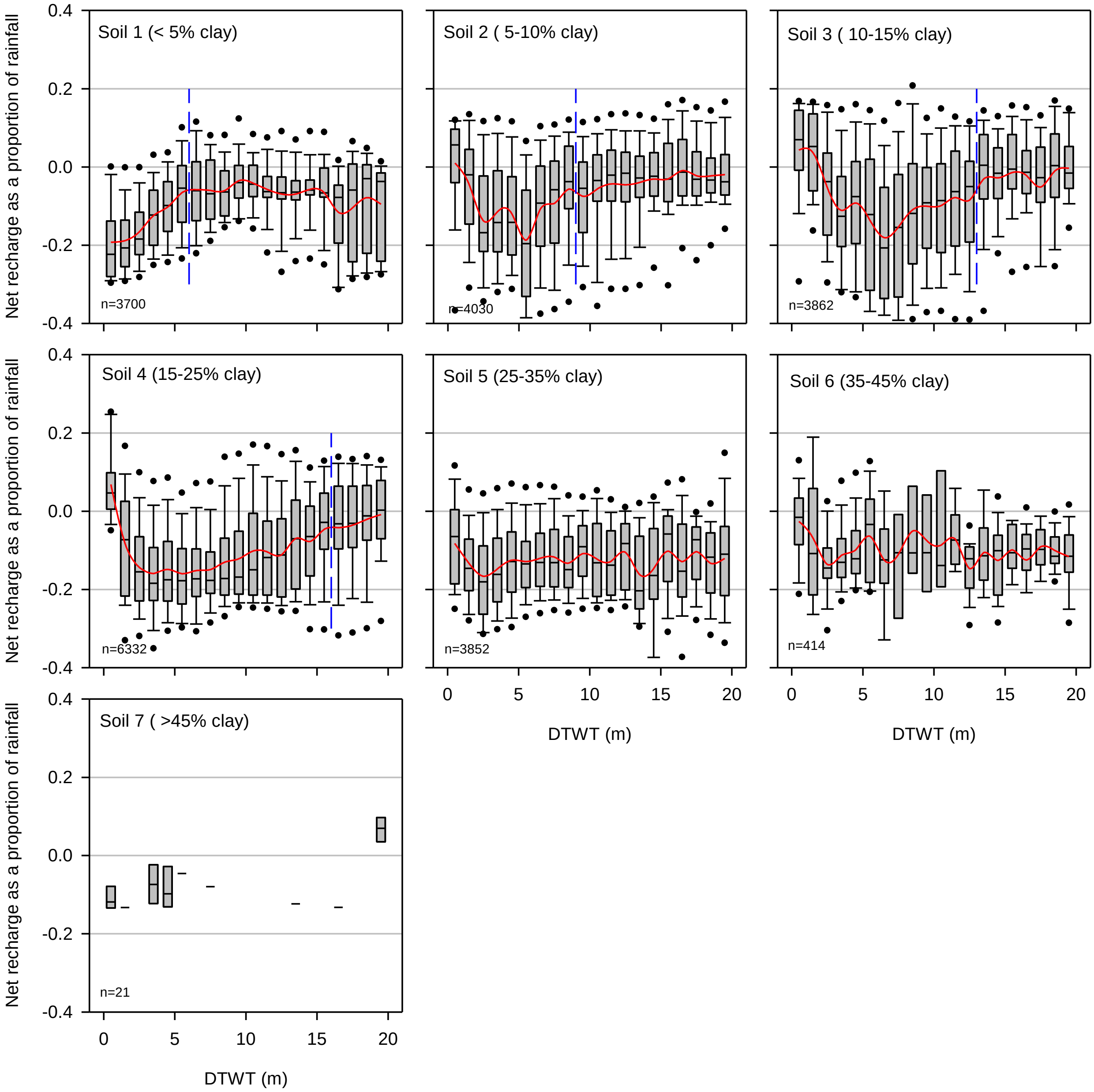


Figure 5.14 Boxplots of average net recharge normalised by rainfall over the period 2001 to 2010 for softwoods with data separated by depth to watertable (DTWT) and soils class based upon clay content (Class 1: 0–5% clay, 2: 5–10%, 3: 10–15%, 4: 15–25%, 5: 25–35%, 6: 35–45%, 7: 45+%). The red line represents the mean of the depth classes and the blue dashed line is an approximate depth at which the net recharge becomes independent of the DTWT.

Examination of the time series of average annual net recharge (Figure 5.15) indicates that considerable inter-annual variability exists. When averaged across the model domain, the extremes of average annual net recharge range from -163 mm (2006) to +126 mm (2010).

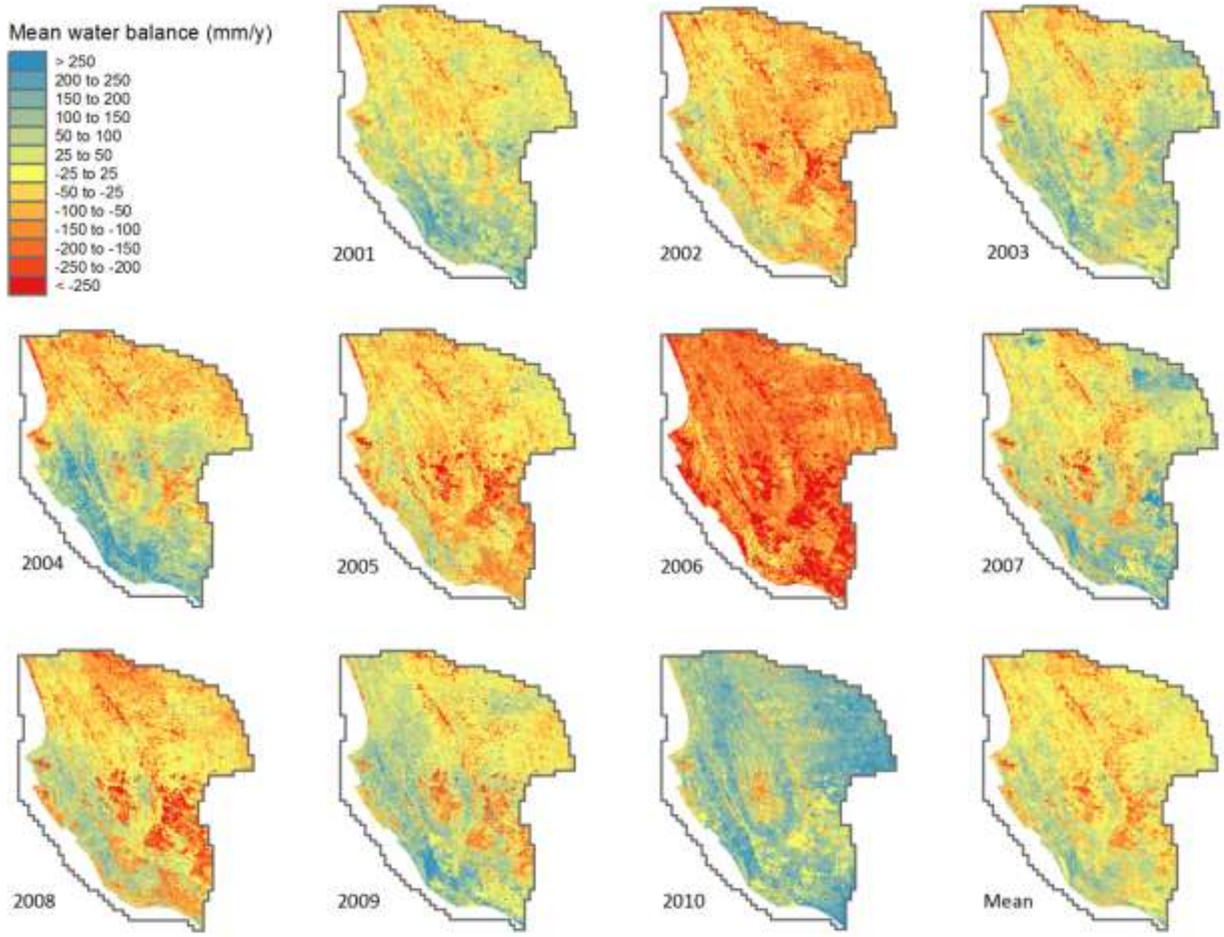


Figure 5.15 Average annual net recharge (mm/y) from 2001 to 2010 estimated using the CMRSET-water balance-based approach.

Time series observations of actual evapotranspiration, precipitation and groundwater level, as well as modelled estimates of net recharge and cumulative net recharge, at groundwater observation wells MAY023, PEC068 and MTB014 are presented in Figure 5.16, Figure 5.17 and Figure 5.18 respectively. Examination of the precipitation and actual ET time series data indicates the presence of seasonal trends in both data types, as well as the fact that the two series are out of phase with one another. This leads to seasonal trends in the CMRSET-water balance-based estimates of net recharge, which feature positive net recharge in winter and negative net recharge in summer. Irrespective of whether a given location features an overall positive net recharge (Figure 5.16) or negative net recharge (Figure 5.18), this is consistent with the seasonality of groundwater level observations.

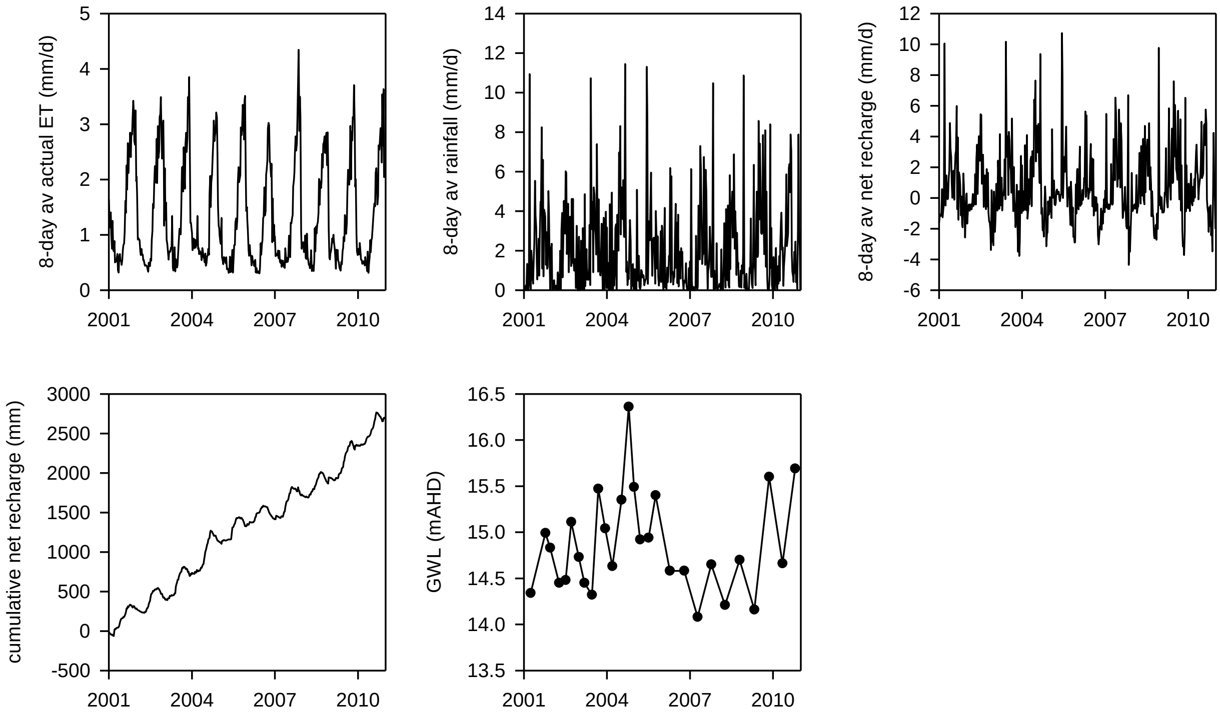


Figure 5.16 Time series at MAY023 of 8 day average actual evapotranspiration, rainfall and net recharge together with the cumulative net recharge and groundwater level observations.

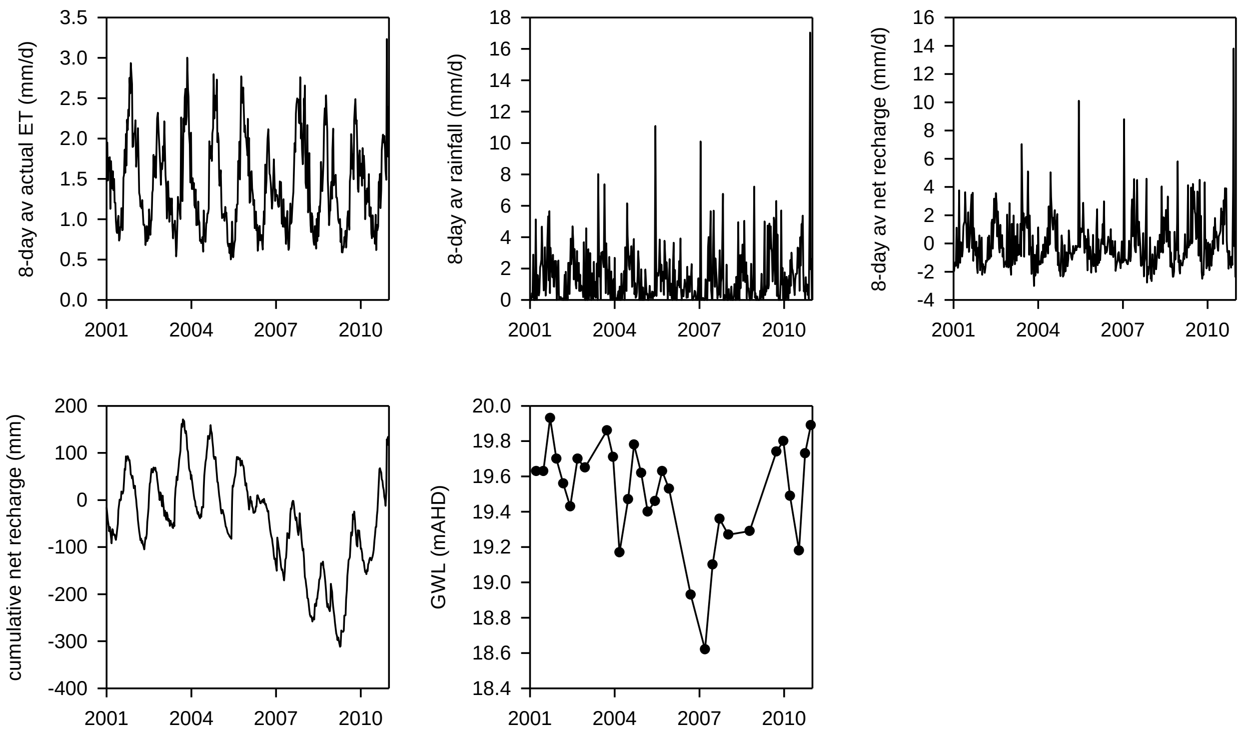


Figure 5.17 Time series at PEC068 of 8 day average actual evapotranspiration, rainfall and net recharge together with the cumulative net recharge and groundwater level observations.

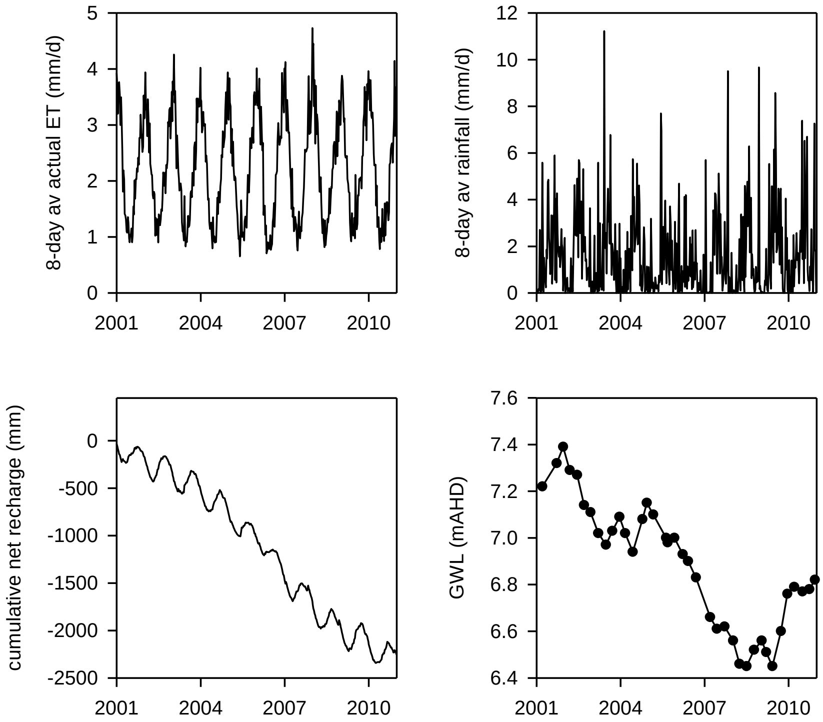


Figure 5.18 Time series at MTB014 of 8 day average actual evapotranspiration, rainfall and net recharge together with the cumulative net recharge and groundwater level observations.

5.2.4 COMPARISON OF RECHARGE ESTIMATION METHODS

The three methods of estimating recharge used in the present study each estimate different quantities of water; therefore it is unsurprising that they are not in agreement. The watertable fluctuation (WTF) method is used to estimate gross recharge, the chloride mass balance (CMB) method is used to estimate net recharge (and is therefore only suited to identified recharge areas), while the water balance (WB) method uses a different definition of net recharge (which is applicable in both recharge and discharge areas). Consequently, and consistent with expectation, the WTF method produces the highest estimate of recharge while the WB method produces the lowest estimate, with CMB method-based estimates falling between. At the model domain scale, the average WTF method-based estimate of gross recharge is 85 mm/year, the average CMB method-based estimate of net recharge is 21 mm/year (from a 13–34 mm/year plausible range), and the WB method-based estimate of net recharge over the period 2001 to 2010 is -5 mm/year (Table 5.1).

Table 5.1 Recharge rate and volume for the model domain and Lower Limestone Coast Prescribed Wells Area (LLC PWA) estimated using each of the three recharge estimation methods. The numbers in brackets after the chloride mass balance (CMB) method estimate of recharge refers to the 5th and 95th percentiles around the median.

	WTF METHOD		CMB METHOD		WB METHOD	
	MM/Y	GL/Y	MM/Y	GL/Y	MM/Y	GL/Y
Model domain	85	2203	21 (13–34)	542 (334–887)	-5	-118
LLC PWA	85	1241	28 (14–46)	411 (253–673)	3	37

At the scale of the management area the results are similar with the WTF generally giving the highest estimate of recharge and the WB the lowest although there are many areas that do not conform to this pattern (Table 5.2).

Table 5.2. A comparison of recharge rates estimated in the present study to those of Brown et al. (2006). The number in brackets after the watertable fluctuation (WTF) method-based recharge rate refers to the number of bores that were averaged, the numbers in brackets after the chloride mass balance (CMB) method-based estimate of recharge refers to the 5th and 95th percentiles around the median.

STATE	MANAGEMENT AREA	WTF (MM/Y)	CMB (MM/Y)	WB (MM/Y)	ADOPTED BY BROWN ET AL (2006) (MM/Y)
SA	BANGHAM		5 (3 - 10)	-27	20
SA	BEEAMMA		5 (2 - 9)	-15	20
SA	BENARA	73 (8)	73 (43 - 126)	98	170
SA	BLANCHE CENTRAL	33 (1)	100 (69 - 144)	55	175
SA	BOOL	110 (3)	10 (7 - 16)	7	105
SA	BOWAKA	77 (2)	25 (14 - 45)	37	85
SA	BRAY	77 (3)	39 (23 - 68)	50	90
SA	COLES	127 (5)	16 (10 - 26)	-88	120
SA	COMAUM	13 (1)	12 (7 - 19)	-83	60
SA	COMPTON	68 (2)	105 (73 - 151)	86	175
SA	CONMURRA	74 (8)	16 (11 - 23)	18	95
SA	DONOVANS	51 (10)	103 (70 - 151)	37	175
SA	DUFFIELD	47 (8)	9 (3 - 22)	-39	50
SA	FOX	98 (4)	22 (15 - 32)	10	100
SA	FRANCES		8 (4 - 16)	-34	30
SA	GLEN ROY	94 (5)	13 (8 - 21)	24	150
SA	GLENBURNIE	35 (1)	109 (77 - 156)	51	100
SA	GREY	85 (7)	28 (18 - 43)	24	150
SA	HACKS	108 (1)	15 (10 - 22)	15	125
SA	HINDMARSH	77 (14)	63 (38 - 106)	54	150
SA	HYNAM EAST		7 (4 - 14)	-26	25
SA	HYNAM WEST	82 (5)	6 (3 - 12)	-38	80
SA	JOANNA		8 (4 - 13)	-49	50
SA	JOYCE	108 (3)	7 (4 - 12)	-32	120
SA	KENNION	129 (5)	34 (21 - 54)	31	120
SA	KILLANOOLA	137 (3)	14 (9 - 22)	0	145
SA	KONGORONG	62 (4)	68 (40 - 115)	59	170
SA	LACEPEDE	79 (5)	12 (6 - 24)	0	100
SA	LAKE GEORGE	93 (3)	35 (19 - 65)	-5	75
SA	LANDSEER	53 (14)	7 (2 - 17)	-22	45
SA	LOCHABER	82 (12)	4 (2 - 9)	-22	90
SA	MACDONNELL	89 (2)	97 (65 - 145)	47	150
SA	MANAGEMENT AREA 1	70 (2)	4 (2 - 8)	-57	75
SA	MANAGEMENT AREA 2A		7 (4 - 11)	-131	75
SA	MANAGEMENT AREA 2B		7 (5 - 11)	-160	75
SA	MANAGEMENT AREA 3		6 (3 - 9)	-57	75
SA	MANAGEMENT AREA 4		6 (3 - 10)	-36	25
SA	MARCOLLAT	98 (32)	4 (2 - 9)	-11	75

STATE	MANAGEMENT AREA	WTF (MM/Y)	CMB (MM/Y)	WB (MM/Y)	ADOPTED BY BROWN ET AL (2006) (MM/Y)
SA	MAYURRA	105 (26)	66 (40 - 110)	99	110
SA	MINECROW	53 (12)	13 (6 - 27)	24	75
SA	MONBULLA	143 (8)	29 (17 - 47)	-28	180
SA	MOORAK		115 (76 - 174)	107	175
SA	MOUNT BENSON	43 (5)	32 (16 - 64)	-40	60
SA	MOUNT MUIRHEAD	117 (9)	60 (38 - 93)	73	110
SA	MOYHALL	89 (3)	6 (4 - 9)	-1	105
SA	MURRABINNA	42 (8)	11 (5 - 26)	5	90
SA	MYORA	54 (12)	80 (55 - 116)	16	160
SA	ORMEROD	105 (3)	7 (4 - 12)	-8	120
SA	PEACOCK	55 (16)	5 (2 - 12)	0	70
SA	RIDDOCH	152 (4)	39 (24 - 63)	15	130
SA	RIVOLI BAY	67 (4)	54 (32 - 92)	57	100
SA	ROSS	91 (2)	18 (10 - 30)	62	110
SA	SHORT	132 (7)	31 (19 - 52)	-48	150
SA	SMITH	92 (4)	26 (17 - 39)	40	100
SA	SPENCE	95 (4)	4 (2 - 6)	-40	115
SA	STEWARTS	130 (6)	15 (9 - 23)	-58	145
SA	STIRLING		3 (1 - 4)	-125	50
SA	STRUAN	154 (2)	9 (6 - 14)	3	95
SA	SYMON	114 (27)	42 (27 - 66)	58	110
SA	TATIARA		2 (1 - 4)	-23	15
SA	TOWNSEND	83 (7)	13 (7 - 23)	26	85
SA	WATERHOUSE	56 (6)	27 (14 - 53)	-15	80
SA	WESTERN FLAT		3 (1 - 5)	-27	20
SA	WILLALOOKA		3 (2 - 5)	-53	40
SA	WIRREGA		2 (1 - 4)	-63	30
SA	WOOLUMBOOL	76 (17)	6 (2 - 14)	-21	90
SA	YOUNG	107 (7)	47 (30 - 75)	12	200
SA	ZONE 2A	54 (23)	36 (23 - 55)	-34	95
SA	ZONE 3A	93 (31)	16 (11 - 25)	-30	100
SA	ZONE 5A	39 (1)	6 (3 - 10)	-46	40
Vic	GLENELG	72 (10)	36 (23 - 56)	1	
Vic	WEST WIMMERA	44 (12)	3 (2 - 6)	2	

When the recharge estimates are compared at the management area scale it can be seen that the results do not agree in most cases (Figure 5.19). The CMB and WTF methods estimate recharge using different definitions and over different time scales, so it is unsurprising that they do not agree. Estimates produced by these two approaches methods appear to be more consistent when WB method-based recharge values are positive. Conversely, recharge estimates are very different when WB method-based results are negative, as the CMB method cannot produce negative numbers and instead tends to zero. The WTF method-based recharge estimates are much greater than the WB method-based estimates because differences in the definition of recharge used by method. Comparison of recharge rates estimated in the present study to previously adopted recharge rates estimated by Brown et al. (2006) indicate that that the CMB and WB method-based recharge estimates are much smaller. The WTF method-based estimates are generally more consistent, since this method was also used by Brown et al. (2006).

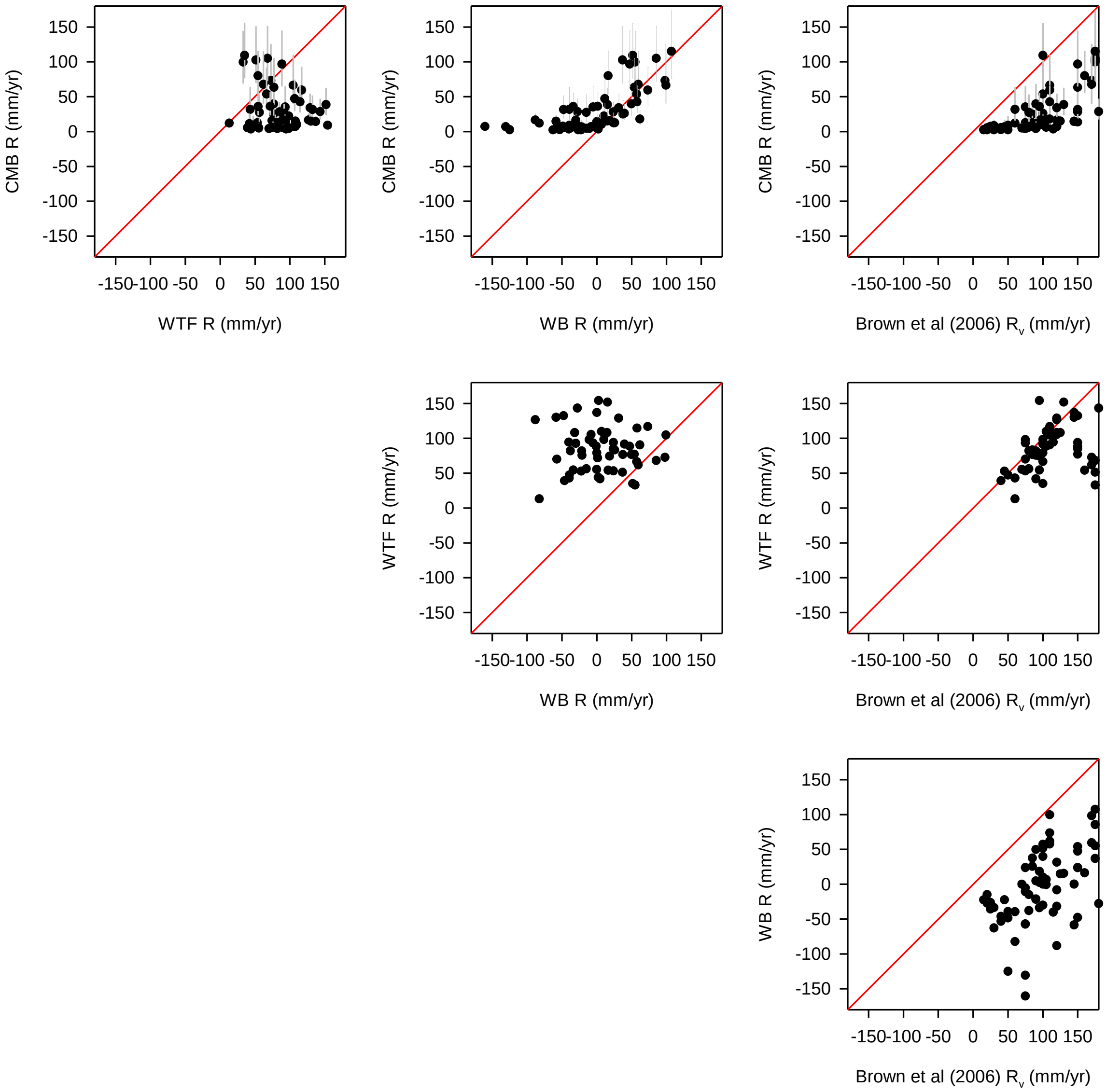


Figure 5.19 A comparison of the different recharge estimation methods aggregated to a management unit scale.

5.3 Recharge modelling

The recharge modelling component of the work will be reported on in Phase 2.

Recharge may be estimated through numerical solutions of Richards' equation (Richards, 1931) for one dimensional unsaturated zone flow and based on spatially distributed data such as soil, vegetation and land use type. Results from such models may then be used as inputs to three-dimensional groundwater flow models, such as MODFLOW. In the present regional scale study this approach is not feasible due to prohibitive model run times; therefore a much simpler approach needs to be developed. The standard recharge (RCH) package for MODFLOW requires that recharge is specified *a priori*; the observed correlation between gross recharge and depth to watertable therefore renders this approach inappropriate. The evapotranspiration (EVT) or evapotranspiration segments (ETS) packages both calculate evapotranspiration as a function of depth to watertable; however, this will not assist in the net recharge calculation that is required. The approach of Doble et al. (2006) is an improvement on previous attempts at the top boundary condition in MODFLOW but what we require is a method that has a depth dependent recharge and discharge component.

Instead, it is proposed that a look-up table approach be developed for net recharge estimation, based upon variables that contribute to the magnitude and direction of net recharge. These variables are:

1. Monthly rainfall
2. Month of the year
3. Vegetation type
4. Soil type
5. Depth to watertable

The look-up table will be populated using the outputs of one dimensional numerical recharge modelling conditioned to the recharge rates estimated in Section 5.2.

The proposed one-dimensional modelling will be conducted using the soil-vegetation-atmosphere-transfer model WAVES (Zhang and Dawes, 1998a). The modelling will be conducted on a transect following the rainfall gradient (approximately Port Macdonnell to Bordertown in 10 steps) for climate information. At each of these locations the model will be run for each combination of soil (7 classes based on clay content) and land use (6 classes) for a series of depths to water table (0.5, 1.0, 1.5, 2, 3, 5, 7, 10, 15, ∞). The model will be run from 1/1/1889 until 31/12/2012 with the first 24 years used as a model spin-up period and the remaining 100 years being used to build relationships between net recharge and the five determinants listed above after being aggregated into a monthly time series.

The one-dimensional modelling will be constrained by the field observations but not necessarily calibrated to it. The spatial and temporal density of the net recharge estimates from the satellite derived water balance is our best source of information on the patterns of recharge; however, the magnitude of the recharge estimates from this method have not been verified. The chloride mass balance estimates of net recharge are less useful in this application. The way the method has been applied means that the chloride in groundwater has been interpolated without regard for the soil and land use which means that some averaging of nearby soil and vegetation groupings is inevitable. The chloride mass balance estimates of recharge also suffer from issues associated with land use change, the travel of chloride along the flowlines and the averaging of the recharge estimates over the residence time of the water in the aquifer. The chloride mass balance estimates can be used as a “sanity check” on the model outputs. The point recharge estimates from the water table fluctuation method and the previous recharge estimates identified during the literature review can be used to check the magnitude of the long term average recharge rates from the modelling. However the point scale recharge estimates do not cover the entire spectrum of soil / vegetation / depth to water table so cannot be used in isolation.

5.4 Summary and implications for numerical groundwater modelling

The gross recharge averaged over the model domain is quite high but not spatially uniform. The gross recharge is strongly correlated with depth to watertable and vegetation type whereas the influence of soil type is not as significant as expected. Gross recharge features a consistent seasonal pattern, with recharge occurring in winter when rainfall is highest and potential evapotranspiration lowest, and also features considerable interannual variability.

Net recharge is generally lower than gross recharge, indicating that evapotranspiration is primarily occurring either directly from the watertable or from groundwater dependent vegetation. Net recharge is strongly influenced by vegetation type, depth to watertable and soil type. Net recharge is generally negative under forestry areas, indicating that the hardwood and softwood vegetation is accessing groundwater. The amount of groundwater used by the plantations is dependent upon depth to watertable and soil type. A consistent seasonal pattern in net recharge is apparent, with recharge occurring in winter and discharge occurring in summer. As for gross recharge estimates, considerable inter-annual variability exists in net recharge estimates.

To be able to replicate the spatial and temporal dynamics of recharge and discharge processes, the groundwater model used in the present study will need to include a feedback mechanism between depth to watertable and net recharge rate. The standard MODFLOW EVT package can be used to represent evapotranspiration processes but the standard RCH package requires recharge to be prescribed *a priori* rather than calculated dynamically by the model. To overcome these limitations, a different approach is proposed in which net recharge is provided as input to the MODFLOW model from a look-up table that tabulates the net recharge for a given monthly rainfall, month, vegetation type soil type, and depth to watertable.

6 Groundwater discharge to the marine environment

Sébastien Lamontagne, Andrew Taylor, Darren Herpich and Gary Hancock

Groundwater discharge from regional aquifers in the South East occurs by pumping, evapotranspiration from the shallow watertable, discharge to drains and by outflow to the marine environment. Of these mechanisms, submarine groundwater discharge (SGD) is the most poorly known and is usually estimated as a part of the calibration process for groundwater models. Besides the need to better quantify this flux for refining the regional water balance, there may be ecosystems both onshore and offshore which rely on SGD or the nutrient flux associated with SGD.

In Task 2 for the Regional Water Balance project, a range of environmental tracers were trialled to explore the location and flux of SGD along a part of the study area (Port MacDonnell to Victoria/SA border). This also complemented previous work using tracers in the region for SGD or coastal groundwater-dependent wetlands (Herpich, 2010; Mustafa et al., 2012; Wood, 2011). Environmental tracers include physical (temperature, etc) or chemical properties of groundwater (salinity, etc) that can be used to differentiate SGD from other water sources. The study had three broad components:

1. Characterisation of the environmental tracer signature for potential sources of water to the coastline
2. Evaluation of the trends in selected tracers in nearshore and offshore seawater
3. Mapping of SGD discharge zones along a 1 km beach section

The environmental tracers evaluated included temperature, salinity, and radioisotopes such as radon-222 (^{222}Rn) and the 'radium quartet' (^{223}Ra, ^{224}Ra, ^{226}Ra and ^{228}Ra). Radon and radium are the most widely used tracers in SGD study (Burnett et al., 2006; Moore, 1996). Groundwater tends to be enriched in these tracers because of contact with rocks and sediments containing their precursors (minerals containing uranium and thorium radionuclides). In addition, helium was trialled as a tracer for SGD for the first time in Australia. Helium-4 (^{4}He) is a stable noble gas that is also generated during the decay of uranium and thorium family radionuclides. Helium-4 accumulates in groundwater over long-time periods (>1,000 years) and is a good tracer for older regional groundwater (Solomon, 2000).

Submarine groundwater discharge can include several water sources. In particular, because of tides, waves and currents, a large component of SGD can be seawater recirculated from beaches and shallow sediments (Burnett et al., 2003). This recirculation can have two different effects; firstly, it can result in fresh groundwater to partially mix with seawater before discharging through the sea floor. Secondly, in some cases regional groundwater can be discharged to the sea in the absence of freshwater inputs. However, by using multiple tracers, it is possible to identify the different components of SGD. For example, recirculated seawater is relatively more enriched in short-lived radionuclides like ^{223}Ra (half-life = 11.4 days) and ^{224}Ra (3.66 days) because these are regenerated more rapidly from their parent material following repeated sediment leaching (Hancock and Murray, 1996). In contrast, regional groundwater tends to be relatively more enriched in ^{228}Ra (half-life = 5.7 years), ^{226}Ra (1600 years) and ^{4}He accumulating over time at a quasi-constant release rate.

In the following, the detailed sampling design for the SGD study is presented along with key results. The implications for the design of a more complete field program aimed at helping to calibrate the regional water balance model are discussed.

6.1 Methods

All sampling took place during a field trip held during 11–18 November 2012 in the Port MacDonnell – Victorian/SA border area, including at the Piccaninnie Conservation Park (Figure 6.1). This region was selected because it is known to be a significant discharge area for the Gambier Limestone aquifer.

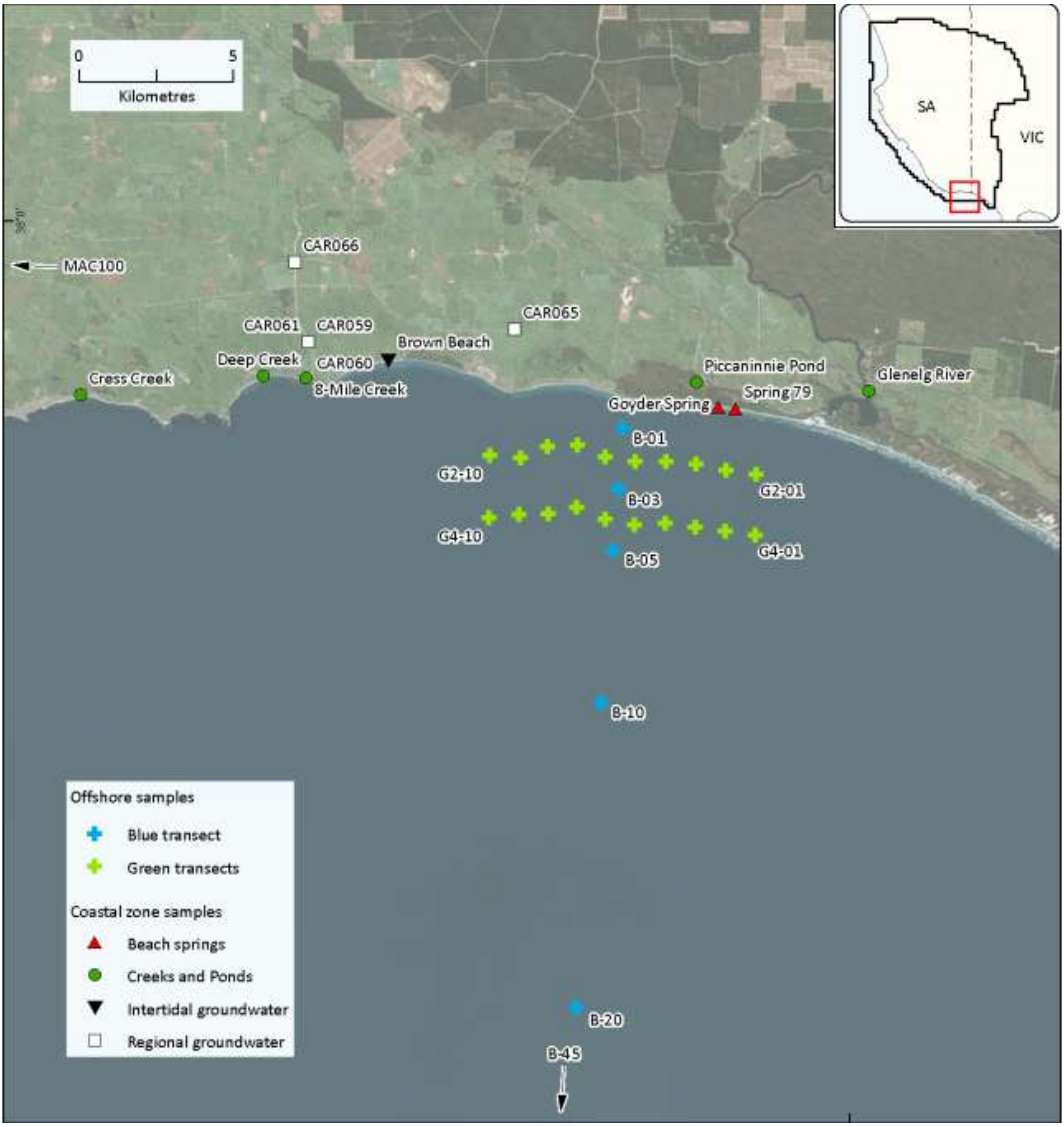


Figure 6.1 Study area, showing the location for the different offshore and coastal water samples.

6.1.1 CHARACTERISATION OF ENVIRONMENTAL TRACER SIGNATURE IN POTENTIAL SOURCE WATERS

The aim for this activity was to establish the signature for different potential sources of water to the coastal zones, including:

- Streams, drains and outlets (Piccaninnie outlet, Glenelg River, 8-Mile Creek, Deep Creek and Cress Creek)
- Groundwater (beach springs, Camel Back, Green Point and Greenways formations)
- Recirculated seawater

The groundwater wells or piezometers selected for sampling aimed to capture the range of salinity found in groundwater in the area. In particular, one nested piezometer straddling the fresh/salt interface near the coastline was included (CAR059, CAR060, CAR061; Mustafa et al., 2012).

The parameters measured included:

- Electrical conductivity, temperature, dissolved oxygen and major ions
- Stable isotopes of water: deuterium (^2H) and oxygen-18 (^{18}O)
- Radium (subset) and radon
- Noble gases (including ^4He)

Sampling procedures for potential source waters

Surface water samples were collected as close to the stream outlet as possible (but above the high tide mark). Due to access problems, the Piccaninnie outlet sample was collected from Piccaninnie Ponds. Beach springs samples were collected at Piccaninnie Ponds Conservation Area. This included two vents from the 'Spring 79' complex and another sample from an unnamed smaller spring ~ 1 km west from it (hereafter referred to as 'Goyder Spring'). Beach spring samples were collected by inserting a small PVC piezometer in the spring vents and by pumping with a bilge pump into a well-rinsed container. Recirculated seawater samples were collected by installing similar shallow PVC piezometers along a beach face at Brown Bay (Lamontagne et al., 2008). A surf sample was also collected at Brown Bay.

All water samples for major ions, stable isotopes, radium and radon were collected using a bilge pump connected to an in-line filtering system (Puretec FP10M with a 20 μm cartridge) with nylon tubing or, for groundwater samples, a Grundfos pump. For major ions, two litres were collected in a well-rinsed bottle and kept cool in an insulated container. Back in the field laboratory, 200 mL was 0.45 μm filtered and split into three subsample. The one for major cations was acidified to a pH of <2, the one for major anions remained unacidified and the one for stable isotopes of water was stored inverted in a McCartney container. Radon-222 samples were collected following the 'PET' method of Leaney and Herczeg (2006). Radium samples were collected in well-rinsed 20 L carboys (20–40 L per sample)and later extracted in a field laboratory using manganese dioxide (MnO_2) coated fibres (Moore, 1976) following the procedures outlined in Lamontagne et al. (2008).

Two methods were used to collect noble gas samples. Whenever possible, passive head-space diffusion samplers (Gardner and Solomon, 2009) were left overnight to equilibrate in the waterway. Alternatively (some groundwater, recirculated seawater and beach springs samples) a bubble-free water sample was collected in a copper tube following (Weiss, 1968).

6.1.2 TRACERS IN SEAWATER

The trends in environmental tracers for inshore and offshore seawater were evaluated by sampling seawater along three transects on 13–14 November 2012 on the charter boat 'Jaymar Star' from Port MacDonnell. The offshore 'Blue' Transect aimed to evaluate the variations in electrical conductivity (EC), radon, radium and ^4He from the shoreline to the continental shelf (Figure 6.1). The inshore 'Green – 2 km' and 'Green – 4 km' transects aimed to locate variations in EC and radon parallel to the shoreline at a distance of 2 km and 4 km, respectively. All transects were located offshore of Piccaninnie Conservation Area. The Green transects started at the Victorian border and stations were sampled every km in a westward direction thereafter for 9 km. The Blue Transect was designed to overlap both the Green ones and 'Ruby Rock' (near Blue – 5 km), a suspected SGD spring based on thermal infrared imaging (Herpich 2010). Sampling stations along the Blue Transect had a 'logarithmic' spacing, with more samples collected inshore than offshore. The furthest Blue station (45 km) was at the edge of the continental shelf and aimed to collect oceanic seawater, that is, to determine the background activity or concentration for the tracers.

The period selected for the field study (Austral spring) corresponded to the time when the watertable is highest in the region and when groundwater discharge should be largest. It also preceded the development of the Bonney Upwelling, a local cold, nutrient-rich current generated by summer southerly winds (Kampf et al., 2004). Inspection of satellite sea surface temperatures indicated that the Bonney Upwelling was not present during the sampling period.

Sampling methods for offshore sampling

Vertical electrical conductivity profiles, vertical temperature profiles and surface water radon were collected at all Blue and Green stations. The electrical conductivity and temperature profiles were collected with a CTD profiler (RCM 9, Aanderra Instruments). Following the convention in oceanographic studies, conductivity measurements were converted into Practical Salinity Units (PSU) following Fofonoff and Millard (1983). For radon, surface seawater was collected with a bilge pump attached to a buoy with the intake weighed down to stay ~ 50 cm below the surface. Radon samples were collected following the 'PET' method (Leaney and Herczeg, 2006). Along the Blue Transect stations, 60 L (inshore) to 140 L (offshore) surface seawater samples were collected in well-rinsed 20 L carboys using the bilge pump and Puretec in-line filtration system. At selected Blue stations, Noble gases were collected using the copper tube method. At the 5 km station (near Ruby Rock), two noble gas passive head-space diffusion samplers were left overnight near the bottom (~ 16 m) attached to a crayfish pot and one ^{222}Rn sample was collected every 4 m using a bilge pump.

6.1.3 SHORELINE RADON SURVEY

To determine if tracers could detect zones of groundwater discharge along beach faces, shallow groundwater and surf seawater samples were collected every 100 m over a 900 m beach section at low tide at Piccaninnie Conservation Area. This beach section was selected because it included areas with and without obvious beach springs (including the Spring 79 complex). At each station, three samples were collected: shallow groundwater at the base of the dune, shallow groundwater at the shoreline, and surf zone seawater. The base-of-dune and shoreline groundwater samples approximately represented the high and low tide marks, respectively. The groundwater samples were collected by shovelling to the watertable and then installing a drive point to 50–75 cm depth (Figure 6.2). Groundwater radon was collected from drive points using a hand-held peristaltic pump and a syringe following Lamontagne and Cook (2007). Field EC was also measured on the groundwater samples. Surf radon samples were collected by wading to ~ 50 cm depth and repeatedly squeezing a 1.25 L PET bottle while it was held underwater. Radon was preserved using the 'Direct' and the 'PET' methods for groundwater and surface water, respectively (Leaney and Herczeg, 2006).

6.1.4 ANALYTICAL METHODS

Major ions, stable isotopes and noble gases

Laboratory EC (Meterlab CDM230) was measured with calibrated probes in a constant temperature room. Total alkalinity was measured by titration to a pH 4.5 end-point. Major cations were measured by Inductively Coupled Optical Emission Spectroscopy (ICP-OES; ARCOS) and anions by ion chromatography (Dionex ICS – 2500). Isotope ratios of water were measured by isotope ratio mass-spectroscopy (Europa Geo 20-20) using the WES technique. The isotopic ratios were expressed in parts per thousand relative to the Vienna Standard Mean Ocean Water (VSMOW) using the delta notation (δ). Neon-20 (^{20}Ne), argon-40 (^{40}Ar) and ^{4}He concentrations were measured using a quadrupole mass spectrometer with cryogenic separation (Poole et al., 1997).

Radon and Radium

Radon-222 samples were analysed by liquid scintillation in an LKB Quantullus counter using the pulse shape program to discriminate between alpha and beta decay (Herczeg et al. 1994). Short-lived Ra isotopes, ^{223}Ra and ^{224}Ra, were measured in Canberra using a counting system (RaDeCC) consisting of photomultiplier tubes and delayed coincidence circuit for the identification of the short-lived radon daughters, ^{219}Rn and ^{220}Rn (Moore and Arnold, 1996). The individual MnO_2 fibre samples were placed in a closed-loop air circulation system connected to the counters. Counting occurred within 4 days of collection.

After measurement of ^{223}Ra and ^{224}Ra was completed the Mn O_2 fibre was ashed at 400 °C and the activities of the long-lived isotope, ^{226}Ra, was determined by alpha-particle spectrometry following the method of

Hancock and Martin (1991). This method entailed the additional of a yield tracer (^{225}Ra) and radiochemical separation procedures.

All radon and radium isotope measurements were corrected for radioactive decay between the time of sampling and measurement. The activities quoted pertain to the time of sample collection. Uncertainties correspond to the one standard error.

Figure 6.2 Sampling for shallow intertidal groundwater along the Piccaninnie Conservation Area shoreline using a drive point and a hand-held peristaltic pump.

6.1.5 ESTIMATION OF THE OFFSHORE RADIUM FLUX

Several steps are required to estimate SGD using trends in Ra and Rn activity in seawater. Following convention (Moore, 2000; 2003), in a first step the short-lived Ra isotopes are used to estimate the offshore coefficient of solute diffusivity (D_o). Secondly, the total offshore Ra flux (F_o) is estimated using the long-lived Ra isotopes. The approach used to estimate D_o and F_o was similar to the one developed by Hancock et al. (2006) and will only be briefly reviewed here. Offshore Ra activity profiles were modelled using the one-dimensional advection-dispersion equation by incorporating radioactive decay, depth and benthic flux terms:

$$\frac{\partial A}{\partial t} + u\frac{\partial A}{\partial x} - H^{-1}\frac{\partial^2 D_o HA}{\partial x^2} + \lambda A + H^{-1}kA = H^{-1}B, \qquad (6.1)$$

where A is the radium activity, t is time, x is offshore distance, u the advection velocity, H is water depth, D_o is the offshore coefficient of solute diffusivity, λ the isotope decay rate, k the gas transfer velocity and B is the Ra benthic flux (that is, the flux of Ra from the seafloor due diffusion and bioirrigation). To solve Eq. 6.1, advection offshore is assumed to be negligible (u ~ 0) so that diffusive-like processes alone control offshore transport (Moore, 2000). This assumption is reasonable based on the absence of obvious river plumes at the time of the study. Another assumption of the model is that the water column is well mixed, which was the case at the time of the study (see Chapter 6.2.2). For Ra, k is set at 0.

At steady-state for Ra, Eq. 6.1 simplifies to:

$$-\frac{\partial}{\partial x}\left[D_o H \frac{\partial A}{\partial x}\right] + \lambda HA = B \quad . \tag{6.2}$$

In a first step, the short-lived isotopes, ^{223}Ra and ^{224}Ra, are used to estimate D_o. For the short-lived isotopes, the boundary conditions for Eq. 6.2 are a constant Ra flux at the coastline (F_o) and a zero flux at 50 km, or:

$$F_{50km} = \frac{\partial A}{\partial x} = 0 \quad . \tag{6.3}$$

Integration of Eq. 6.2 with respect to *x* yields:

$$-\left[D_o H \frac{\partial A}{\partial x}\right]_{x=0}^{50km} = \int_{x=0}^{50km} (B - \lambda HA) dx \, . \tag{6.4}$$

The left hand side of this equation is just $F_{50km} - F_o$, but since we assume that $F_{50km} = 0$ then:

$$F_o = \int_{x=0}^{50km} (\lambda HA - B) dx \, . \tag{6.5}$$

The integral on the right hand side is evaluated using the measurements of radium activity along the two transects. Two formulations for diffusivity were tested:

$$D_x = D_o \, , \tag{6.6}$$

$$D_x = D_o [1 - \exp(-x/\Delta)] \, . \tag{6.7}$$

In both formulations D_o is constant. In the second formulation, the diffusivity increases from zero at the coast to asymptote to D_o further offshore. The lengthscale for this increase is Δ. Two formulations for *B* were also used to estimate F_o. In the first formulation, the convention used in previous studies was used (Moore, 2003), where there is no benthic flux. For this case, the Ra generation capacity of bottom sediments is assumed so low that the combined effects of molecular diffusion and bioturbation produces a negligible Ra flux. In a second formulation, the *B* flux along *x* was assumed to follow Hancock et al. (2006), where *B* is constant inshore but declines exponentially thereafter:

$$B = B_o \qquad x < 10 \text{ km} \, , \tag{6.8}$$

$$B = Ce^{-bx} \qquad x \geq 10 \text{ km} \, . \tag{6.9}$$

Values for B_o, *C* and *b* were taken from Hancock et al. (2006) for each Ra isotope.

Four models with different combinations for the formulation of D_o and *B* were tested. Solutions were developed for D_o, Δ, and *B* by discretising Eq. 6.2 in mass-conserving form with a cell size of 500 m from the shoreline to 50 km. Depth was allowed to vary between cells and was approximated from depth measurements made during Ra sampling using a series of linear equations. The resulting discretised equations with their two boundary conditions were solved by LU factorisation (a form of Gaussian elimination). Optimal parameter values for each model were evaluated by minimising the negative log-likelihood between predicted and observed activities (Hancock et al., 2006). The negative log-likelihood (**L**) is defined as:

$$\mathbf{L} = n\left[\log(\sigma) + \frac{1}{2}\log(2\pi)\right] + \sum_{i=1}^{n}\frac{(X_i - m)^2}{2\sigma^2}. \qquad (6.10)$$

Where X_i is the measured Ra activity at distance *i*, *m* the predicted activity at *i*, *n* the number of observations, and σ is:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - m_i)^2}{n-1}}. \qquad (6.11)$$

Using the likelihood ratio test (Hillborn and Mangel, 1997), the negative log-likelihoods were also used to evaluate what formulation for D_o gave the best fit to the data. The rationale behind the test is that negative log-likelihoods will tend to decrease (i.e., indicate a better fit) when more parameters are included in a model even if the supplementary parameters have little or no relationship to the observed data. The likelihood ratio test (*R*) is defined as:

$$R = 2\cdot(\mathbf{L}_A - \mathbf{L}_B), \qquad (6.12)$$

where $\mathbf{L}_A$ and $\mathbf{L}_B$ are the negative log-likelihoods for model A and B, respectively, and where model B has more parameters than A. The test has a chi-square distribution with degrees of freedom equal to the difference in the number of parameters between models B and A. Thus, if B has one more parameter than A, *R* must be >3.84 for B to be considered better than A at the 0.05 probability level.

The estimates of D_o obtained using the short-lived isotopes can be used to estimate F_o for the long-lived Ra isotopes. The isotopes ^{226}Ra and ^{228}Ra have half-lives sufficiently long that on the timescale of transport across BGB decay can be neglected. Thus, for long-lived Ra isotopes, Eq. 6.2 simplifies to:

$$\frac{\partial}{\partial x}\left[D_o H\frac{\partial A}{\partial x}\right] = B. \qquad (6.13)$$

A key difference relative to short-lived Ra isotopes is that F_o cannot be directly estimated because $F_{50km} > 0$ for the long-lived isotopes. Thus, the boundary conditions here are a constant offshore flux at the coastline and at 50 km. Equation 6.13 was solved using a numerical model similar to the one used for the short-lived isotopes. F_o was estimated for ^{226}Ra only because the ^{228}Ra data was incomplete at the time of writing this report.

6.2 Results

6.2.1 TRACER SIGNATURE IN POTENTIAL SOURCE WATERS

In general, source waters were slightly or moderately enriched in radiogenic tracers (Table 6.1; Note that all tables are appended at the end of this Chapter). Surface waters and coastal springs were relatively fresh (EC = 1.5–3.9 mS/cm; Figure 6.3), with the exception of the tidal section of the Glenelg River, which was brackish (~ 14 mS/cm). Groundwater was also relatively fresh (0.78–2.9 mS/cm), with the exception of the CAR061 well which is located within the coastal salt wedge (45.6 mS/cm). Intertidal groundwater varied from brackish to marine (4.30–48.6 mS/cm). Radon-222 was enriched in all source waters, with activities ranging from 0.29 Bq/L (Glenelg River) to 11 Bq/L (Cress Creek). The patterns in radium activity were more complex, with the highest activities found in the more saline samples, in particular CAR061. For example,

^{224}Ra activities were 1.3–2.2 mBq/L in surface waters and coastal springs, ~ 13 mBq/L in intertidal groundwater with marine salinities, and 41.3 mBq/L in CAR061. Helium-4 concentrations were generally low (4–8e–8 cc STP/g), except in Cress Creek (1.2 e–7 cc STP/g).

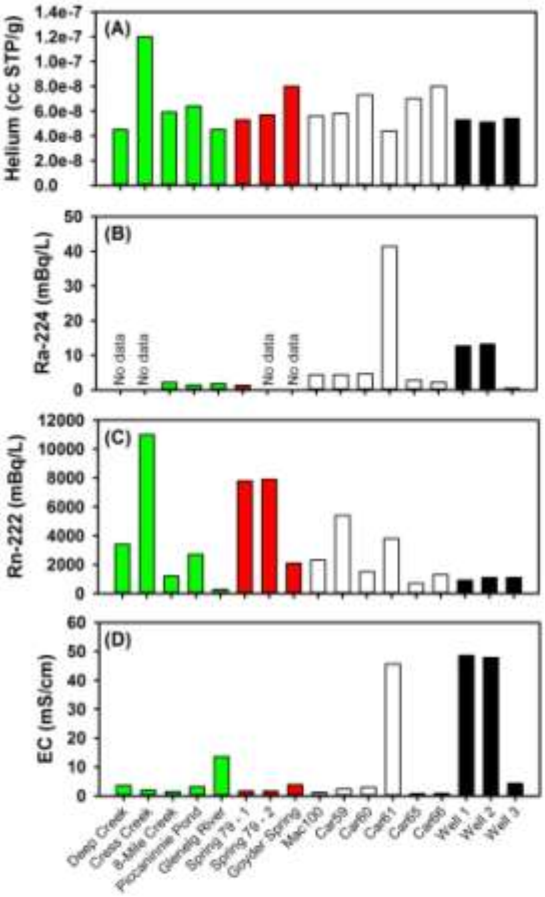


Figure 6.3 Variations in (a) ^{4}He, (b) ^{224}Ra, (c) ^{222}Rn and (d) EC in source waters

The patterns in major ions and in the stable isotopes of water clearly indicate two origins for the source water samples (Table 6.2; Figure 6.4) that is, seawater and terrestrial groundwater. Aside from having a high (Na+K)/(Ca+Mg) ratio, seawater in the study area is also relatively enriched in stable isotopes and has an evaporation signal (plots to the right of the meteoric water line; Figure 6.4b). Several source samples appear a mixture of terrestrial and seawater, in particular some surface water and intertidal groundwater. On the other hand, CAR061 groundwater mostly has a marine signature.

Temperature in creeks and ponds ranged between 15.6 to 18.3 °C, similar to what was observed in regional groundwater (17.0 to 19.2 °C; Table 6.1). However, the coastal springs were slightly warmer than other sources (20.3 to 20.6 °C), including recirculated seawater (14.3 to 19.3 °C).

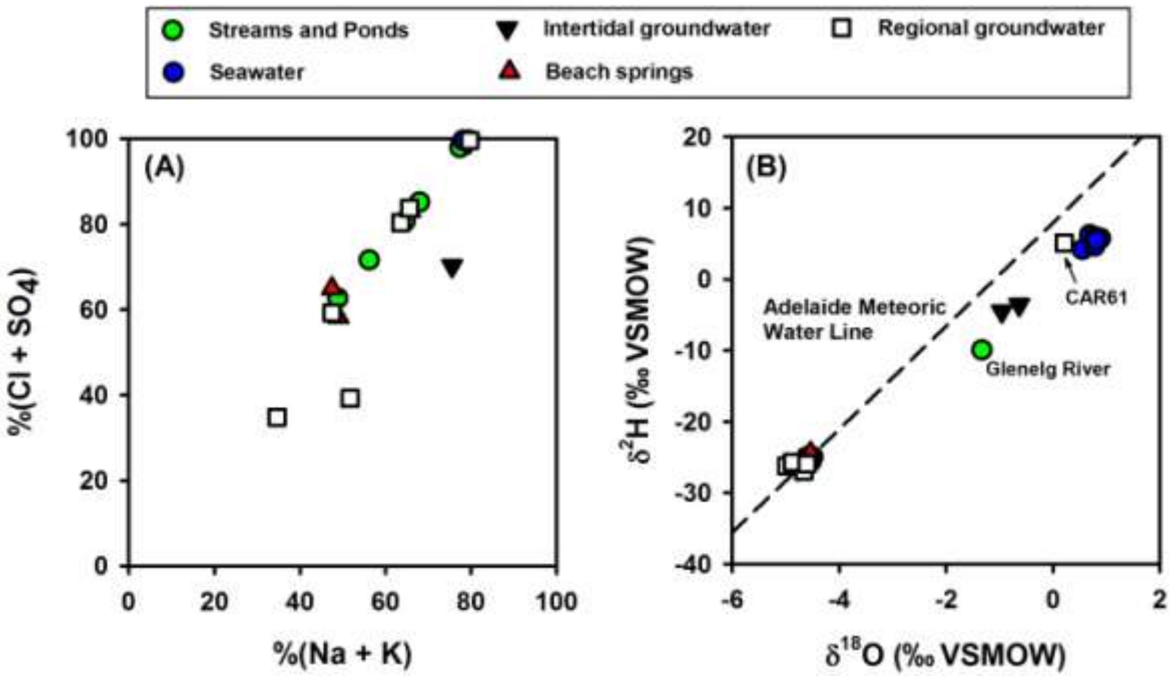


Figure 6.4 Trends in major ion composition and in the stable isotopes of water in seawater and in potential sources of water to the coastline. Sample details in Tables 6.2 and 6.3. (a) Percentage of (Na+K)/major cations and (Cl+SO_4)/major anions (on a meq basis). (b) Stable isotope ratios of water.

6.2.2 TRACERS IN SEAWATER

Salinity and temperature

There were weak horizontal inverse temperature and salinity gradients perpendicular to the coastline on 13–14 November 2013. Such inverse gradients (warmer and saltier seawater closer to the shore) are common along the South Australian coastline and are generated by the high evaporation in a semi-arid climate and low terrestrial runoff. Offshore (Blue Transect), there was a weak vertical thermal gradient at the 1 km station but not further offshore (Figure 6.5a). Surface temperatures ranged from 17.2 °C at the 1 km station to 14.7 °C at the 45 km station. A weak vertical temperature gradient was also evident along the Green – 2 km transect but was not always present along the Green – 4 km transect (Figure 6.5b-c). None of the temperature profiles showed obvious signs of submarine groundwater discharge. However, groundwater temperature in coastal wells (16 to 19 °C) and coastal springs (~ 20 °C) was only slightly warmer than seawater at the time of the survey.

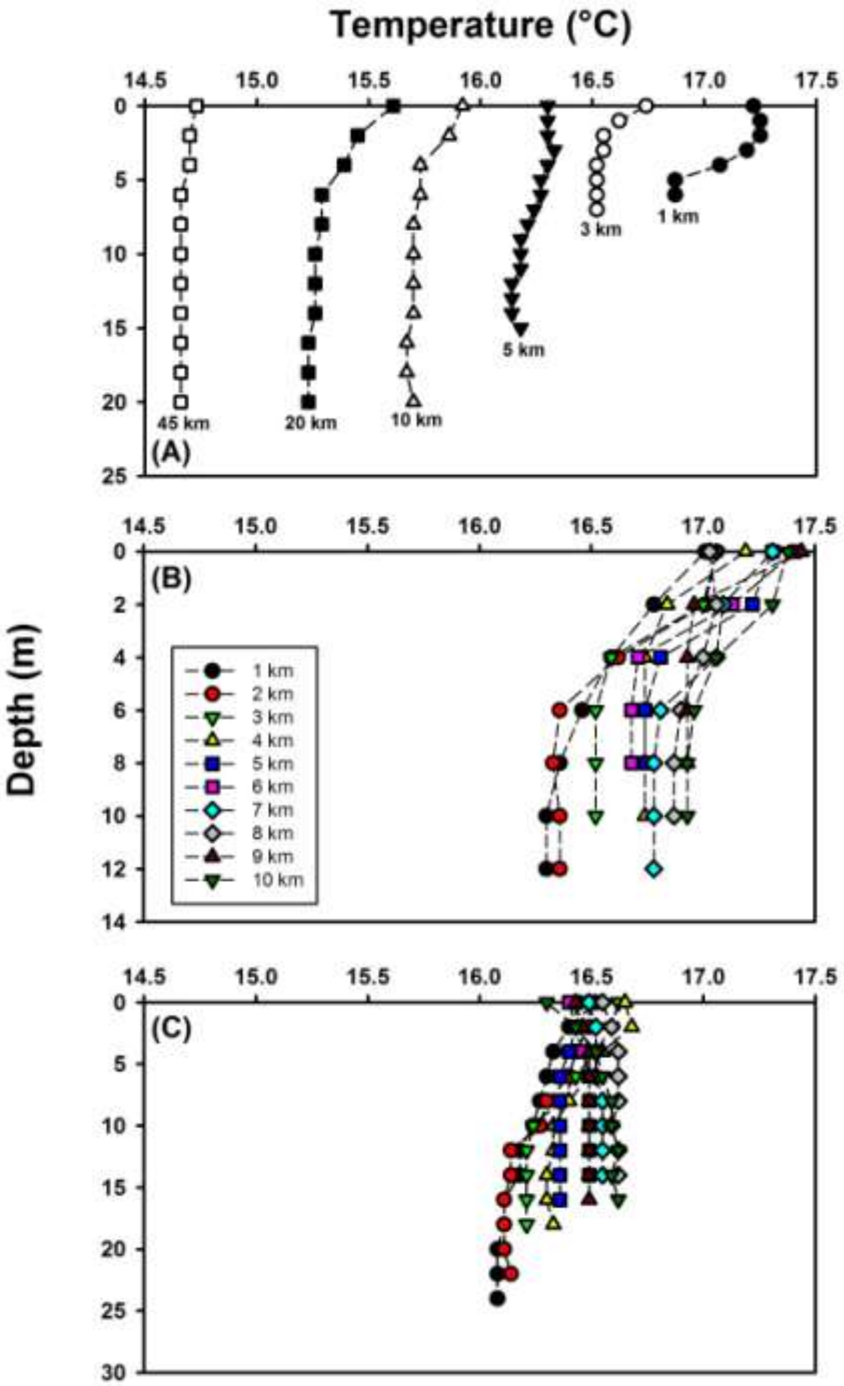


Figure 6.5 Vertical temperature profiles along the (a) Blue, (b) Green – 2 km and (c) Green – 4 km transects, 13–14 November 2013.

Unlike for temperature, vertical salinity gradients were not evident and the differences between transects smaller. For example, Along the Blue Transect surface salinity varied from ~ 36 PSU at the 1 km station to ~ 35.5 PSU at 45 km (Figure 6.6). Like for temperature, no obvious 'freshwater' anomaly was found (note that the profiles did not extend to the seafloor past the Blue – 5 km station). However, the temperature and salinity profiles are consistent with a gradual warming-up of the water column during the Austral spring in a semi-arid environment. Similar salinities between the Blue – 1 km, 3 km and 5 km stations may be consistent with some dilution of inshore waters by either, fresh surface water, or fresh groundwater inputs at the coast. This is also consistent with seawater having a slightly less enriched isotopic signature at the shoreline than at 3–5 km offshore (Table 6.3).

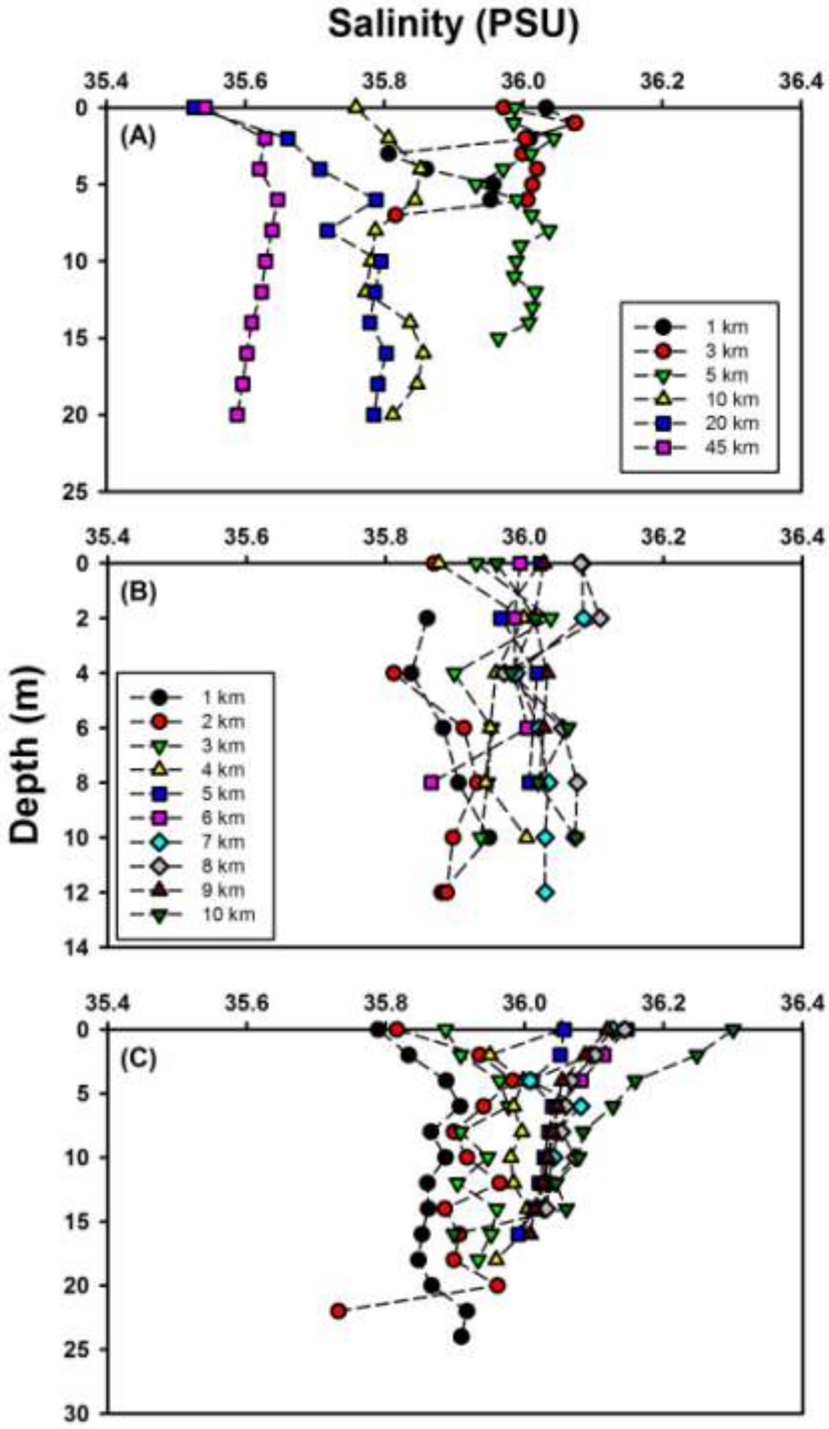


Figure 6.6 Salinity profiles at the (a) Blue, (b) Green – 2 km and (c) Green – 4 km transects, 13–14 November 2013.

Radionuclides

Radon-222 activities were generally low at the Blue and Green transects, ranging from <0.005–0.013 Bq/L (Table 6.4 and Table 6.5; Figure 6.7). Radon activities were mostly at background at the Blue Transect and varied from background to slightly above background at the Green transects, without any clear trends in space. Radium isotopes along the Blue Transect had a more traditional profile, with the highest activities at the coastline generally declining exponentially offshore (Figure 6.7). For example, ^{224}Ra activities were 2.5 mBq/L in the surf zone and declined to 0.1 mBq/L at the 45-km station. The range in ^{226}Ra in seawater was smaller than the one of the shorter-lived Ra isotopes (from 1.4–1.7 mBq/L) but activities also declined exponentially offshore. At the time of writing the report, ^{228}Ra analyses were only partially completed and will be presented elsewhere.

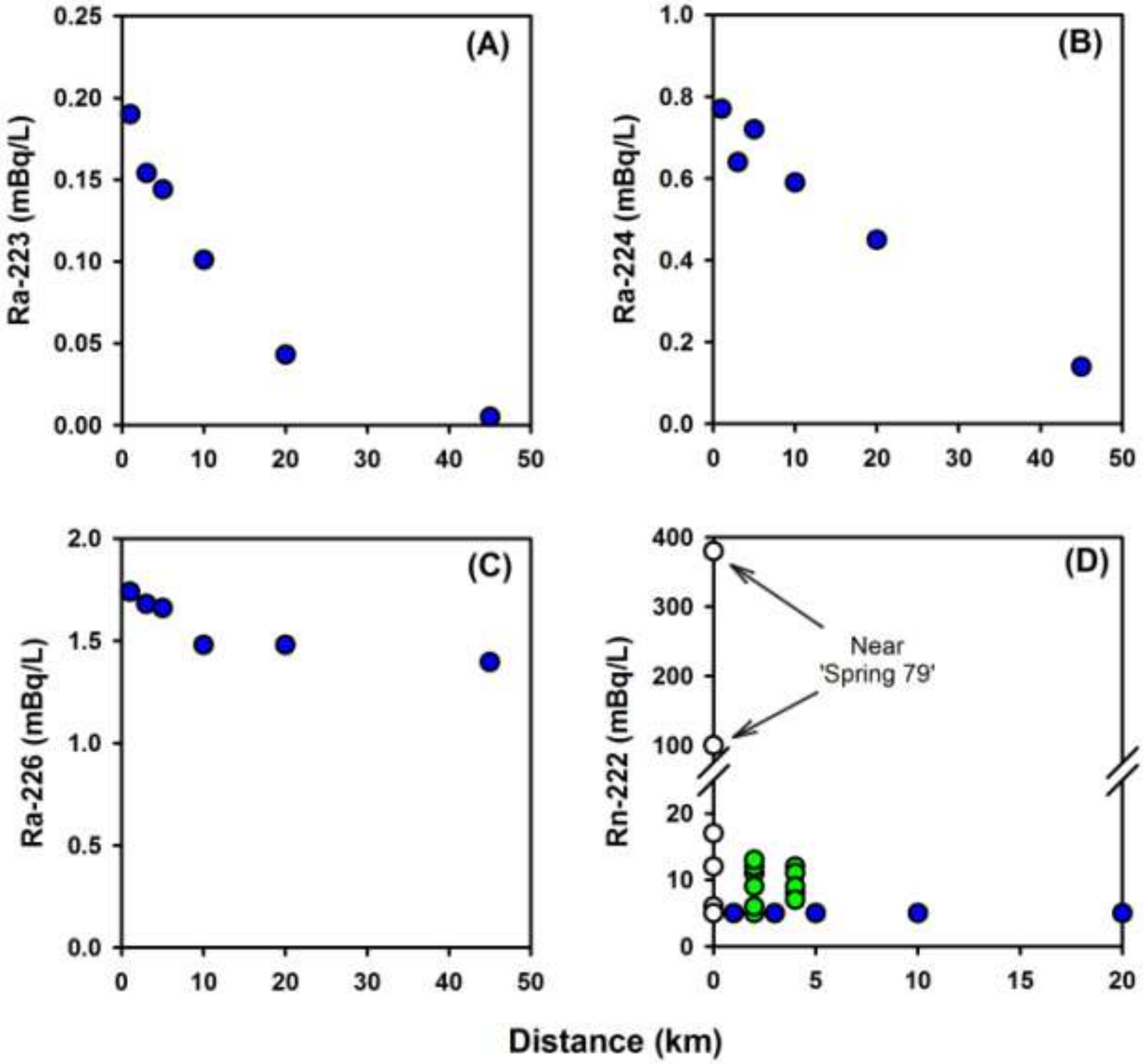


Figure 6.7 (a) ^{223}Ra, (b) ^{224}Ra, (c) ^{226}Ra and (d) ^{222}Rn in seawater relative to distance offshore. For ^{222}Rn, white circles at 0 km represent surf zone radon collected along the Piccaninnie Conservation Area shoreline and the green ones the Green – 2 km and Green – 4 km transects.

Helium-4

The patterns in ^{4}He concentration require careful consideration because concentrations are a function of temperature-dependent equilibrium concentration with the atmosphere, salinity, geological inputs (the source of interest here) and the presence of excess air. These different factors were evaluated by plotting the ^{4}He concentrations relative to Ne and by showing the expected equilibrium concentration relative to temperature at a given salinity (fresh vs. saline) and amount of excess air. Thus, samples were separated in two group, namely the 'fresh' ones (Figure 6.7a) and the 'saline' ones (Figure 6.7b). In addition, samples collected with diffusers were inspected independently as this technique is usually considered more reliable than the copper tube one (Figure 6.7c).

In general, the ^{4}He concentrations fell either on or close to the solubility equilibrium lines (with or without excess air). In other words, there was limited evidence of a significant enrichment in ^{4}He from a geological source other than in a few samples (such as Cress Creek). Thus, as most potential sources were not enriched in ^{4}He, it is not surprising that no ^{4}He enrichment from a geological source was found in seawater.

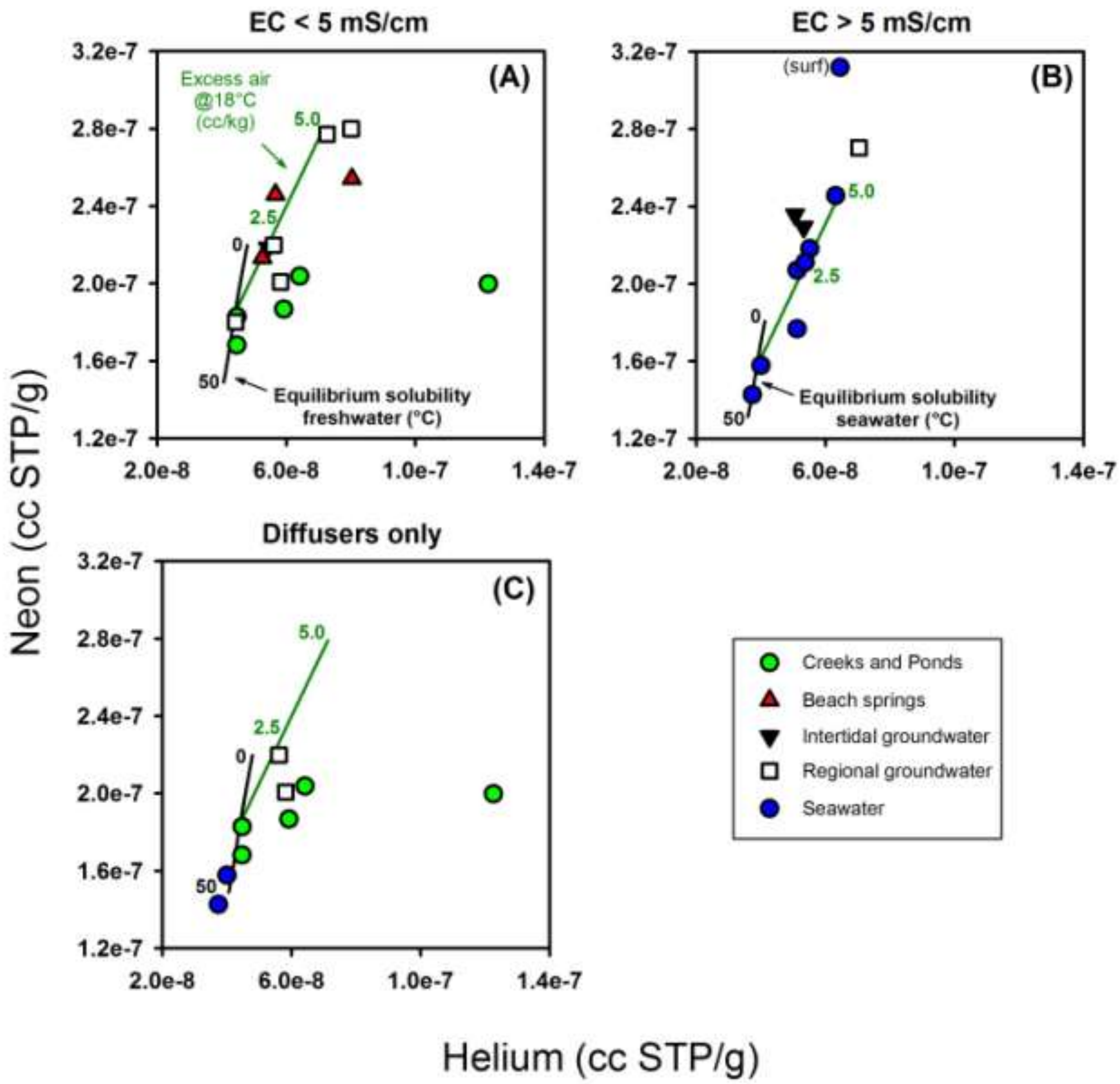


Figure 6.8 Helium-4 and total Ne concentrations in source samples and in seawater. Also shown are the air-water equilibrium solubility lines (black) and the excess air enrichment line at 18 °C (green). Samples falling to the right of either line may represent ^{4}He enrichment from a geological source. (a) Freshwater samples; (b) Saline samples; (c) Diffuser-only samples.

6.2.3 SHORELINE RADON SURVEY

There were significant variations in ^{222}Rn activity in the surf zone along the 900 m test section, with the highest values usually associated with beach springs (Figure 6.9). Radon activities in the surf zone were highest at the Spring 79 complex (Station 0 km) and for up to 200 m away from it (17–370 mBq/L). A smaller surf zone radon peak occurred near Goyder Spring (12 mBq/L). In contrast, radon activities in shoreline and base-of-dune groundwater had a relatively narrow range (600–1100 mBq/L), with the highest values at stations 0.7–0.9 km. Radon-222 activity in intertidal groundwater from beach sand was noticeably smaller than in the nearby springs (2100–7100 mBq/L).

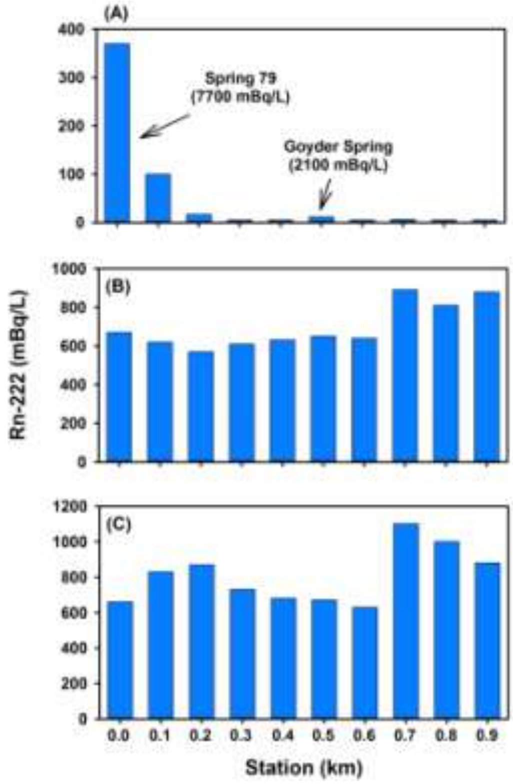


Figure 6.9 Variations in ^{222}Rn activity in (a) the surf zone, (b) shoreline groundwater and (c) base-of-dune groundwater along a 900 m beach section in Piccaninnie Conservation Area.

There was a significant contrast in salinity between shoreline and base-of-dune groundwater along the test section (Figure 6.10). Along the shoreline, groundwater was saline but usually less so than in seawater, in particular near the two springs. However, at the base of the dune, groundwater was fresh to brackish, with some of the freshest samples away from the two springs. Overall, while the greatest groundwater discharge is probably associated with springs, the patterns in salinity suggest that diffuse groundwater discharge also occurs elsewhere. Whether the source of diffuse groundwater is the same for the springs is not clear, but the trends in ^{222}Rn suggest that it is not.

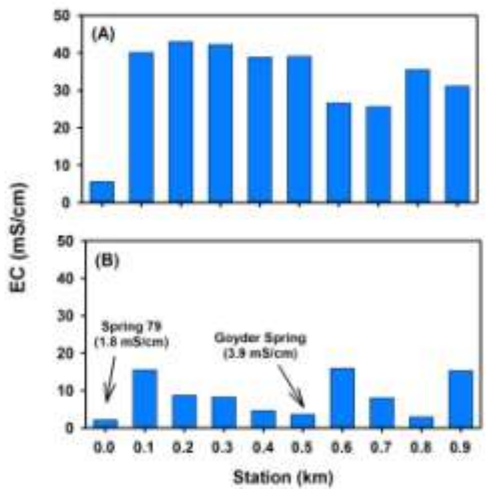


Figure 6.10 Variations in salinity along the test section in (a) shoreline and (b) base of dune groundwater.

6.2.4 OFFSHORE RADIUM FLUXES

D_o could only be estimated using ^{223}Ra, the trends in ^{224}Ra suggesting that this isotope was controlled by processes other than offshore diffusivity (Figure 6.11). Both the constant D_o and the asymptotic increase in

D_o model could fit the ^{223}Ra data equally well (Figure 6.11). However, the relatively low Δ of the asymptotic D_o model (41 – 104 m) indicates that diffusivity would be lower only near the shoreline (<1 km). Thus, a constant D_o model is probably sufficient at a 50 km scale. Inclusion of B in the models only improved the fits slightly (Table 6.6) but the improvements were not statistically signficant. None of the models could fit the monotonic decline in ^{224}Ra activity with distance offshore very well.

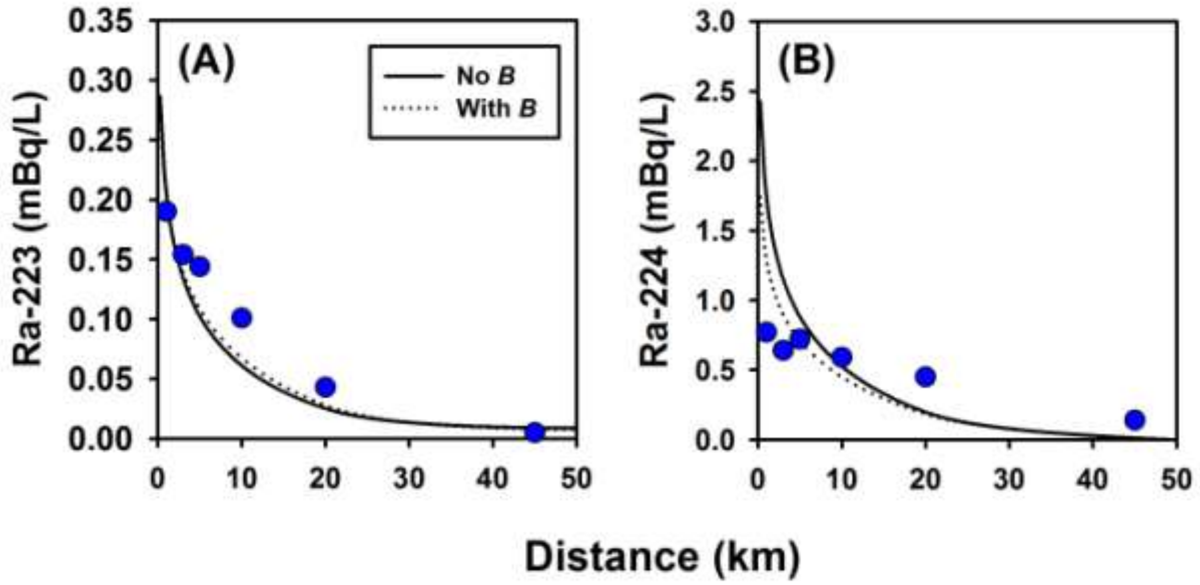


Figure 6.11 Observed (symbols) and predicted (lines) ^{223}Ra and ^{224}Ra activities in the Souther Ocean using a constant D_o model.

The offshore flux for ^{226}Ra was estimated using the mean (396 m^2/s) and 95% confidence intervals for the estimated D_o (303 and 559 m^2/s) using the model with B = 0 (Figure 6.12). The estimated mean F_o was 0.120 Bq/m/s, with a range of 0.092 to 0.170 Bq/m$^/$s. As for the short-lived isotopes, the inclusion of B in the models improved the fits slightly but was not statistically significant. Assuming that the shoreline in the study area is ~25 km in lenght, the ^{226}Ra load to the Southern Ocean ranges between 2300 – 4250 Bq/s.

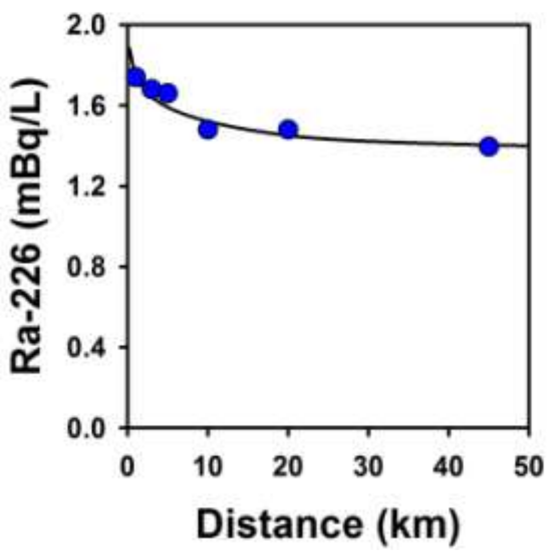


Figure 6.12 Observed (symbols) and predicted (line) ^{226}Ra activity in the Southern Ocean for D_o = 396 m^2/s. The predictions from the models with and without B are indistinguishable.

6.3 Discussion

This preliminary survey for the use of environmental tracers to estimate SGD along the Limestone Coast aimed to answer three basic questions – In this environment can we:

1. Locate inshore and offshore SGD sources using tracers
2. Identify the source of SGD, and
3. Quantify the SGD flux

Several tracers were trialled in order to find the combination that would be most successful and cost effective in this environment. Overall, based on the results of the November 2012 survey and other studies, a partial 'yes' can be given to the three above questions. These and other questions will be explored in more detail in the following.

6.3.1 WHAT TRACERS TO USE?

As carbonate rocks are not typically enriched in uranium and especially thorium (Kraemer and Genereux, 1998), there was the possibility that Limestone Coast groundwater would not be enriched in radon, radium and helium. This was only partially true, with reasonably high radon concentrations found in the beach springs in particular. However, despite the potential for relatively long groundwater flow paths (that is long residence times) there was not a large enrichment in ^{4}He in groundwater. Helium-4 would have been an ideal tracer because the regional groundwater component of SGD would then have been easier to separate from recirculated seawater. Groundwater discharging along the coast may have been low in ^{4}He because it could be principally derived from local, shorter, groundwater flow paths. However, similar ^{4}He values were found in relatively old groundwater (thousands of years old) elsewhere in the region (See Chapter 7). Actually, some sources of relatively old groundwater may be discharging along the coast, as demonstrated by the relatively high ^{4}He values in Cress Creek. Temperature was also higher at the beach springs relative to regional groundwater from the well network. This is consistent with different geological formations contributing groundwater along the coastline, or that a mixture of flow paths are discharging along the coastline.

Overall, the best tracers to use in this environment would be salinity, temperature and radon because these have some contrast between groundwater and seawater and are relatively easy to measure. These tracers can also be measured continuously during ship-borne surveys, which would enable finer scale studies to locate offshore SGD in the future. Interestingly, the stable isotopes of water could also be used as a SGD tracer, especially considering the significant isotopic enrichment common in South Australian coastal seawater.

6.3.2 IS THERE OFFSHORE SGD ALONG THE LIMESTONE COAST?

There was no evidence found in this study for offshore SGD. Herpich (2010) had hypothesised an offshore SGD near 'Ruby Rock' based on the presence of a temperature anomaly near this feature using remote thermal infrared imagery. However, detailed sampling at that location during the November 2012 survey found no evidence for SGD. The patterns in radon and radium activity in seawater also suggest SGD mostly at or near the shoreline (see below). In a homogeneous unconfined aquifer, SGD would be focussed along the coastline because the salt wedge would help focus freshwater discharge there. This may also be possible in a fractured limestone or karstic system if enough conduits are available to enable most of the discharge along the coastline.

However, while no evidence for it was found, offshore SGD may still occur along the Limestone Coast. The offshore surveys where at a coarse scale (km or more) and may have missed offshore springs. The radon footprint of the larger beach springs (~ 100–200 m) suggest that finer scale sampling than the one used here would be required to detect offshore springs. Continuous high-resolution sampling for temperature, salinity and radon may be required to detect offshore SGD along the Limestone Coast. However, a different approach may be required to evaluate offshore SGD, especially when the aquifers underlies a thick permeable seabed. In such cases, mixing between groundwater and seawater could occur in the seabed rather than at the seabed surface (Moore and Wilson, 2005). Thus, offshore groundwater discharge could be evaluated by looking for evidences of freshwater in the seabed rather than in the water column (Evans, 2007).

6.3.3 RADIUM-226 FLUX

The estimated ^{226}Ra flux at the coastline for the Limestone Coast was quite large (0.120 Bq/m/s). In comparison, using the same modelling technique, F_o for ^{226}Ra was 0.020 – 0.061 Bq/m/s in the Great Barrier Reef (GBR) Inner Lagoon (Hancock et al., 2006), 0.011 Bq/m/s in Gulf St Vincent (Lamontagne et al., 2008) and 0.028 Bq/m/s in Bowling Green Bay (Cook et al. 2011). This is consistent with the large offshore diffusivity also found at the Limestone Coast (396 m^2/s using ^{223}Ra), higher than similar estimates for Gulf St. Vincent (29 – 57 m^2/s), the GBR Inner Lagoon (96 – 256 m^2/s) or Bowling Green Bay (132 m^2/s). Thus, the ^{226}Ra flux at the coast could be higher for the Limestone Coast in part because it is an hydrodynamically active environment.

At the scale of the study area (~25 km), the ^{226}Ra load (= F_o·25,000 m) is 2300 Bq/s. There are three possible sources for this radium: surface runoff, recirculated seawater and terrestrial groundwater discharge. Surface runoff can be discarded as a significant source of ^{226}Ra to the coastline. The mean annual discharge is ~3 m^3/s for the creeks and drains in the study area (Wood 2011) and 20 m^3/s for the Glenelg River (SKM, 2003). The two combined would represent a ^{226}Ra load of ~100 Bq/s. Fresh terrestrial groundwater discharge is unlikely to be a major source of radium to the coastline because it is depleted in radium isotopes. For example, ^{223}Ra activity in the surf zone (~0.35 mBq/L) is higher than in fresh groundwater (0.08 – 0.25 mBq/L). Thus, recirculated seawater appears the main source of radium to coastal waters. However, the possibility remains that groundwater discharge that has partially mixed with seawater in the seabed could contribute to the radium flux (Moore and Wilson, 2005). This would be consistent with the elevated radium activities found in brackish and saline groundwater in the region. Better defining the groundwater flux using radium would require independently defining the magnitude of the recirculated seawater flux, which is unknown for Australian coastal waters.

6.4 Conclusion

Along the Limestone Coast, source waters have a different signature in temperature, salinity, stable isotopes of water, radon and radium relative to seawater, but not for helium. Trends in salinity and radon activity along the coastline (that is, in the surf zone or in intertidal groundwater) could be used to map areas of point or diffuse groundwater discharge. Under the right conditions (that is, when seasonal differences in temperature are largest) temperature could be used as well. It is unclear if these tracers could be used in a similar fashion offshore. Instead, looking for evidence of freshwater in the seabed may be more practical. Based on the available evidence, most of the SGD between Port MacDonnell and the Victorian border seems to occur relatively close to the coastline.

Table 6.1 Signature for key tracers in potential source waters for the coastline. Counting errors are ±SE.

SAMPLE	LOCATION (E/N)	TEMPERATURE (°C)	EC (mS/cm)	^{222}Rn (Bq/L)	^{224}Ra (mBq/L)	^{223}Ra (mBq/L)	^{226}Ra (mBq/L)	^{4}He (cc STP/g_{water})
				Surface waters				
Deep Creek	480975/5789122	17.6	3.6	3.4±0.18	–	–	–	4.5e–8
Cress Creek	475060/5788484	18.3	2.0	11±0.50	–	–	–	1.2e–7
8-Mile Creek	482356/5789041	16.4	1.5	1.2±0.07	2.15±0.10	0.13±0.018	1.11±0.06	5.9e–8
Piccaninnie Pd.	495032/5788916	15.6	3.2	2.7±0.14	1.41±0.09	0.085±0.014	3.29±0.13	6.4e–8
Glenelg River	500623/5788616	18.0	13.6	0.29±0.021	1.85±0.09	0.088±0.014	2.55±0.11	4.5e–8
				Coastal springs				
Spring 79–1	496269/5788033	20.5	1.8	7.8±0.39	1.33±0.12	0.12±0.025	2.83±0.10	5.3e–8
Spring 79–2	496239/5788024	20.3	1.7	7.7±0.39	–	–	–	5.7e-8
Goyder Spring	495747/5788097	20.6	3.9	2.1±0.12	–	–	–	8.0e–8
				Regional groundwater				
MAC100	467450/5793255	17.3	1.2	2.3±0.13	4.37±0.28	0.79±0.11	7.18±0.33	5.6e–8
CAR059	482442/5790218	17.1	2.4	5.4±0.28	4.36±0.27	1.85±0.15	26.1±0.8	5.8e–8
CAR060	482440/5790216	17.8	2.9	1.5±0.08	4.63±0.18	0.207±0.027	2.67±0.14	7.3e–8
CAR061	482437/5790211	18.2	45.6	3.8±0.20	41.3±1.08	2.79±0.21	22.1±0.70	4.4e–8
CAR065	489139/5790625	19.2	0.78	0.69±0.044	2.75±0.15	0.237±0.033	2.46±0.16	7.0e–8
CAR066	482004/5792811	17.0	0.81	1.3±0.08	2.15±0.10	0.064±0.009	1.53±0.070	8.0e–8
				Intertidal groundwater				
Well 1	(near Well 3)	15.4	48.6	0.92±0.056	12.7±0.70	1.70±0.19	2.25±0.12	5.3e–8
Well 2	(near Well 3)	19.3	47.9	1.1±0.06	13.2±0.59	1.82±0.16	1.52±0.07	5.1e–8
Well 3	485457/5789632	14.3	4.3	1.1±0.07	0.48±0.07	0.080±0.022	0.198±0.023	5.4e–8

Table 6.2 Major ion chemistry and stable isotope of water in potential source waters for the coastline.

SAMPLE	Na^{+} (meq/L)	K^{+} (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	Cl^{-} (meq/L)	SO_4^{2-} (meq/L)	Alkalinity (meq/L)	NO_3^{-} (meq/L)	δ^2H (‰ V-SMOW)	$\delta^{18}O$ (‰ V-SMOW)
Surface waters										
Deep Creek	19.91	0.34	4.12	5.42	25.11	2.71	4.85	0.27	-24.94	-4.49
Cress Creek	9.00	0.13	3.83	3.29	11.57	1.33	5.11	0.21	-25.24	-4.58
8-Mile Creek	5.78	0.09	3.72	2.43	7.33	0.81	4.86	0.42	-24.77	-4.55
Piccaninnie P.	15.83	0.27	4.18	4.63	20.31	2.08	5.36	0.21	-25.57	-4.52
Glenelg River	89.57	1.53	5.74	20.82	112.84	11.88	2.65	0.04	-9.93	-1.33
Coastal springs										
Spring 79	5.78	0.10	3.80	2.51	8.18	0.84	5.56	0.17	-25.28	-4.66
Goyder Spring	17.35	0.33	4.24	4.96	23.98	2.50	5.41	0.21	-24.41	-4.53
Regional groundwater										
MAC100	5.13	0.13	3.72	2.09	6.49	1.02	5.17	0.02	-25.90	-4.60
CAR059	14.13	0.32	4.71	3.58	18.62	1.65	4.96	0.29	-27.05	-4.70
CAR060	16.17	0.32	4.36	4.28	22.28	2.29	4.78	0.39	-26.90	-4.66
CAR061	416.09	10.20	21.36	87.24	507.76	58.33	2.35	0.05	5.10	0.21
CAR065	3.26	0.35	0.93	2.44	2.71	0.44	4.87	0.01	-26.20	-4.98
CAR066	2.40	0.12	2.86	1.88	2.40	0.29	5.04	0.42	-25.70	-4.87
Intertidal groundwater										
Well 1	320.00	6.14	13.72	69.55	423.13	47.92	3.63	0.10	-3.60	-0.63
Well 2	300.43	5.68	13.82	68.64	423.13	45.83	4.29	0.12	-4.49	-0.96
Well 3	12.04	0.42	0.87	3.16	10.44	2.71	5.57	0.00	-26.62	-4.76

Table 6.3 Major ions and stable isotopes in seawater along the Blue Transect.

SAMPLE	lab EC (mS/cm)	Na^+ (meq/L)	K^+ (meq/L)	Ca^{2+} (meq/L)	Mg^{2+} (meq/L)	Cl^- (meq/L)	SO_4^{2-} (meq/L)	Alkalinity (meq/L)	NO_3^- (meq/L)	δ^2H (‰ V-SMOW)	$\delta^{18}O$ (‰ V-SMOW)
Surf	57.3	491.30	10.67	22.41	116.05	535.97	58.33	2.42	0.14	5.48	0.81
Blue – 1 km	58.0	433.48	7.88	18.26	95.47	564.17	62.50	2.39	0.10	5.95	0.79
Blue – 3 km	58.1	422.61	7.90	17.86	93.00	564.17	62.50	2.38	0.11	6.26	0.69
Blue – 5 km	58.1	495.65	10.84	22.95	118.52	564.17	62.50	2.38	0.02	5.72	0.89
Blue – 10 km	57.9	456.52	8.52	19.41	101.23	564.17	62.50	2.38	0.08	4.67	0.79
Blue – 20 km	57.7	456.52	8.49	19.31	99.59	564.17	62.50	2.39	0.02	5.17	0.77
Blue – 45 km	57.4	439.13	8.11	18.86	97.12	564.17	60.42	2.38	0.09	4.15	0.55

Table 6.4 Radiogenic tracers along the Blue Transect, including a vertical profile at the 5-km Station. The two ^{4}He samples at the 5-km Station 16 m were from two diffusers left to equilibrate overnight near the seafloor. All the other samples are for surface seawater unless otherwise shown. Errors ±SE.

SAMPLE	LOCATION (E/N)	SALINITY (PSU)	^{222}Rn (Bq/L)	^{224}Ra (mBq/L)	^{223}Ra (mBq/L)	^{226}Ra (mBq/L)	^{4}He (cc STP/g_{water})
Surf (Brown Bay)	485457/5789632	35.60	<0.005	2.48±0.16	0.346±0.047	1.65±0.07	6.5e–8
1-km	492677/5787425	36.03	<0.005	0.77±0.06	0.190±0.023	1.74±0.11	5.4e–8
3-km	492513/5785445	35.97	<0.005	0.64±0.05	0.154±0.019	1.68±0.08	5.1e–8
5-km (surface)	492350/5783466	35.99	<0.005	0.72±0.05	0.144±0.018	1.66±0.09	5.5e–8
5-km (4 m)	492350/5783466	35.97	0.012±0.003	–	–	–	–
5-km (8 m)	492350/5783466	36.04	0.007±0.004	–	–	–	–
5-km (12 m)	492350/5783466	36.02	<0.005	–	–	–	–
5-km (16 m)	492350/5783466	35.96	0.015±0.004	–	–	–	3.7/4.0e–8
10-km	491943/5778519	35.76	<0.005	0.59±0.04	0.10±0.012	1.48±0.06	–
20-km	491128/5768626	35.53	<0.005	0.45±0.03	0.043±0.008	1.48±0.06	6.3e–8
45-km	489094/5743908	35.54	<0.005	0.14±0.02	0.005±0.002	1.40±0.07	5.1e–8

Table 6.5 Surface salinity and radon activity at the Green transects.

SAMPLE	GREEN – 2 KM			GREEN – 4 KM		
	LOCATION (E/N)	EC (mS/cm)	^{222}Rn (Bq/L)	LOCATION (E/N)	EC (mS/cm)	^{222}Rn (Bq/L)
1 km	496973/5785943	45.66	0.011±0.004	496947/5783952	45.31	0.011±0.003
2 km	496003/5786070	45.95	0.012±0.003	495989/5784078	45.31	0.011±0.003
3 km	495032/5786256	46.02	<0.005	495009/5784213	45.52	0.012±0.004
4 km	494044/5786334	46.09	0.005±0.004	494031/5784347	45.74	0.007±0.003
5 km	493054/5786332	46.38	0.009±0.004	493039/5784302	45.52	0.011±0.003
6 km	492088/5786494	46.45	<0.005	492074/5784471	45.59	0.008±0.004
7 km	491178/5786868	46.45	0.006±0.003	491166/5784851	45.66	0.011±0.003
8 km	490213/5786841	46.16	0.006±0.004	490242/5784640	45.74	0.009±0.004
9 km	489334/5786477	46.52	0.013±0.004	489286/5784627	45.59	–
10 km	488349/5786555	46.38	0.009±0.004	488303/5784510	45.66	0.007±0.004

Table 6.6. Offshore diffusivity estimates for the Southern Ocean for two diffusivity models, with and without a benthic flux (*B*). The likelihood ratio tests (*R*) evaluated whether the models with an increased number of variables were statistically better at explaining the data. ns – not statistically different.

Model Number	D_o (m^2/s)	Δ (m)	r^2	L	*R* test
			No *B*		
Ra-223					
1	396	–	0.942	–13.073	–
2	435	104	0.945	–13.073	0^{ns}
Ra-224					
3	~2000	–	0.835	4.733	–
4	625	6	0.799	4.057	1.35^{ns}
			With *B*		
Ra-223					
5	215	–	0.959	–14.175	–
6	215	41	0.959	–14.175	0^{ns}
Ra-224					
7	~2000	–	0.860	1.481	–
8	625	6	0.822	11.358	0^{ns}

7 The influence of geological faults on groundwater flow

Chris Turnadge, Stanley Smith and Glenn Harrington

Groundwater supplies in the Lower South East region of South Australia are sourced primarily from both the Pleistocene Bridgewater Formation and the Tertiary Gambier Limestone aquifer. It is known that groundwater predominantly flows in a westerly to south-westerly direction through the Gambier Basin and toward the southern coast. The influence of two significant geologic faults, the Tartwaup and Kanawinka faults (Figure 7.1a), upon the regional groundwater flow gradient has also been noted from potentiometric mapping (Figure 7.1b); both faults appear to impede the flow of water.

(a) (b)

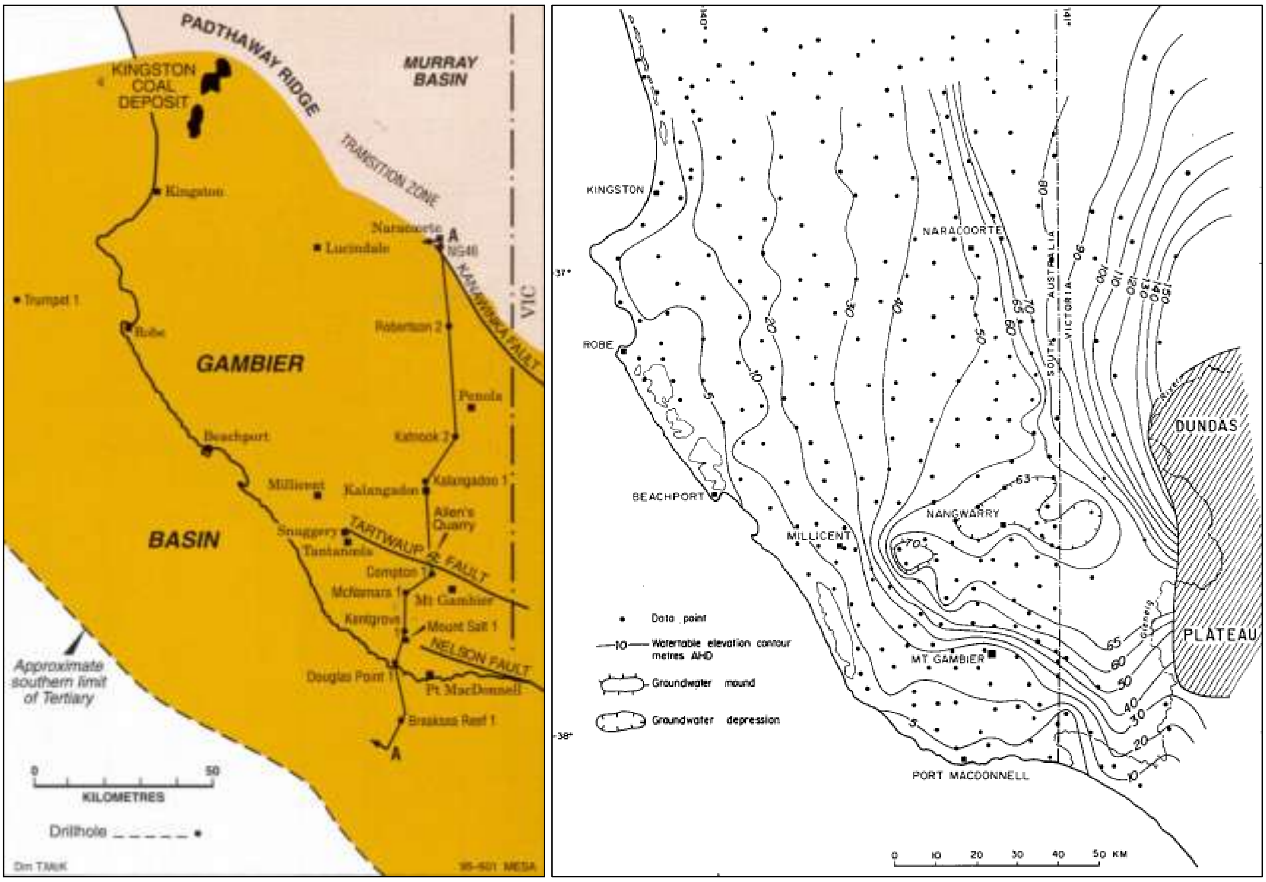
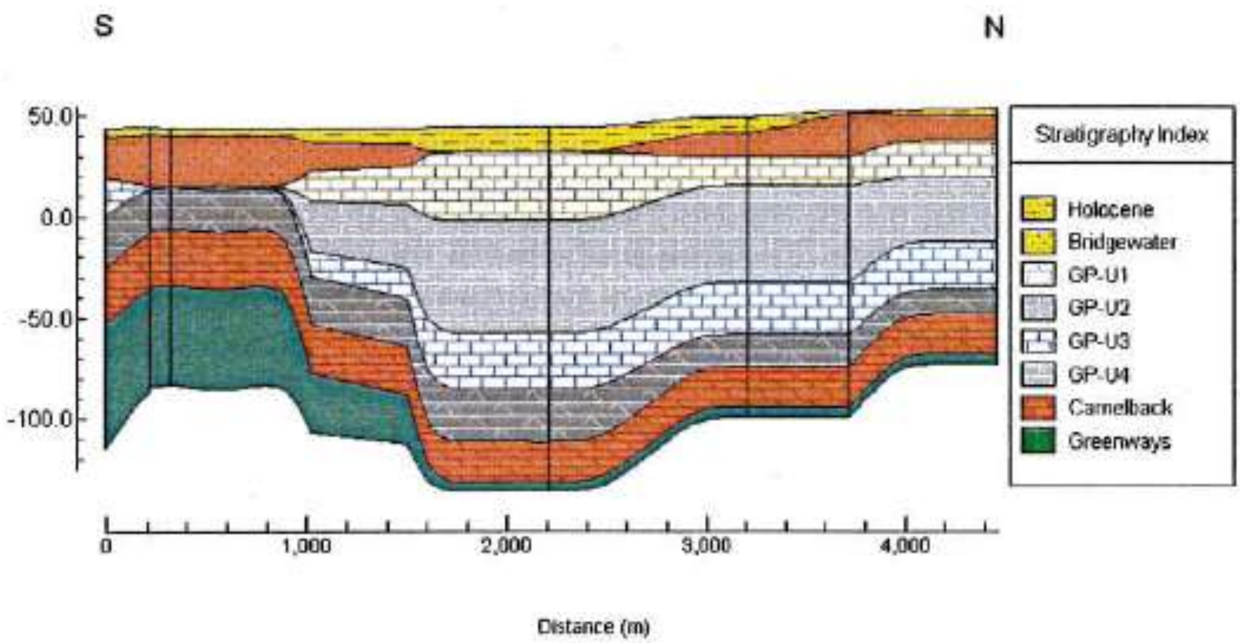


Figure 7.1 The study area showing (a) locations of the Tartwaup and Kanawinka faults in the Tertiary age Gambier Basin (Drexel and Dreiss, 1995) and (b) watertable contours for the unconfined Gambier Limestone aquifer (Love et al., 1993).

Recently, the Department of Environment, Water and Natural Resources (DEWNR) undertook localised studies at transects spanning either fault. These involved the drilling of deep (i.e. >100 m depth) observation wells and the use of borehole geophysical tools. From the data obtained, the influence of the faults upon the local stratigraphy was identified, as depicted in Figure 7.2.

(a)



(b)

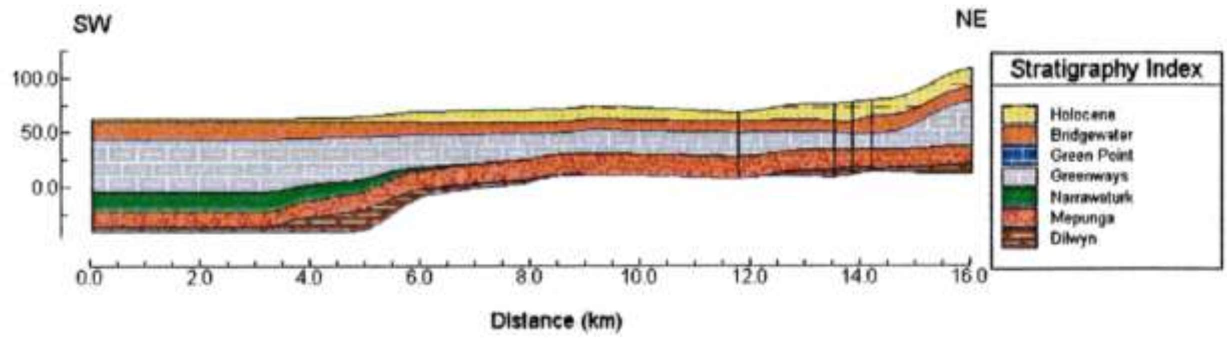


Figure 7.2 Vertical cross-sections interpreted from stratigraphic log data for (a) the Tartwaup fault transect and (b) the Kanawinka fault transect (Lawson et al., unpublished).

For the Tartwaup fault transect, the impediments to groundwater flow may be seen in the pinching out of the Bridgewater Formation at approximately *x*=2400 m and the Green Point Members 1 to 3 at *x*=1000 m. Similar impediments to flow across the Kanawinka fault are not as obvious; however, it is hypothesised that similar geological controls may exist between *x*=14 km and *x*=16 km but have not yet been directly observed. The aim of the present study was to sample groundwater wells located along the two transects for chemical and isotopic constituents in order to provide further insight into the dynamics of flow across the faults. Numerical modelling of groundwater flow and age was also undertaken in order to make predictions of the likely variability of groundwater ages (and therefore environmental tracer concentrations) between hydrostratigraphic units. A two dimensional vertical cross-sectional model was developed for each transect and used to model groundwater flow as well as the transport of groundwater age.

7.1 Methods

7.1.1 ENVIRONMENTAL TRACERS IN GROUNDWATER

Sampling of groundwater wells along the Tartwaup and Kanawinka fault transects was undertaken in November 2012. Wells were sampled for major ion chemistry, stable isotope (^{2}H and ^{18}O) composition, and for concentrations of the following commonly-used age dating tracers: chlorofluorocarbon (i.e. CFC-11 and

CFC-12), sulphur hexafluoride (SF_6), carbon-14 (^{14}C) and ^4He. Details and locations of wells sampled are provided in Table 7.1 and Figure 7.3.

Table 7.1 Details of sampled fault transect wells

UNIT NO	OBSWELL NO	LATITUDE (DECIMAL DEGREES)	LONGITUDE (DECIMAL DEGREES)	TOTAL WELL DEPTH (M)	WELL SCREEN EXTENT (M)	HYDROSTRATI-GRAPHIC UNITS INTERSECTED*
Tartwaup fault transect wells						
7022-10574	GAM262	-37.8217306	140.9341093	102	92	GP1–4, CB
7022-10573	GAM261	-37.8325716	140.9309632	149	146	GP1–4, CB
7022-10572	GAM260	-37.8415851	140.9314776	165	163	GP1–4, CB
7022-128	GAM079	-37.8478040	140.9313355	35	21	GP1
7022-10687	GAM257	-37.8594204	140.9287214	150	148	GP1–4, CB
7022-10688	GAM258	-37.8614032	140.9284353	150	148	GP1–4, CB
7022-139	GAM078	-37.8964472	140.9224397	35	18	GP1
Kanawinka fault transect wells						
7023-7134	CMM093	-37.2570133	140.9617708	76	61	GW
7023-7259	-	-37.2673277	140.9447349	12	10	GW
7023-7133	CMM092	-37.2691742	140.9419139	66	30	GW
7023-7135	CMM094	-37.2844908	140.9285904	42	4	GW
7023-5280	-	-37.3673119	140.8407254	75	25	GP1–4, CB

* CB = Camelback Formation; GP1= Green Point Formation subunit 1; GP1–4 = Green Point Formation subunits 1 to 4; GW = Greenways Formation

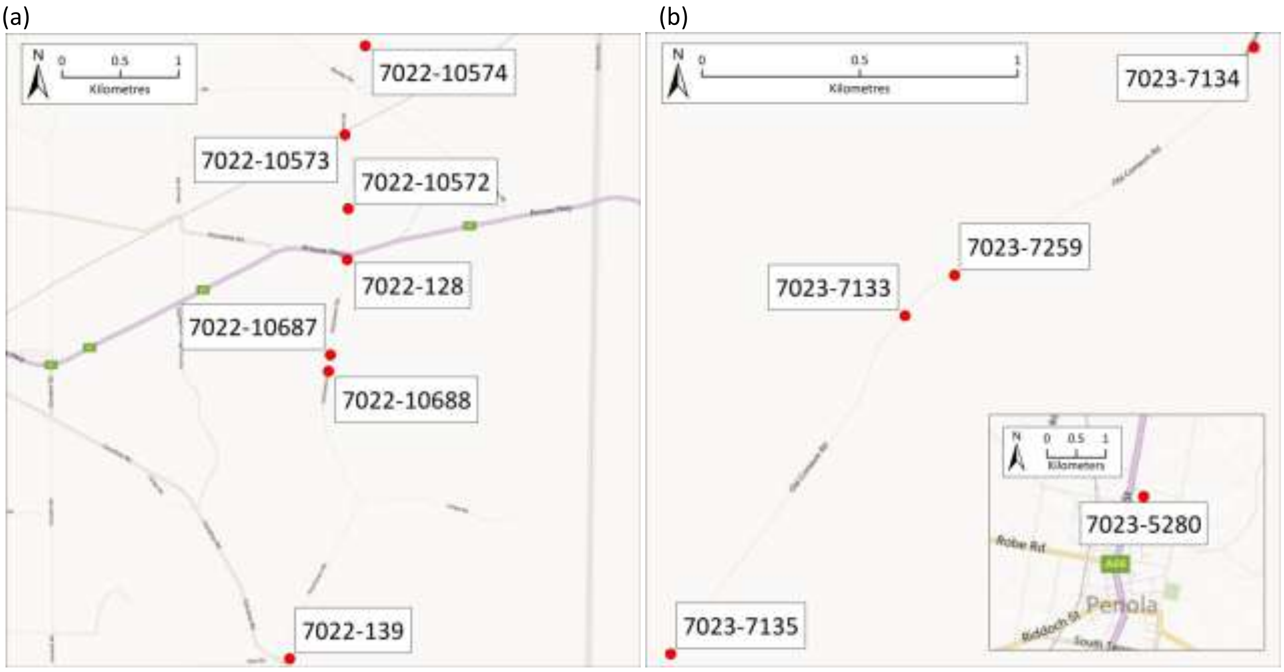


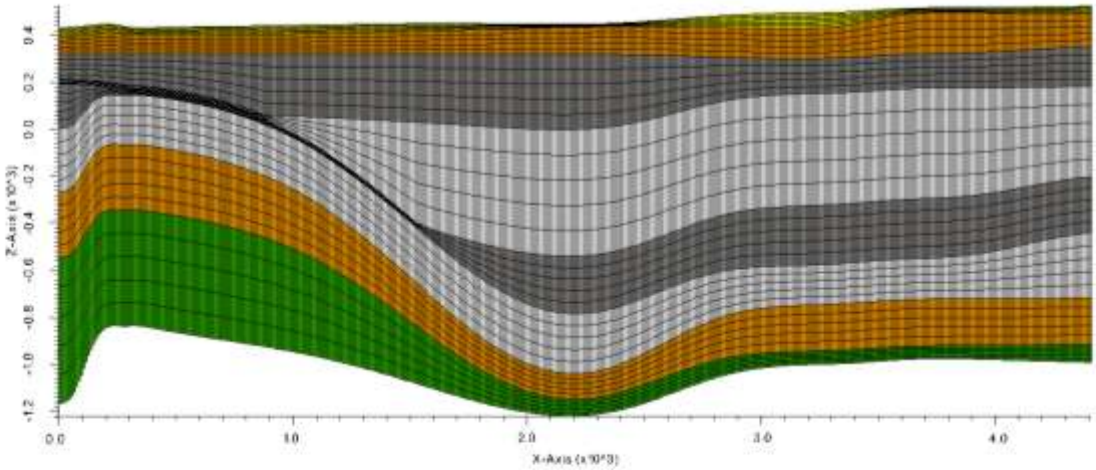
Figure 7.3 Locations of sampled wells for the (a) Tartwaup and (b) Kanawinka fault transects

Prior to sampling, each well was purged of at least three casing water volumes using either a truck-mounted Legra pump (at approximately 5 L/second) or a Grundfos portable MP-1 pump (at approximately 0.1 L/second). For wells that were pumped using the Legra pump, standing water levels were recorded prior to pumping. For wells that were pumped using the MP-1 pump, standing water levels were not recorded due to a damaged water level meter. Electrical conductivity, pH and groundwater temperature were measured at the end of a discharge pipe at each well using a TPS 90-FL field probe. Alkalinity was measured at each well using a Hach field alkalinity kit. Water samples were collected for major ion and stable isotope analysis in 50 mL plastic vials and 10 mL McCartney bottles respectively. Cation samples were acidified with nitric acid in the field. Samples for ^{14}C analysis were collected in 3x1.25 L plastic bottles. Samples for CFC analysis were collected in 125 mL glass bottles after being filled from a high density nylon hose whilst submerged in a metal bucket. Samples for SF_6 analysis were collected in a 1 L glass Winchester bottle. Samples for dissolved noble gas analysis were collected using a mixture of diffusion cells and copper tubes. Major ion chemistry analyses were performed by the Analytical Services Unit of CSIRO Land and Water at Glen Osmond, SA. Carbon-14 analyses were performed by the Accelerator Mass Spectrometry laboratory of the Australian Nuclear Science and Technology Organisation at Canberra, ACT. All other analyses were performed by the Isotope Analysis Service of CSIRO Land and Water at Glen Osmond, SA.

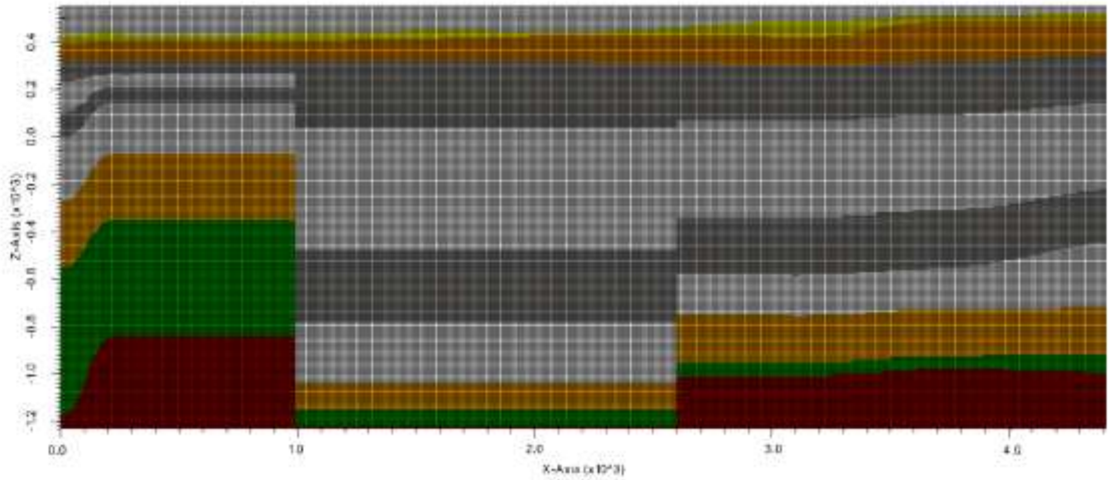
7.1.2 GROUNDWATER FLOW MODELLING

Groundwater flow was modelled using the finite difference code MODFLOW-2000 (Harbaugh et al., 2000). The stratigraphic detail at each transect was interpolated from stratigraphic logs provided by Lower South East DEWNR staff (JS Lawson, pers. comm. 06/02/13) using the RockWorks software package (http://www.rockware.com). These data were subsequently used to provide layer geometry information to the flow and transport models, as depicted in Figure 7.4a and Figure 7.4b. An alternative conceptual model of the Tartwaup fault transect stratigraphy was also considered (Figure 7.4c). Based upon the available stratigraphic logs, as well as knowledge of downthrow on the downgradient side of the Tartwaup fault (Smith et al., 1995), a graben fault structure was proposed featuring abrupt changes in stratigraphy. This facilitated comparisons to modelling results produced using the smoothly-varying stratigraphy depicted in Figure 7.4a. Vertical faults were represented at approximately x=980 m and x=2550 m. The hydrostratigraphic unit underlying the Greenways Member was assumed to be the Mepunga Formation.

(a)



(b)



(c)

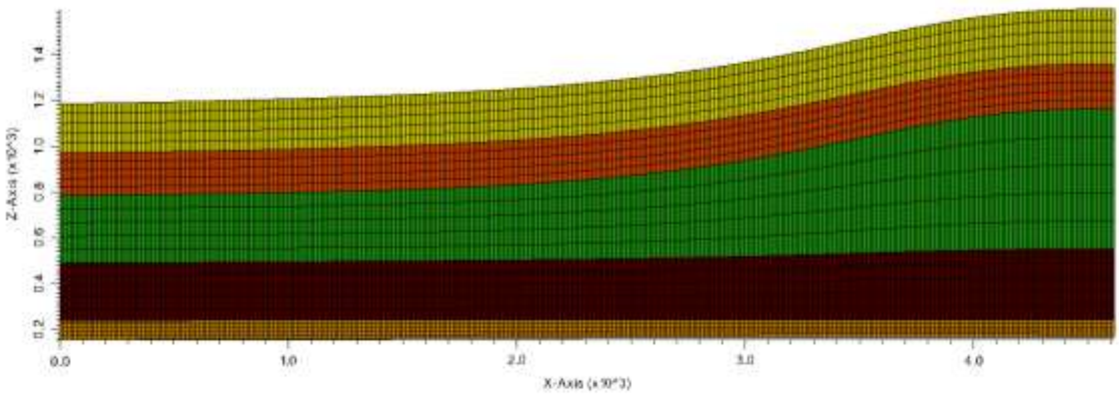


Figure 7.4 Grid discretisation, including stratigraphic layers, used in (a) Tartwaup fault transect model, (b) alternative Tartwaup model and (c) Kanawinka transect model; colours correspond to hydrostratigraphic units shown previously in Figure 7.2; *Z*-axis dimensions are exaggerated by factors of 10, 10, and 15 respectively for display purposes

A simplification used in the present modelling is that the base of the deepest stratigraphic unit is impermeable. This assumption is made on the basis of incomplete knowledge of unit thickness; our current knowledge is limited by the maximum depths of well completion, which are approximately 150 and 76 m for the Tartwaup and Kanawinka fault transects, respectively (Table 7.1). This assumption results in groundwater flow parallel to the base of the deepest modelled hydrostratigraphic unit; in reality, it is possible that upward flow does occur.

Transmissivity (*T*) values were assigned to hydrostratigraphic units in accordance with the following methodology. Various State Government department reports have reported or assigned transmissivity and/or hydraulic conductivity (*K*) values to the hydrostratigraphic units of the Gambier Basin. Numerical flow modelling by Brown (2000) assigned log(*K*) values ranging from 0 to +2 to the Gambier Limestone aquifer. The confining clay/marl layer was assigned log(*K*) values ranging from -9 to +2. The Dilwyn Sand aquifer was assigned log(*K*) values of 0 to +2. Numerical flow modelling by Stadter and Yan (2000) assigned log(*K*) values of +1 to +2 to the Gambier Limestone aquifer. The Dilwyn Sand aquifer was assigned log(*K*) values of -1 to +1. Mustafa and Lawson (2002) reviewed a large number of published *T* values based on hydraulic testing of the Gambier Limestone aquifer and reported a range of 35–560 m^2 /day, with most values in the range of 200–500 m^2/day. Harrington et al. (2008) reported that permeability testing by Love and Stadter (1990) determined log(*K*) values of -7 to -3 for the Tertiary aquitard. Harrington et al. also state that past hydraulic testing determined a transmissivity range of 200 to more than 10,000 m^2/day for the Gambier Limestone aquifer. Discussions with Lower South East DEWNR staff confirm that *T* values for the Gambier Limestone aquifer could likely range from 300–400 m^2/day for more transmissive subunits and from 100–200 m^2/day for less transmissive subunits (JS Lawson, pers. comm. 19/02/13). Representative transmissivity ranges for other units estimated on the basis of field testing experience include the Bridgewater Formation (500–600 m^2/day), Green Point Member (100–400 m^2/day), Camelback Member (500–5000 m^2/day), Greenways Member (100–200 m^2/d), Mepunga Formation (50–100 m^2/day) and Dilwyn Formation (1500–2000 m^2/day; JS Lawson, pers. comm. 27/03/13).

The various parameter ranges described above were used to inform the specification of first–order transmissivity estimates for each hydrostratigraphic unit of each modelled transect; these values are summarised in Table 7.2.

Table 7.2 First–order estimates of transmissivity used in fault transect models

HYDROSTRATIGRAPHIC UNIT	TRANSMISSIVITY (m^2/d)
Quaternary sand/clay	20
Bridgewater Formation	500
Green Point unit 1	300
Green Point unit 2	100
Green Point unit 3	300
Green Point unit 4	100
Camelback Member	500
Greenways Member	100
Mepunga Formation	50
Dilwyn Member	1500

Overlying the Bridgewater Formation is a discontinuous layer composed of unconsolidated fine sand (0.1-0.3 mm grain size) overlaying a clay layer (JS Lawson, pers. comm. 27/03/13). In the present modelling, and for purposes of simplicity, this layer was treated as confined and assigned a representative transmissivity of 20 m/day. The sand/clay layers represented in the models range in thickness from 0.5–3.0 m, which yield hydraulic conductivities of 40–7 m/day respectively; these values are consistent with those of a fine to coarse sand (Spitz and Moreno, 1996).

Generalised head (GH) boundary conditions, which allow both hydraulic heads and flow velocities to vary at a model boundary, were applied at both lateral extents of the flow model. GH boundary conditions require the specification of a conductance term, which is essentially a fitting parameter composed of a distant hydraulic head value; the distance to the distant observation; and transmissivity between the model boundary and the distant observation. Choices of hydraulic head values and distances from transect boundaries were informed after identifying adjacent wells using the DEWNR WaterConnect website (https://www.waterconnect.sa.gov.au). For the Tartwaup fault transect model, the boundary conditions represent an upgradient hydraulic head of 60 mAHD located approximately 4 km upgradient from well 7022-10574 and a downgradient hydraulic head of 15 mAHD, located approximately 4 km downgradient from well 7022-139. Similarly, for the Kanawinka fault transect model, the boundary conditions represent an upgradient hydraulic head of 95 mAHD located approximately 2 km upgradient from well 7023-7134 and a downgradient hydraulic head of 10 mAHD located approximately 9 km downgradient from 7023-5280.

The conductance values used in the GH boundary conditions were chosen so that the hydraulic gradients along the modelled transects were consistent with those observed. Reference elevations for transect wells located on model boundaries were not available from the WaterConnect database, so proxy elevations (in metres above sea level (mASL)) were obtained from the AUSLIG one-second resolution digital elevation model (DEM) dataset instead. The Tartwaup fault transect features a head difference of about 27 m between observation wells 7022-10574 (49 mAHD) and 7022-10688 (22 mAHD). The distance between these two wells is approximately 4400 m, so the hydraulic gradient is approximately 0.006. The Kanawinka fault transect features a head difference of about 20 m between observation wells 7023-7134 (92 mAHD) and 7023-7135 (72 mAHD). The distance between these two wells is also approximately 4400 m, so the hydraulic gradient is approximately 0.005.

GH boundary condition transmissivity terms were adjusted so that boundary hydraulic heads and hydraulic gradients across the models were consistent with the observations described. This resulted in a conductance value of 1.5 m^3/day for the Tartwaup fault transect model, which infers a bulk upgradient transmissivity of 6600 m^2/day. Assuming an average total thickness of 150 m results in a bulk upgradient hydraulic conductivity of 44 m/day. GH boundary condition conductivity term adjustments for the Kanawinka fault transect model resulted in a conductance value of approximately 5 m^3/day, which infers a bulk upgradient transmissivity of 22,000 m^2/day. Assuming an average total thickness of 150 m results in a bulk upgradient hydraulic conductivity of 147 m/day.

It should be noted, however, that this process of determining GH boundary condition conductance values is dependent upon the transmissivity values specified for each hydrostratigraphic unit in the model. Future work to further constrain transmissivity and storativity values would likely require GH boundary conductance values to be updated accordingly.

7.2 Results and discussion

7.2.1 ENVIRONMENTAL TRACERS IN GROUNDWATER

To assist the interpretation of results, wells have been ordered in terms of position along the groundwater flow path at each fault transect.

Major ion chemistry

Results of major ion chemistry analyses as well as measured laboratory parameters are presented in Table 7.3 and Table 7.4.

Table 7.3 Measured laboratory and field parameters and major ion chemistry analyses for wells located along the Tartwaup fault transect

UNIT NO.	lab EC µS/cm	field EC µS/cm	lab pH	field pH	lab Alk meq/L	field Alk meq/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO_4 mg/L
7022-10574	1149	1092	7.41	6.99	6.07	5.7	131.00	10.60	65.20	0.68	140.00	67.00
7022-10573	996	950	7.44	6.76	6.01	5.9	115.00	10.70	56.40	0.76	110.00	40.00
7022-10572	1121	1057	7.53	6.75	6.90	7.0	81.80	29.20	88.90	3.78	150.00	7.50
7022-128	952	950	7.74	6.97	6.02	5.6	94.30	10.70	62.40	2.20	120.00	15.00
7022-10687	1176	1167	7.55	8.93	7.10	6.7	77.00	30.90	99.70	4.15	160.00	10.00
7022-10688	1191	1147	7.54	7.16	6.96	6.9	71.80	34.50	103.00	7.00	170.00	18.00
7022-139	818	814	7.68	10.85	5.97	5.8	64.80	22.60	49.30	2.09	79.00	9.60

Table 7.4 Measured field laboratory and parameters and major ion chemistry analyses for wells located along the Kanawinka fault transect

UNIT NO.	lab EC µS/cm	field EC µS/cm	lab pH	field pH	lab Alk meq/L	field Alk meq/L	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	Cl mg/L	SO_4 mg/L
7023-7134	1749	1660	7.33	7.34	7.42	7.5	146.00	21.10	157.00	1.84	300.00	40.00
7023-7259	1365	1419	7.81	6.94	7.09	9.0	121.00	21.40	111.00	1.50	220.00	17.00
7023-7133	944	919	7.33	6.93	4.49	4.4	80.10	18.80	66.50	0.98	150.00	12.00
7023-7135	1393	1417	7.66	7.36	5.67	5.0	73.70	28.20	145.00	3.06	270.00	8.50
7023-5280	1414	1361	7.49	7.12	6.07	5.9	96.70	23.40	129.00	3.12	250.00	16.00

Spatial trends are not apparent for EC, pH or alkalinity along the Tartwaup fault transect (Table 7.3). Calcium concentrations appear to decrease along the flow gradient; however, no other clear trends are apparent for other ionic species. Spatial trends are also not apparent for EC, pH or alkalinity along the Kanawinka fault transect (Table 7.4). Calcium concentrations again appear to decrease along the flow gradient; however, no other trends are apparent for other ionic species. Bilinear plots of major ions versus chloride (in which all values are in molar units) were produced using data from both fault transects. The consistent lack of trends in ionic chemistry may be reflective of the extensive (i.e. > 100m) production zones of many wells sampled (summarised in Table 7.1). Such conditions can result in mixing of waters from a range of depths and hydrostratigraphic units. Major ion chemistry results were also plotted as Piper diagrams and are presented in Figure 7.5.

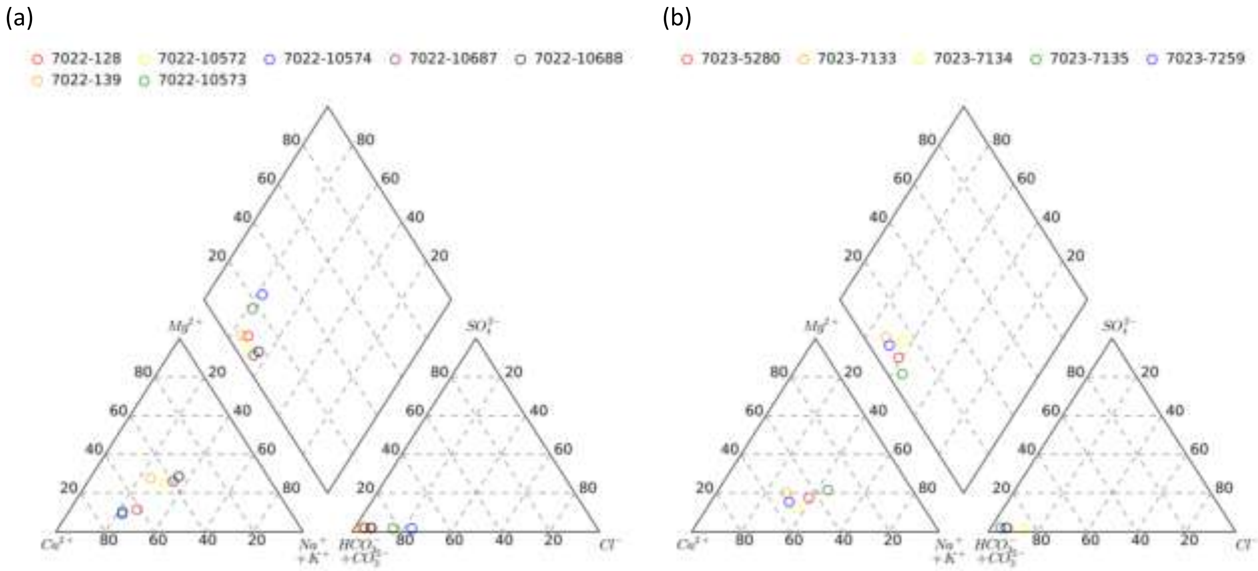


Figure 7.5 Piper diagrams based on major ion chemistry data from (a) Tartwaup and (b) Kanawinka fault transect wells.

The general chemical composition of the sampled groundwater from both the Tartwaup and Kanawinka fault transects appears to be of calcium-bicarbonate type. Bicarbonates accounted for >80% of anion species in all but one well sampled, which is consistent with expectation for a limestone aquifer. Sulphate accounted for approximately 2% of anion species at all sampled wells, while the proportion of chloride varied between 3–23%. Greater variability was observed in cation species, which were typically dominated by calcium (35–60% of cation species), while proportions of sodium/potassium and magnesium were generally 20–40% and 10–30% respectively.

Stable isotopes

Plots of δ^2H and δ^{18}O composition are presented in Figure 7.6. For comparison purposes, the global meteoric water line (GMWL) and the Adelaide and Melbourne local meteoric water lines (LMWL; Crosbie et al., 2012) are also plotted. A stable isotope dataset for rainfall (*n*=36) provided by Lower South East DEWNR staff (S Mustafa, pers. comm. 14/02/13) is also presented.

Sampled stable isotope data are consistent with the range of regional groundwater stable isotope data presented in Chapter 6 (Figure 6.4). Stable isotope data for the Tartwaup fault transect are generally located in the vicinity of the GMWL, with two data points (7022-10572 and 7022-10688) located to the right of the GMWL. The GMWL itself lies to the right of both Australian LMWLs. Stable isotope data for the Kanawinka fault transect are generally located in the vicinity of the Melbourne LMWL, with two points located below the GMWL. Both sampled fault transect datasets are relatively consistent with the existing Lower South East rainfall dataset, although some data points feature depleted ^{18}O values, particularly the Tartwaup dataset. Comparisons are hindered somewhat by uncertainty associated with the source of the samples. Due to the large screen extents of many of the sampled wells, it is unclear which depths and/or hydrostratigraphic units these samples represent; consequently, estimations of their original recharge location are also confounded. When compared with stable isotope results from coastal groundwater bores (Section 6.2.1), the fault zone analyses have a greater spread and are slightly more enriched in ^{18}O.

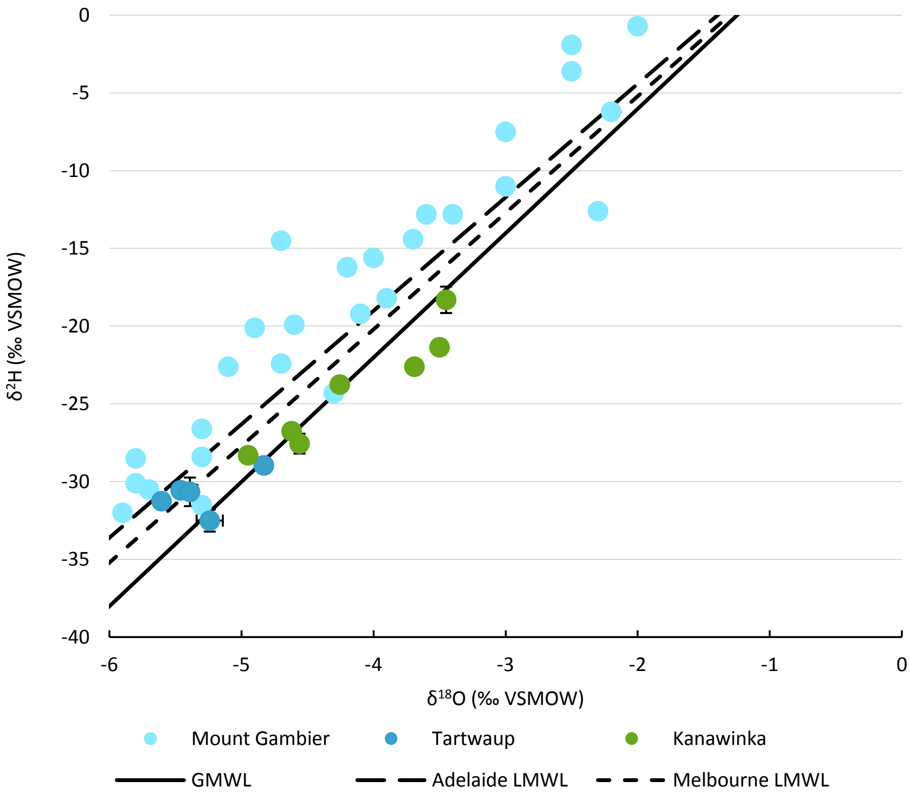


Figure 7.6 Stable isotope data from Tartwaup and Kanawinka fault transect wells, also showing local stable isotope data recorded in the Mount Gambier area, as well as LMWLs for Adelaide, SA, and Melbourne, Vic, and the GMWL.

Age dating tracers

Results of age dating tracer sampling are summarised in Figure 7.7. No clear trends in isotopic concentrations across either the Tartwaup or Kanawinka fault transects are discernible. The absence of linear gradients suggests that it is possible that mixing between aquifers is being facilitated by both faults. Carbon-14 results for the Tartwaup fault transect indicate a general increase in age along the groundwater flow path and with increasing depth of aquifer sampled. Carbon-14 results for the Kanawinka fault transect do show a linear, but poorly constrained, decrease in percent modern carbon (pMC) along the groundwater flow path (Figure 7.7). The absolute difference in age is 15700 years, yielding a horizontal groundwater velocity of 1.0 m/year assuming no mixing of old and young waters.

Sampled SF_6 concentrations for wells 7022-10572, -10573, -10573, -10687, and -10688 were in excess of anticipated concentrations and suggest an additional non-atmospheric source of SF_6. This may be due to input from the volcanic and igneous basement rocks (Busenberg and Plummer, 2000) that (indirectly) underlie the Gambier Limestone. Alternatively, this may have been due to inadvertent contamination by either the truck-mounted pumped used to purge the wells prior to sampling, or by geophysical testing undertaken by a third party in the days prior to sampling. A lack of correlation between these activities and the contaminated samples appears to suggest that contamination by volcanic rock is the more likely hypothesis. It should also be noted that, as stated previously, interpretation of isotopic results is hindered by the uncertainty associated with the source of the samples. Due to the large screen extents of many of the sampled wells, it is unclear which depths and/or hydrostratigraphic units these samples represent.

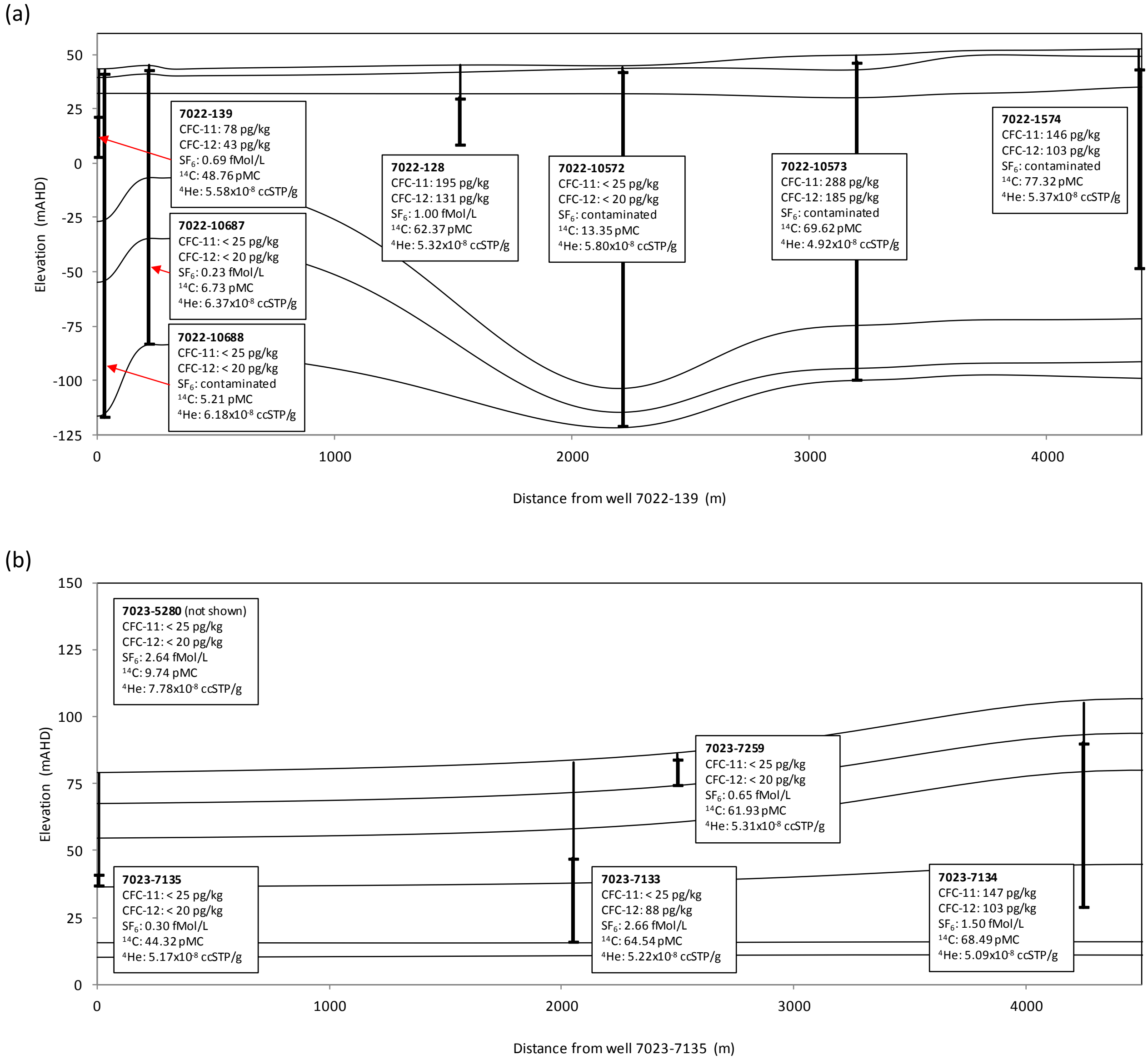


Figure 7.7 Vertical cross-sections summarising isotope sampling results for (a) Tartwaup and (b) Kanawinka fault transect wells; surface and hydrostratigraphic unit elevations and well screen extents are provided for context only.

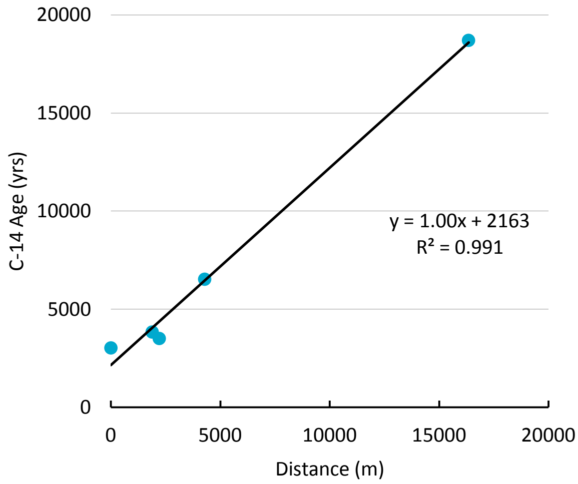


Figure 7.8 Carbon-14 age trend from north to south along the Kanawinka fault transect.

Results of dissolved noble gas sampling are summarised in Table 7.5 and Table 7.6. Noble gas analysis results can be divided into two groups: those collected with the diffusion sampler method have concentrations within the range expected for groundwater recharged under normal environmental conditions, while samples collected with the copper tube method yielded questionable ^{20}Ne and ^{40}Ar concentrations and will be considered separately.

Groundwater recharge temperatures were calculated from diffusion cell samples using the unfractionated excess air model (Heaton and Vogel, 1981). This model yielded an average groundwater recharge temperature of 8.2 °C (excluding well 7023-7135, which gave an erroneously low recharge temperature). This temperature is indicative of recharge during a climatic regime similar to present as mean median winter (June-August) air temperatures from 1942 to 2012 are 9.6 °C with mean minimum ground temperatures being 2.3 °C lower than mean minimum air temperatures (Bureau of Meteorology, 2013). After correcting for ^{4}He derived from atmospheric sources (atmospheric equilibration plus excess air), the mean terrigenic ^{4}He concentration is 4.0 x 10^{-9} cc ^{4}He STP/g, which represents an excess of 10% relative to atmospheric equilibrium. This represents approximately 1000 years of accumulation assuming uranium and thorium concentrations of the average upper crust (see Ballentine et al., 2002). If lower uranium and thorium concentrations representing an average carbonate (Gao et al., 1998) are used, this represents approximately 3000 years of ^{4}He accumulation.

Copper tube sample analyses showed erroneously high concentrations of ^{20}Ne and ^{40}Ar, indicative of implausible recharge temperatures below 0 °C. It was determined that nonlinearity in the ^{40}Ar measurement may fully explain the high ^{40}Ar concentrations, while the high ^{20}Ne measurements remain questionable. Regardless, ^{4}He concentrations were deemed correct. As a result, terrigenic ^{4}He concentrations were calculated by removing ^{4}He concentrations attributable to atmospheric equilibrium at the mean recharge temperature and mean excess air concentration determined for diffusion samplers. Terrigenic ^{4}He concentrations vary between 0.04–2.90 x 10^{-8} cc STP/g, representing 350–26,000 years of accumulation (assuming U and Th concentrations of average carbonates; Gao et al., 1998). These terrigenic ^{4}He concentrations roughly agree with the trend seen in ^{14}C values (Figure 7.9) suggesting that ^{4}He may be useful as a semi quantitative tracer of age for future studies in this area.

Terrigenic ^{4}He concentrations exhibit no discernible spatial trends along the Tartwaup fault. However, there is a linear, but poorly constrained trend along the Kanawinka fault transect with ^{4}He increasing toward the south. This trend inversely correlates with the decrease in pMC toward the south. The increase in ^{4}He concentrations can be used to estimate the horizontal velocity of the groundwater. Assuming horizontal piston flow of water, the water velocity is 0.6 m/year. However, it is noted that with a range of tracers indicating a mixture of old and young water, this interpretation is likely oversimplified.

Table 7.5 Summary of noble gas analysis results for Tartwaup fault transect wells

UNIT NO.	TYPE*	^{4}He (x 10^{-8})	^{40}Ne (x 10^{-7})	^{40}Ar (x 10^{-4})	RECHARGE TEMPERATURE (°C)	EXCESS AIR (x 10^{-3})	TERRIGENIC ^{4}He (x 10^{-8})	APPARENT AGE** (y)
7022-10574	C	5.37	-	-	-	-	0.49	4502
7022-10573	C	4.92	-	-	-	-	0.03	354
7022-10572	C	5.80	-	-	-	-	0.92	8442
7022-128	D	5.32	1.89	3.93	8.5	-	0.44	4331
7022-10687	C	6.37	-	-	-	-	1.49	13632
7022-10688	C	6.18	-	-	-	-	1.30	11937
7022-139	D	5.58	2.04	4.05	8.0	1.29	0.70	2413

All concentrations (including excess air) in cc STP/g_{water}; *C=copper tube, D=diffusion sampler; **Based on U and Th concentrations of average carbonates (Gao et al., 1998) and 30% porosity.

Table 7.6 Summary of noble gas analysis results for Kanawinka fault transect wells

UNIT NO.	TYPE*	^{4}He (x 10^{-8})	^{40}Ne (x 10^{-7})	^{40}Ar (x 10^{-4})	RECHARGE TEMPERATURE (°C)	EXCESS AIR (x 10^{-3})	TERRIGENIC ^{4}He (x 10^{-8})	APPARENT AGE** (y)
7023-7134	C	5.09	-	-	-	-	0.21	1949
7023-7259	D	5.31	1.98	4.21	6.5	0.61	0.42	2844
7023-7133	D	5.22	1.79	3.89	9.9	0.00	0.34	5646
7023-7135	D	5.17	1.87	4.82	0.7	0.00	0.29	3085
7023-5280	C	7.78	-	-	-	-	2.90	26606

All concentrations (including excess air) in cc STP/g_{water}; *C=copper tube, D=diffusion sampler; **Based on U and Th concentrations of average carbonates (Gao et al., 1998) and 30% porosity.

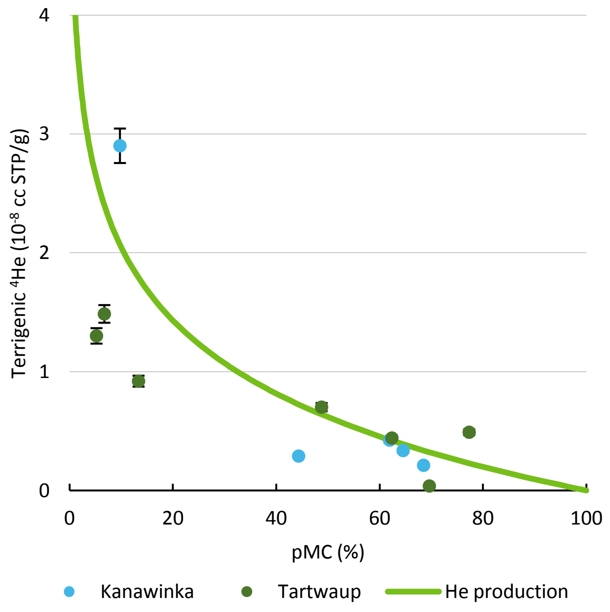


Figure 7.9 Percent modern carbon compared with terrigenic ^{4}He concentrations. The ^{4}He production line represents average carbonates (Gao et al., 1998).

7.2.2 GROUNDWATER FLOW MODELLING

Steady-state modelling of hydraulic head for both the Tartwaup and Kanawinka fault transects yielded linear hydraulic head distributions that were constant with depth, in accordance with specified boundary condition values. Interpretation of the alternative Tartwaup fault transect flow model involved the examination of streamline paths; a selection of these is presented in Figure 7.10. This interpretation demonstrates the potential for the Tartwaup fault to act as a barrier to horizontal flow due to the offset of hydrostratigraphic units. It may be seen that horizontal flows through the Camelback Member (orange, third unit from bottom) are restricted by the presence of the lower transmissivity Green Point subunit 4 (dark grey) downgradient of the fault at *x*≈2600 m. Flow is instead directed both upward and downward toward relatively higher transmissivity units. Similarly, it may be seen that horizontal flows through Green Point Member subunits 1 and 3 (both dark grey) are restricted by the presence of the lower transmissivity Greenways Formation (green) downgradient of the fault at *x*≈1000 m. In this case, the tendency for flow toward higher transmissivity layers may be observed in the convergence of streamlines downgradient of the fault in the relatively higher transmissivity Camelback Member.

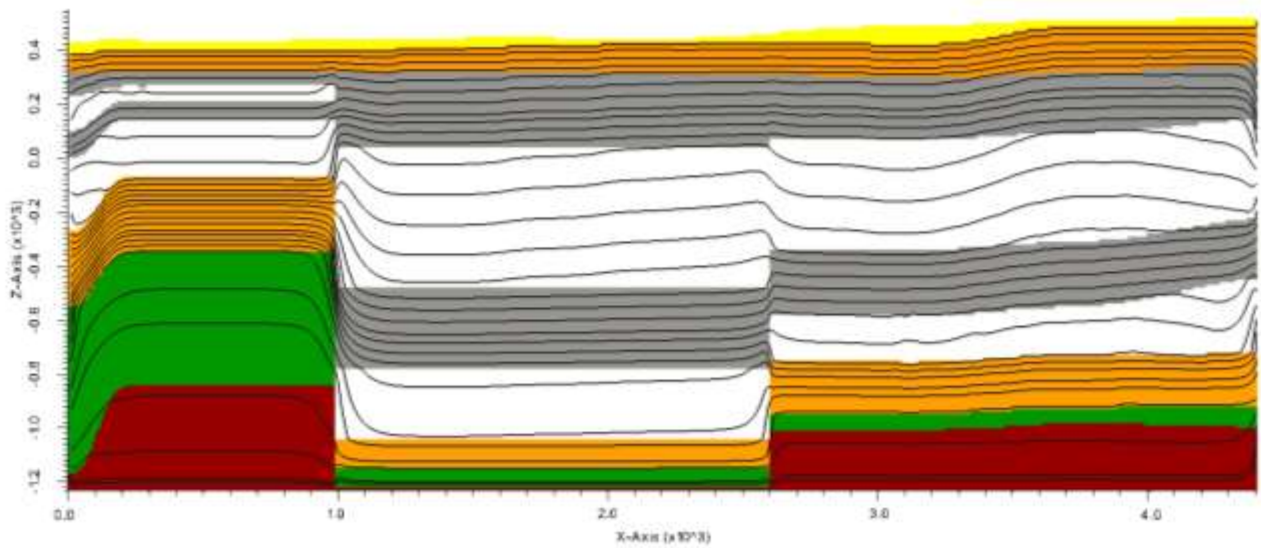


Figure 7.10 Selected streamlines from alternative Tartwaup fault transect flow model; colours correspond to hydrostratigraphic units shown previously in Figure 7.2; *Z*-axis dimensions are exaggerated by a factor of ten for display purposes.

7.3 Conclusions

Building upon previous work by Lawson et al. (unpublished), twelve groundwater wells located along transects perpendicular to the Tartwaup and Kanawinka regional geologic faults were sampled for hydrochemistry and environmental tracers. Hydrochemical analyses did not identify significant, consistent spatial trends in ionic composition associated with well location or sampling depth, which may be attributed to confounding effects caused by the broad extents of many well screens. Anion species were dominated (>80%) by bicarbonates, while cation species were generally dominated by calcium (35–60%), as would be expected for a limestone aquifer. Stable isotope composition was found to be consistent with that of rainfall datasets recorded in the Lower South East, with some samples featuring depleted ^{18}O values. Similarly, environmental tracer sampling did not identify significant, consistent spatial trends associated with well location or sampling depth, which may again be attributed to confounding effects caused by the broad extent of many well screens. Environmental tracer results suggest that the groundwater sampled was a mixture of both young (< 60 years old) and old (>5000 years old) water. The large screen extents present likely facilitate the mixing of waters between different aquifers; therefore it is not possible to identify the variation in groundwater ages with depth, nor the contribution of various water ages to the volume sampled. The future completion of deep wells as multi-level piezometer nests, followed by subsequent re-sampling, could identify differences in hydrochemistry and environmental tracer concentrations between hydrostratigraphic units.

Groundwater flow modelling was undertaken for both fault transects, based upon stratigraphic interpretations presented previously by (Lawson et al., unpublished). For the Tartwaup fault transect, an additional conceptualisation was also considered, in which abrupt changes in vertical stratigraphy were represented. Groundwater flow modelling was used to demonstrate the possible effects of the regional geologic faults on flow paths. Future re-sampling of wells after adequate completion could identify differences in environmental tracer concentrations between hydrostratigraphic units, which could subsequently be used to constrain model fluxes, boundary conditions and hydraulic parameters.

7.4 Recommendations

The primary recommendation for future investigations of groundwater flow across the Tartwaup and Kanawinka faults is to complete the recently-drilled (c.2009) wells as multi-level piezometer nests. This would enable sampling to be undertaken at discrete depths below surface. Vertical profiles of chemical and isotopic concentrations could then be obtained, which would likely provide greater insights into the dynamics of flow between hydrostratigraphic units.

A second recommendation is that the deep (>100 m depth) wells be extended in order to intersect the confined Dilwyn Sands aquifer. It is possible that displacement at or around the faults is sufficient to facilitate upward flow of water from the Dilwyn aquifer into the Gambier Limestone aquifer. Deeper well completions (followed by installation of multi-layer piezometer nests) could provide significant insight into connections between the confined and unconfined aquifers.

A third recommendation is to undertake additional drilling along the Kanawinka fault transect. Similarities in the stratigraphic logs of wells drilled to-date suggest that the location of fault displacement has not been identified. It has been hypothesised that the fault offset may occur upgradient of well 7023-7259; future drilling activities may wish to target this section of the transect.

8 Data review and conceptual model

Nikki Harrington, Chris Li, Juliette Woods, Steve Barnett, Jeff Lawson, Ben Plush and Matthew Skewes

This chapter provides details of work carried out for Phase 1 of Task 1, specifically to fulfil Objective 1 of that Task, which is:

Collate and assess all available data and information required for input to a regional numerical groundwater flow model of the Lower Limestone Coast Prescribed Wells Area.

Whilst a lot of the information provided in this chapter represents the collation and organisation of existing data sets, a number of activities have been undertaken to further interpret some data sets to improve the conceptual understanding of the water system in the study area. Such activities include redevelopment of the hydrostratigraphic model to include both the South Australian and Victorian portions of the study area, collation and comparison of all available historical irrigation equivalent (IE) and recent metered groundwater extraction data, and development of coastal cross sections summarising the results of multiple investigations into the position of the seawater interface in the area to the south of Mount Gambier. The historical land use mapping activity, described in Chapter 4, and the recharge estimation project (Chapter 5) were carried out as part of Task 1. A number of diagrams and maps included in this chapter assist with the visualisation and understanding of the conceptual model. Although all of the available data has now been collated and summarised, there is still some effort required to convert this to datasets that can be directly input into a numerical model. This will occur as part of the model development phase of Phase 2 of this project.

8.1 Overview of data collection and archive of data sets

The datasets that were likely to provide the greatest challenges and risk to the success of the modelling project were identified at the beginning of the project, and prioritised for an immediate start. Collation of these prioritised datasets, which were 1) the hydrostratigraphic model of the model domain (SA and Victoria), 2) the groundwater extraction data, and 3) historical land use information have been a major focus of Phase 1. Other datasets described in this chapter are more readily available.

A broad range of data and conceptual information has been collected as part of Phase 1. As described above, some of this is readily available on web-based government databases. Other information has been extracted from a range of reports and journal papers, as well as from less accessible parts of the government data archives. Specific details of data sources and collection methodologies are provided in the relevant sections, however, the main sources of data were:

1. The DEWNR Mount Gambier office, which provided numerous datasets and reports, as well as metered groundwater extraction data.
2. DEWNR databases, both web-based and internal departmental databases, particularly for spatial datasets, stratigraphic information and observation well data.
3. Government of Victoria Department of Sustainability and Environment. Victorian spatial information (GMU and WSPA boundaries, surface water information, observation well information – web-based), stratigraphic information.
4. United States Geological Survey (USGS) – Landsat data (Chapter 4)
5. South Australian Government Parliamentary Papers for historical land use information prior to 1975 (see Chapter 4).

The key datasets obtained through this project have been archived in a filing system that is consistent with DEWNR's Groundwater Model Warehouse. In addition, the project team has developed a metadata database to facilitate archiving the data through Australian National Data Service (ANDS). CSIRO already has data archiving systems that are compatible with the ANDS and Flinders University is in the process of developing this capacity. Integration with this system will be an ongoing activity through Phase 2 of the project. In the meantime, all data collated through Phase 1 of this project is to be provided to DEWNR for archiving within their data storage systems.

8.2 Hydrostratigraphic model

8.2.1 OVERVIEW

A conceptual hydrostratigraphic framework for the South East region of South Australia was compiled as part of the South East National Water Initiative (NWI) project, and a three-dimensional model constructed from this (Lawson et al., 2009). The model included stratigraphic logs from a combination of groundwater observation wells, water supply and irrigation bores and petroleum exploration holes, which were available from the state drill hole database, SAGeodata, or as microfiche records held by DEWNR (then the Department for Water – DFW). Additional investigation holes that had been recently drilled were also included. Overall, the model included data from 327 well logs, including 5 newly drilled wells in the Victorian Border Zone 3B.

Subsequent to this, and at commencement of this project, the hydrostratigraphic model for the whole South East region (including the Gambier Basin and the south-western portion of the Murray Basin) was being revised by DEWNR for the Bureau of Meteorology National Aquifer Framework project (S. Barnett, pers. comm., 2013). This new model incorporated additional stratigraphic interpretation, particularly for the Murray Basin portion of the study area. In collaboration with the current project, it was decided to extend the study area for the hydrostratigraphic model across the border to the Dundas Plateau, considered to be a natural hydraulic boundary for groundwater flow.

As mentioned above, the existing hydrostratigraphic model included only 5 data points from the Victorian side of the Border. Additional hydrostratigraphic data from Victoria was obtained from the Victorian DSE and, although the interpretations and unit descriptions were slightly different, it was believed that the spatial coverage in the study area was good and this data could be interpreted to extend the South Australian hydrostratigraphic model to the whole study area.

8.2.2 APPROACH TO SIMPLIFIED THREE-DIMENSIONAL HYDROSTRATIGRAPHIC MODEL DEVELOPMENT

LAYERS

The general approach applied to develop the simplified hydrostratigraphic units involved grouping formations broadly by geological age, as shown in Table 8.1.

Table 8.1 Otway Basin and Murray Basin geological and hydrostratigraphic units and their representative layers in the preliminary hydrostratigraphic model.

HYDROSTRATIGRAPHIC MODEL LAYER	GEOLOGICAL UNIT (OTWAY BASIN)	GEOLOGICAL UNIT (MURRAY BASIN)	HYDROSTRATIGRAPHIC UNITS
1	Padthaway Fm Bridgewater Fm Coomandook Fm		Quaternary Limestone Aquifer
2	Gambier Limestone	Duddo Limestone (Murray Group)	Upper Mid-Tertiary Aquifer (Tertiary Limestone Aquifer - TLA)
3	Gellibrand Marl, Narrawaturk Marl, Upper Mepunga Fm	Geera Clay, Ettrick Formation, Renmark Clay	Upper Tertiary Aquitard
4	Lower Mepunga Fm		Lower Tertiary Aquifer
4	Dilwyn Sand Pember Mudstone Pebble Point Formation	Renmark Group Sand	Lower Tertiary Confined Aquifer (Tertiary Confined Sands Aquifer – TCSA)
5	Sherbrook Group	Cretaceous aquifer / aquitard system	Pre-Cainozoic Sediments and Basement

CREATION OF HYDROSTRATIGRAPHIC ELEVATION SURFACES

Several methods were used to create the hydrostratigraphic elevation surfaces for the simplified hydrostratigraphic three-dimensional model.

1. Extent of Simplified Hydrostratigraphic Units

The extent of simplified hydrostratigraphic units was developed from simplified geology GIS layers and from interpretation from prior projects in South Australia and Victoria, and identifies the extents of outcrop and subsurface features for each simplified hydrostratigraphic unit, as shown in Table 8.1.

2. Point Interpolation Data

Point elevation data was extracted from the NGIS Database (May 2013), which is based on DEWNR’s SA Geodata system, using SQL (Structured Query Language) queries in ArcGIS to obtain the top elevation (in mAHD) of generalised hydrostratigraphic units, e.g. Murray Group Limestone, Ettrick, Renmark and Basement (identified in borehole log data as map units), within the Murray-Otway Basin Region. Point data was also sourced from GHD for the study area crossing into Victoria.

3. Contour Interpolation Data

Contour data was used in conjunction with the point data. Contour data was provided by GHD for the Victorian region of the study area. Contour data was also obtained for the top of Cretaceous surface in the Otway Basin from PIRSA (S. Barnett, pers. comm., 2013).

4. Outcrop Features

Outcropping boundaries were determined by a combination of surface geology layers and geologists' interpretation of the data (S. Barnett, pers. comm., 2013). The boundaries of the outcropping areas were converted to points and these points were given the value of the DEM at that point. The points were used in the interpolation process to 'pull the layer up' around the areas of outcrop. Outcropping features were created from the South Australian/Victorian state one second Digital Elevation Model (SA 1 Sec. DEM/Vic 1 Sec. DEM). The extents of outcrops (with a 150 m buffer, later used to mosaic outcrop surfaces with subsurface layers) were used to clip the 1 second DEM to create an outcrop surface elevation raster for the simplified hydrostratigraphic units.

5. Absent Areas

Absent areas for the northern part of the study area on the South Australian side were determined. Absent areas for the Victorian portion of the study area, near the border and around the Mount Gambier area utilised the Victorian interpretation of the extent of the stratigraphic units.

6. Subsurface Features

The ArcGIS 10.1 Topo to Raster (TTR) interpolation algorithm was used to interpolate an elevation surface from the extracted NGIS point data. Additional point data were created along the boundary of outcrop extents to assist the interpolation process. The height values for these points were obtained from the SA 1 Sec. DEM/Vic 1 Sec. DEM. The purpose of these additional points was to 'raise' the interpolated subsurface surface up to meet extents of outcrop.

The TTR interpolation tool has been developed by the Australian National University to interpolate and hydrologically correct raster surfaces. The TTR interpolation method uses many types of input data commonly available such as contour lines, spot height data, fault lines, etc and considers the known characteristics of elevation surfaces. The TTR method uses an iterative finite difference interpolation technique. TTR is optimized to have the computational efficiency of local interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity of global interpolation methods, such as Kriging and Spline. It is essentially a discretised thin plate spline technique for which the roughness penalty has been modified to allow the fitted elevation surface to follow abrupt changes in terrain, such as streams and ridges.

TTR interpolation produced the 'best fit' to the NGIS point height data when compared to IDW (Inverse Distance Weighted), Spline and Kriging interpolation methods available in ArcGIS 10.1 while also allowing the use of contour data. The default settings in the TTR tool allow sink features to be filled (which creates 'stream' features), in the case of creating subsurface elevation, the fill sink feature was disabled and therefore no 'streams' have been created.

The subsurface elevation rasters were clipped (with a 100 m buffer, used to mosaic subsurface with outcrop extents) to their known extents, resulting in a subsurface elevation raster for the simplified hydrostratigraphic units.

7. Mosaic of Subsurface and Outcrop Extents

ArcGIS 10.1 was used to mosaic the outcrop extents with the subsurface extents. Where the two extents overlapped (buffer zones as previously described) a surface elevation averaging method was used to determine surface elevation.

8. Overcoming Problems Encountered with the Interpolated Elevation Surfaces

Analysis of the raster elevation surfaces was conducted to identify areas where subsurface features intersected/breached overlying elevation surfaces. An ‘error‘ raster was created by subtracting the subsurface elevation raster from overlying surface elevation rasters using ArcGIS 10.1 Raster Calculator. The negative values in the resulting calculated raster indicated areas where subsurface elevation rasters were intersecting/breaching overlying elevation surfaces. Overlaying the interpolation point data on the ‘error ‘ raster identified that the errors were either due to some areas of the outcropping extent ‘ramping up ‘ and breaking the surface prematurely, a lack of point data, and/or possible errors within the borehole log information of the point data.

9. Indentifying and correcting errors within the borehole log information

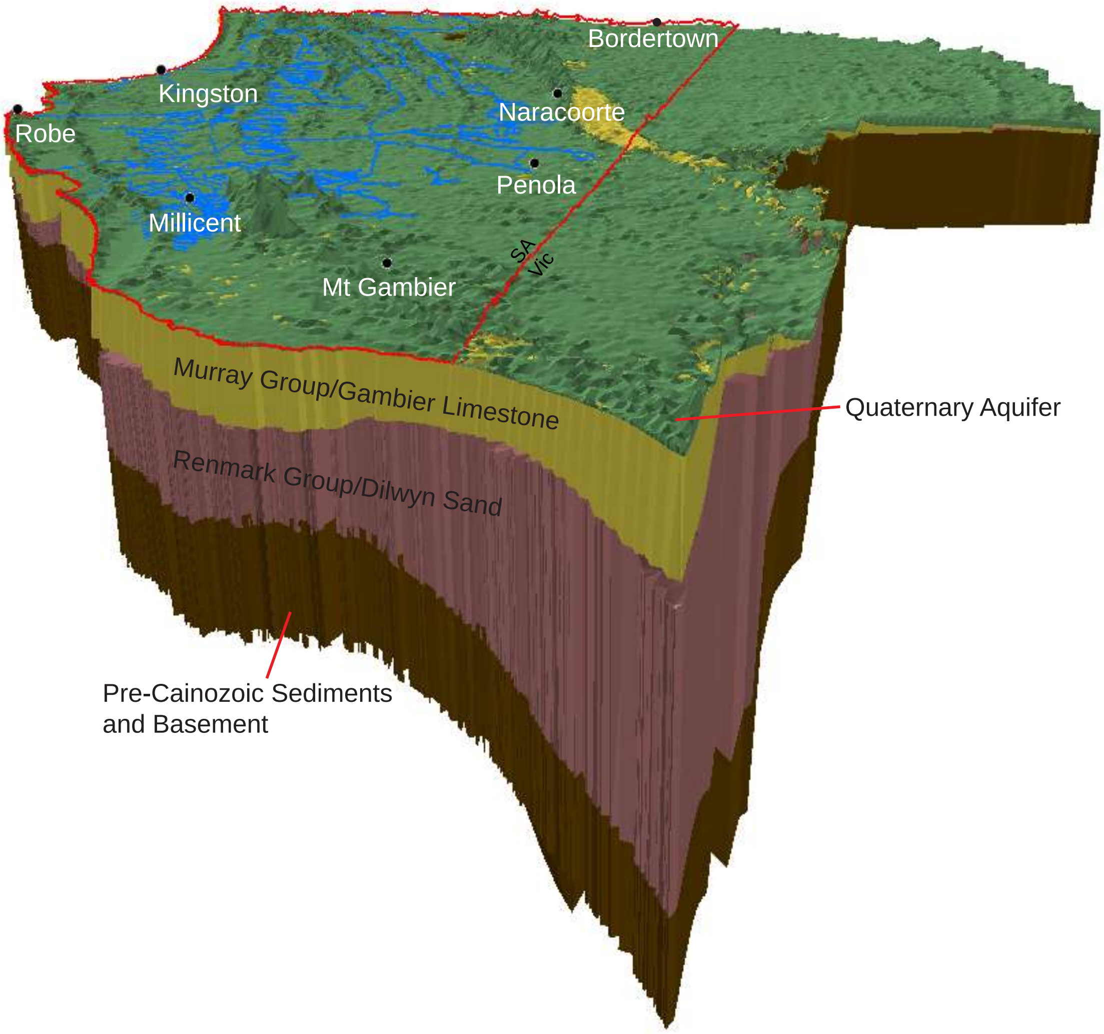
Analysis of the borehole log information identified that misinterpretation and errors were present. Dubious borehole log data was either reinterpreted/adjusted or deleted/ignored. A re-run of the interpolation method, once a data cleansing was completed through SA GeoData (which is used to update the NGIS database nightly), demonstrated that cleansing the borehole log information decreased the amount of error (subsurface elevation rasters intersecting overlying elevation surfaces).

10. Resolving lack of point data and other areas of error

Errors in the interpolated elevation surface rasters attributed to a lack of point data or other unknown reasons were adjusted by forcing the subsurface elevation raster below overlying rasters using a condition statement in ArcGIS 10.1 raster calculator. The condition statement entered into the raster calculator altered any cell within the subsurface raster that had a height value higher than the overlying raster cell to be 3 m below the overlying cell.

8.2.3 PRELIMINARY HYDROSTRATIGRAPHIC MODEL

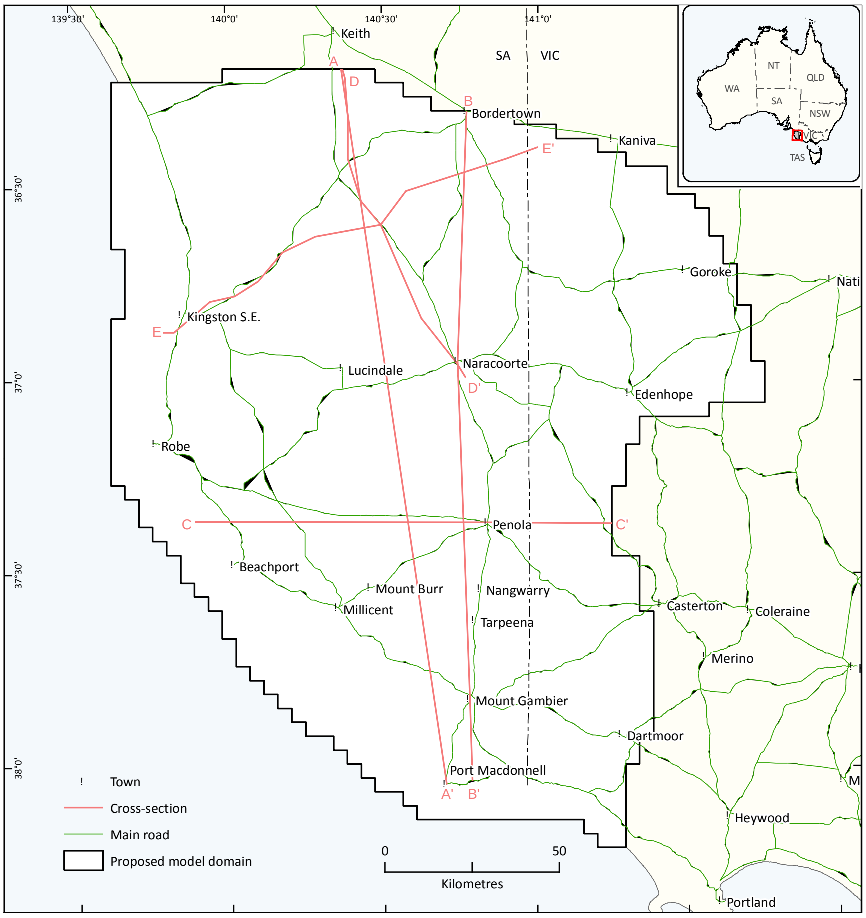
The preliminary hydrostratigraphic model is shown in Figures 8.1, Figure 8.2 and Figure 8.3. For illustrative purpose, the Pre-Cainozoic Sediments and Basement layer is assigned a constant thickness of 500 m in these figures.



The Upper Tertiary Aquitard is present in the hydrostratigraphic model, although it is very thin, appearing absent in the view above. Renmark Group / Dilwyn Sand represents the Lower Tertiary Confined Aquifer, which also includes the Lower Tertiary Pember Mudstone and Pebble Point Formation.

Figure 8.1 Preliminary three-dimensional hydrostratigraphic model of the study area (vertical exaggeration is 30x).

(a)



(b)

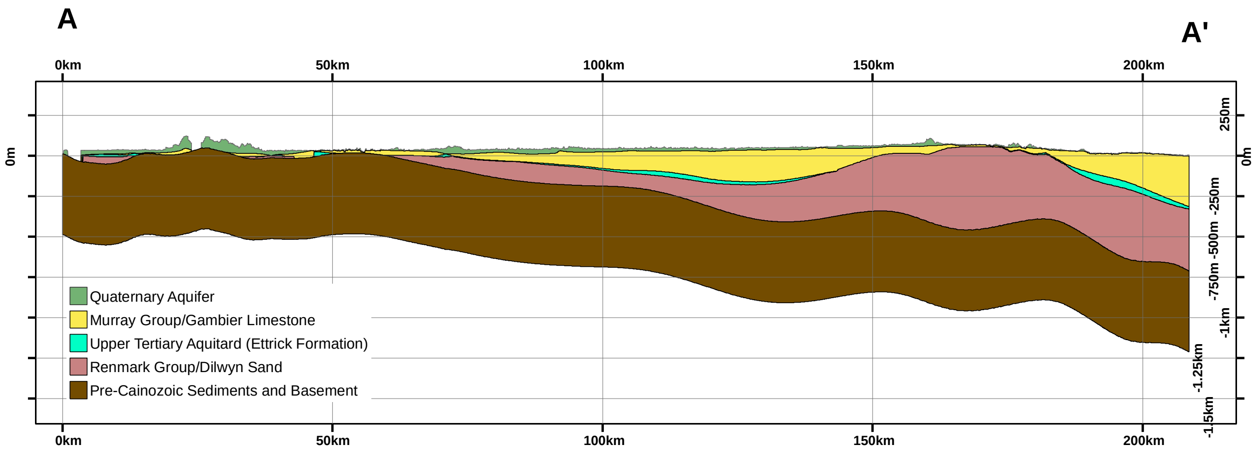
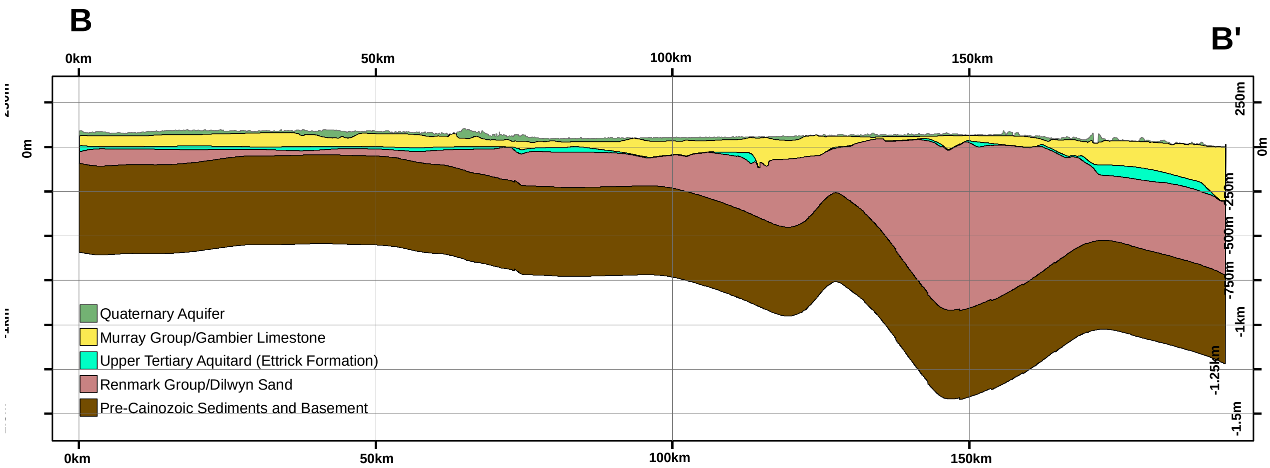


Figure 8.2 (a) Cross-section location map, and (b-f) cross-sections extracted from the preliminary hydrostratigraphic model; Dark green: Quaternary aquifers; Yellow: Unconfined Upper Tertiary Aquifer / Tertiary Limestone Aquifer (TLA); Cyan: Upper Tertiary Aquitard; Pink: Lower Tertiary Aquifer / Tertiary Confined Sand Aquifer (TCSA) (this also includes the Lower Tertiary Pember Mudstone and Pebble Point Formation); Brown: Pre-Cainozoic sediments and basement

(c)



(d)

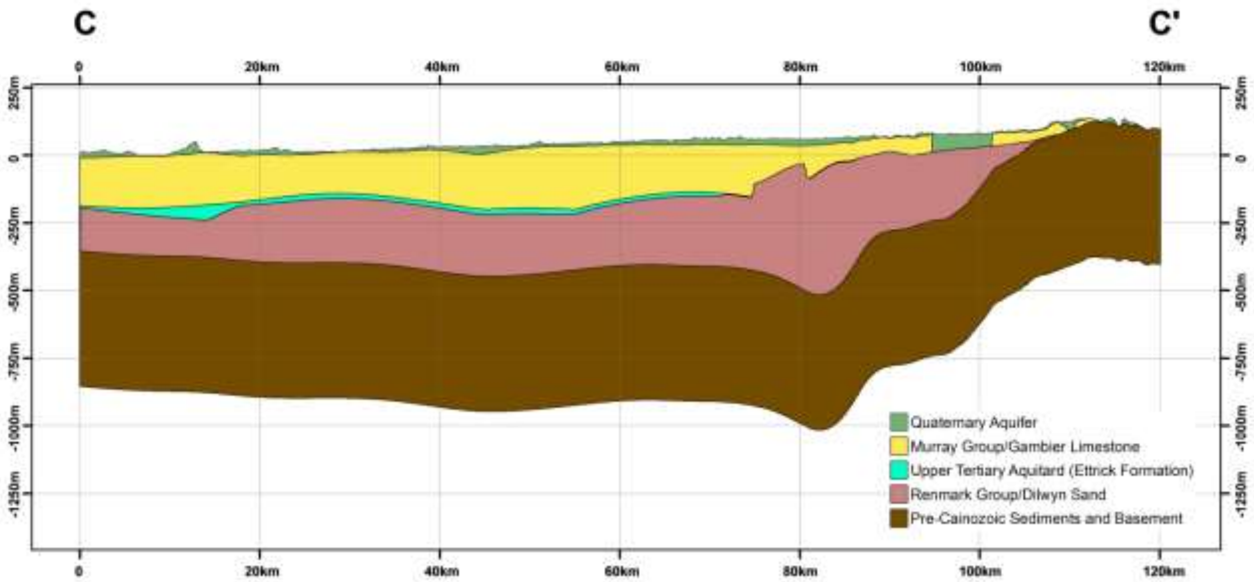
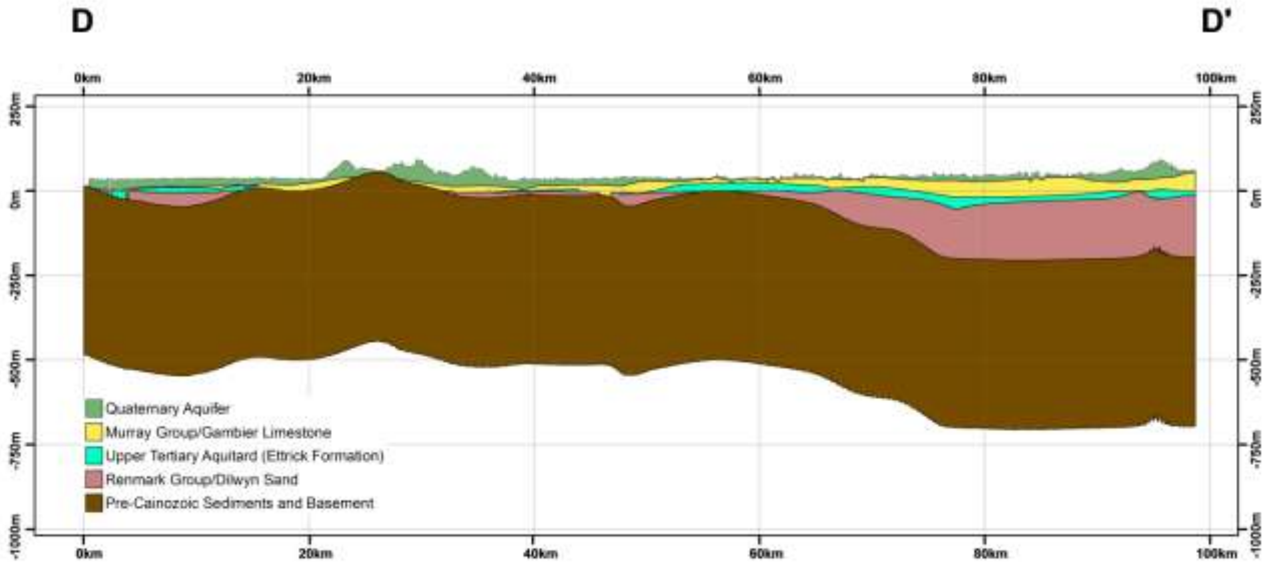


Figure 8.2 continued

(e)



(f)

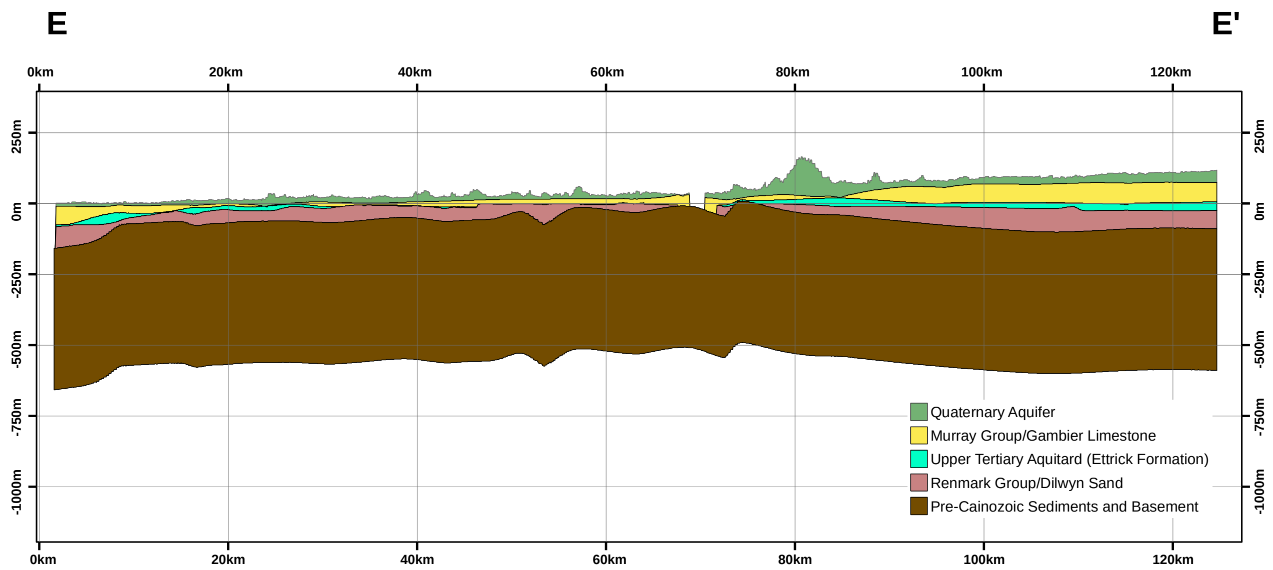


Figure 8.2 continued

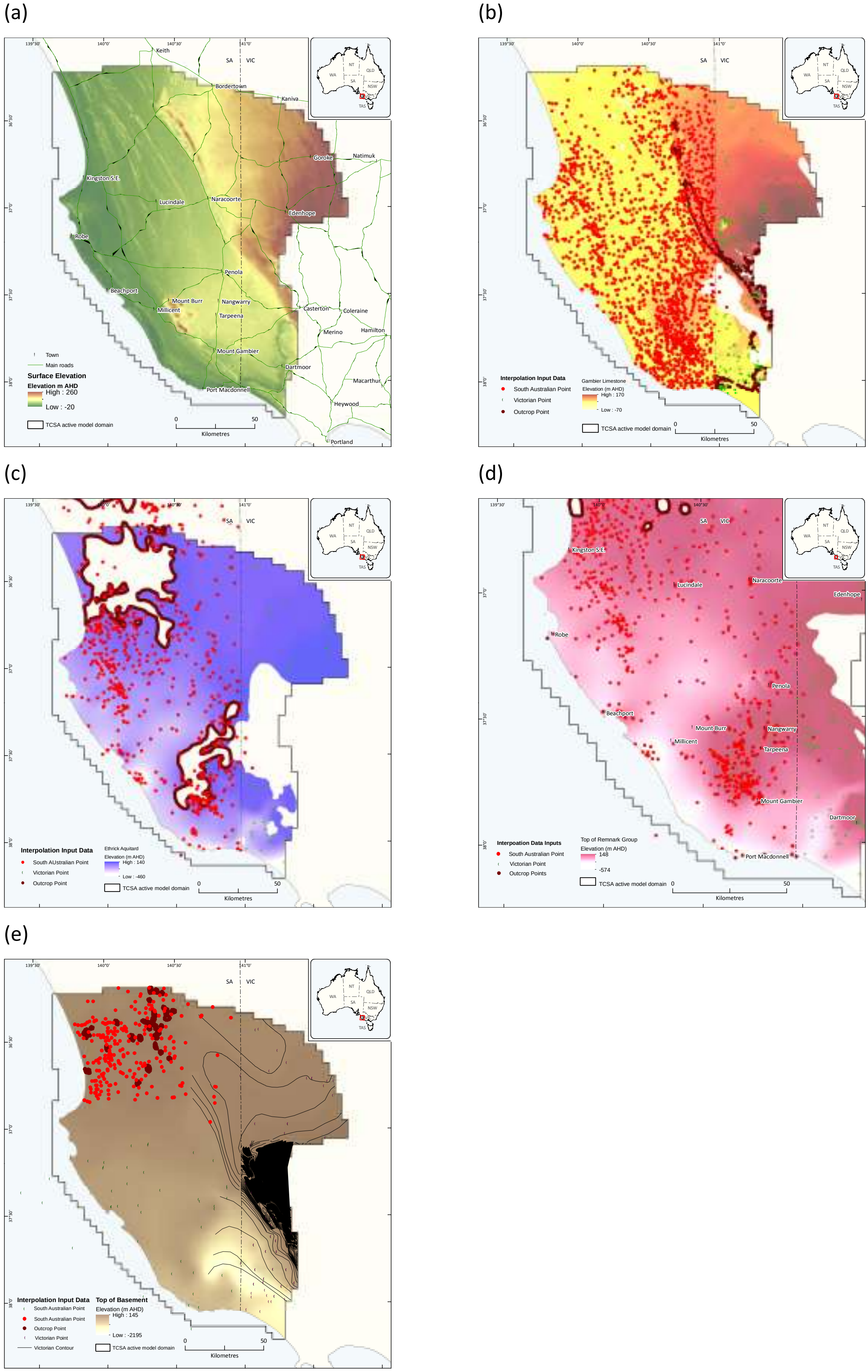


Figure 8.3 Raster surfaces for the preliminary hydrostratigraphic model: (a) DEM, (b) top of Unconfined Upper Tertiary Aquifer / Tertiary Limestone Aquifer (TLA), (c) top of Upper Tertiary Aquitard, (d) top of Lower Tertiary Aquifer / Tertiary Confined Sand Aquifer (TCSA) and (e) top of Pre-Cainozoic sediments and basement.

8.2.4 CHECKING OF SURFACES

Cross-sections and raster surfaces from the preliminary hydrostratigraphic model have been checked against existing cross-sections from DEWNR reports and hydrogeological maps, and have been reviewed by a local hydrogeologist with expertise in the South East (J. Lawson, pers. comm., 2013). Some areas for correction have been identified. These were:

1. The surface for the bottom of the TCSA/top of Pre-Cainozoic Sediments and Basement contained a number of sharply sloping features, which were considered to be unrealistic and probably an artefact of the interpolation method, using a combination of point data and structural contours (J. Lawson, pers. comm., 2013). These have been amended in the current model shown in Figure 8.1, Figure 8.2 and Figure 8.3. However, it has been brought to our attention that the final surface presented in this preliminary model still contains some inaccuracies caused by differences in the datasets used to amend it (S. Barnett, pers. comm., 2013). The original datasets included the base of the Lower Tertiary Pember Mudstone and Pebble Point Formation (i.e. these were included in Layer 4), but the dataset used to amend the surface may have only represented the base of the Dilwyn Sand. This will be rectified as we move into Phase 2 of the project with a revised stratigraphic model produced for use in the numerical model.
2. Some areas along the SA/Victorian border, where the current hydrostratigraphic model shows the Tertiary Limestone Aquifer and the Upper Mid-Tertiary Aquitard to be absent have been queried (J. Lawson, pers. comm.). Datasets to be used to rectify this are being compiled and this will be carried out and the hydrostratigraphic model finalised as part of Phase 2 of the project.

8.3 Groundwater flow and aquifer and aquitard properties

As shown in Figure 8.1 and Figure 8.2, the study area comprises three main hydrostratigraphic units. From oldest to youngest, these are the Lower Tertiary Confined Sand Aquifer (TCSA), the Upper Tertiary Aquitard and the Upper Tertiary Limestone Aquifer (TLA). Harrington et al. (2011) provide a general summary of all available information on the groundwater flow characteristics and hydraulic properties of these units for the South Australian portion of the study area. Some of the information provided below is also provided in that report.

8.3.1 LOWER TERTIARY CONFINED SAND AQUIFER

General Characteristics

The Lower Tertiary Confined Sand Aquifer (TCSA) in the Gambier Basin comprises interbedded gravels, sands, silts and carbonaceous clays of the early Tertiary Dilwyn and Mepunga Formations, and generally increases in thickness towards the south, being up to 800 m thick offshore to the south of Mount Gambier (see Figure 8.1; (Love, 1991)). In the Murray Basin, the equivalent of the Dilwyn Sands aquifer is the Renmark Formation and the aquifer is also often referred to as the Lower Tertiary Confined Aquifer or Tertiary Confined Sand Aquifer (TCSA). The aquifer system thins and wedges out towards the basement highs of the Padthaway Ridge at the northern margin and the Dundas Plateau at the eastern margin of the basin. As with the overlying aquifers and aquitard, it is also elevated above the structural high of the Gambier Axis in the Nangwarry area.

The TCSA is a multi-aquifer system, but is treated as one aquifer unit for management purposes. There are few data and hence little understanding of the hydraulic interconnection between the sub-aquifers of the Dilwyn Formation. Most wells only penetrate the uppermost sand unit of the aquifer for economic reasons, but a number of deeper petroleum exploration wells have provided some valuable stratigraphic information (Brown et al., 2001). The aquifer is dominated by sands and gravels in the north of the basin, with clay being a relatively minor component and not forming any regionally extensive confining layer (Love et al., 1993). The clay/sand ratio increases towards the south and the number of confining beds increases. The Pember Mudstone sits at the base of the Dilwyn Formation and forms an aquitard over much of the

Gambier Basin. This lies above the Pebble Point Formation Aquifer, which also occurs throughout the Gambier Basin and forms part of the Lower Tertiary Aquifer. Little is known about the hydrological properties of the Pember Mudstone and Pebble Point Formation due to the quality of the resources that lie above them and the consequent lack of exploratory drilling at depth. However, the extent and thickness of the Dilwyn Sand Aquifer has led to the conceptualization that this dominates flow processes within the Lower Tertiary Aquifer (SKM, 2010).

Groundwater Flow

Regional groundwater flow in the TCSA aquifer is in a south-westerly direction towards the coast (Figure 8.4). Along the SA-Victorian border, flow becomes predominantly south. Recharge to the TCSA is believed to occur in areas where the layer is close to the surface. Major recharge zones for this aquifer, indicated by the presence of groundwater mounds, have been identified in the Nangwarry – Tarpeena area on the South Australian side of the border, and south of Strathdownie, which is approximately 33 km north-east of Mount Gambier, on the Victorian side (SKM, 2010). The mound in the Nangwarry-Tarpeena area coincides with a slight depression in the watertable of the unconfined aquifer, as described in Section 8.3.3, as well as being a region where the TCSA is close to the surface and the overlying aquitard is relatively thin. The Lake Mundi area, approximately 21 km east of Nangwarry, over the SA/Victorian border is also expected to be a major recharge area for the TCSA as no aquitard exists here (J. Lawson, pers. comm., 2013). Brown et al. (2001) investigated the mechanisms of recharge to the TCSA from the overlying Tertiary Limestone Aquifer (see Section 8.3.2 below).

Love et al. (1993) describe a potential for recharge to the TCSA from underlying Cretaceous aquifers based on the orientation of equipotential lines, although no direct evidence for this exists. Discharge to the overlying unconfined aquifer has also been suggested to occur offshore, but again no direct evidence exists (Blake, 1980).

Love et al. (1993; 1994) investigated trends in groundwater hydrochemistry, $\delta^{18}O$, $\delta^{2}H$ and ^{14}C in the unconfined and confined aquifers along two transects within the study area. The transects run approximately (a) east – west, from north-west of Edenhope in the north east of the study area to Kingston at the coast, and (b) north – south from north-east of Nangwarry to just east of Port Macdonnell at the coast (Figure 8.5). They calculated groundwater travel times in the TCSA, along the east-west transect between the ZHD line (point at which the head difference between the unconfined and confined aquifers switches from positive to negative) and the coast using both Darcy's Law and the interpretation of ^{14}C data. They found that water within the TCSA has a total residence time of at least 30 000 yrs (i.e. time since recharge), with a groundwater travel time between the ZHD line and the coast in the TCSA of 12 800 years. This implies a mean groundwater velocity of 4 m/yr, but velocity apparently decreased towards the coast. The apparent decrease in groundwater velocity could be due to either a reduction in hydraulic conductivity or loss of water from the system by upward leakage. An error of ±20% was assigned to the ^{14}C water velocity calculations based upon uncertainties in carbon isotope measurements and the length of the flow path. The reader is referred to the original papers for full details of the data used and the full methodology, including the correction models applied to the ^{14}C data.

The groundwater velocity estimated using Darcy's Law for the same section of transect AA' was approximately one quarter of that estimated using the ^{14}C data (Love et al., 1993). This estimate utilised a porosity value of 20% and hydraulic conductivity values of 0.9 m/day to 3.9 m/day based on field data. The error associated with this estimate was considered to be ±32%. If upward leakage of water to the unconfined aquifer is important, this hydraulic velocity would represent an upper bound. Love et al. (1994) considered the discrepancy between the ^{14}C derived groundwater travel time and that derived from hydraulic parameters to be due to changes in the potentiometric driving force throughout the late Pleistocene-Holocene due to a reduction in sea level. They considered that sea levels during the Pleistocene glaciation may have been as much as 150 m below current sea levels. The effect of this on groundwater flow would be recorded in the ^{14}C data, resulting in greater groundwater velocities than those estimated from hydraulic data, which rely on measurement of the present-day (lower) hydraulic gradient.

Harrington et al. (1999) extended the work of Love et al. (1994) by using their ^{14}C isotopic data in a Compartmental Mixing Cell model to calibrate a two-dimensional MODFLOW groundwater flow model of the east-west transect of Love et al. (1993; 1994) (Figure 8.5). The two models were run and re-calibrated iteratively until the modelled hydraulic and tracer values matched field data. This approach resulted in estimated lateral flow velocities in the TCSA ranging between 0.4 m/year and 5.5 m/year, as well as estimates of vertical leakage rates as described in Section 8.3.2.

Aquifer Properties

Hydraulic data for the confined aquifer is sparse, but what is available suggests that hydraulic properties are not as spatially variable as for the unconfined aquifers. For the entire Gambier Basin region, porosity values estimated from borehole geophysical logs vary between 20% and 30%, whilst historical transmissivity estimates range from 200 to 1600 m^2/day (Bowering, 1976; Cobb, 1976; Floegel, 1972; Shepherd, 1978). Pumping tests carried out on the Robe Town Water Supply wells (TWS1, TWS5 and TWS6; Figure 8.4) provided transmissivities of 64 m^2/day to 82 m^2/day (hydraulic conductivities of around 20 to 25 m/day) and storage coefficients of 1×10^{-7} to 5×10^{-5} (Osei-Bonsu and Dennis, 2004).

A recent drilling and aquifer testing program was carried out in Province 1 of the Border Zone to investigate inter-aquifer leakage between the TCSA and TLA. The locations of the observation wells installed and tested are shown in Figure 8.4 as SA1-4 and Vic1-4) (Mustafa and Lawson, 2011; SKM, 2012).Estimates of transmissivity of the TCSA from the pumping tests for the South Australian side of the study area ranged between 267 and 2260 m^2/day (K = 33 to 226 m/day). Storage coefficients ranged between 1.2×10^{-5} and 6.4×10^{-4}. For the Victorian portion of the study area, hydraulic conductivity of the TCSA ranged between 13 and 91 m/day, with storage coefficients ranging between 9×10^{-5} and 6.5×10^{-4}. The pump test data appeared to suggest the presence of flow boundaries in the vicinity of the test wells, which were suggested to be potentially the result of faulting.

In their model of the region to the south of Mount Gambier, Stadter and Yan (2000), assigned zones of hydraulic conductivity ranging between 0.5–10 m/day to the Dilwyn Sand aquifer, based on limited hydraulic testing results and local knowledge. A uniform specific storage value of 10^{-6}/m was also applied in that model. In the regional model of the confined aquifer, Brown (2000) assigned hydraulic conductivities ranging from 1 m/day to 80 m/day.

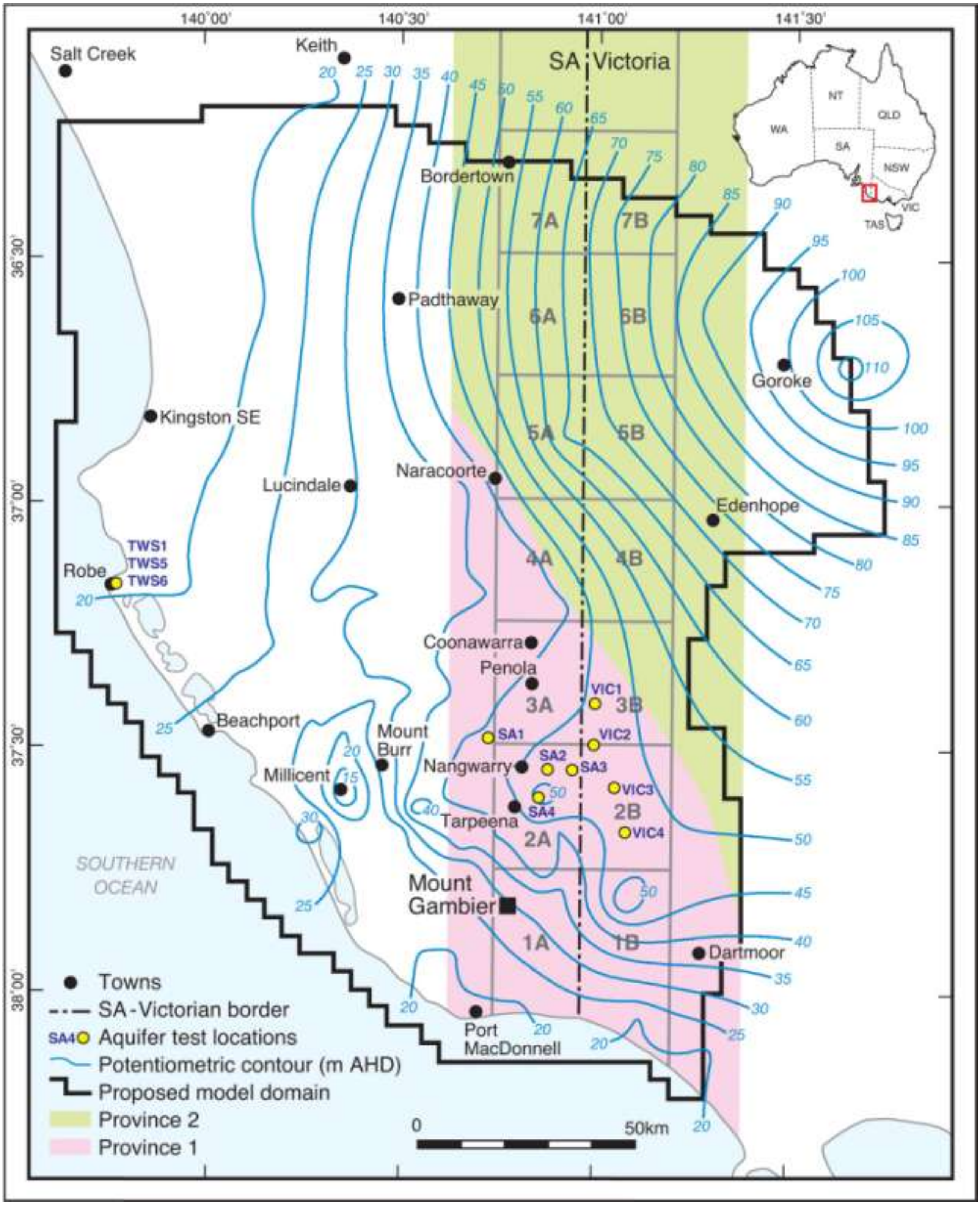


Figure 8.4 Confined aquifer potentiometric surface for June 2010, showing the Border Zones and Provinces in the Border Designated Area described in the text, and the locations of recent aquifer tests.

8.3.2 UPPER TERTIARY AQUITARD

Hydraulic Properties

Little information exists on the hydraulic properties of the Upper Tertiary aquitard, which comprises the glauconitic and fossiliferous marls of the Narrawaturk Marl and clay of the Mepunga Formation, as well as the Dilwyn Clay in the Gambier Basin and the Ettrick Formation in the Murray Basin. Vertical hydraulic conductivities of the aquitard were determined via triaxial permeability testing to range between 10^{-7} and 10^{-3} m/day in the northern portion of the Gambier Basin, near Lucindale (Love and Stadter, 1990). Laboratory tests carried out on the Dilwyn Clay in the Nangwarry / Tarpeena Area provided vertical hydraulic conductivity values ranging between 3.4 x 10^{-6} and 7.2 x 10^{-6} m/day (Brown et al., 2001). The recent NWI stratigraphy project (Lawson et al., 2009) obtained three porosity estimates for the aquitard through borehole geophysics. These were for the Mepunga Formation (7.1 % and 7.2%) and Narrawaturk Marl (9.5%). The joint Border Zone project on inter-aquifer leakage described above concluded that the aquitard in the study area was relatively leaky, with estimated vertical hydraulic conductivities ranging between 3.1 x 10^{-4} m/day and 4.4 x 10^{-2} m/day (Mustafa and Lawson, 2011). The authors acknowledged large limitations associated with the derivation of these aquitard conductivities and suggested that they be used with caution.

Inter-aquifer Leakage

There are a number of areas within the study area in which flow between the confined and unconfined aquifers, across the aquitard, is believed to occur. The direction of this potential inter-aquifer flow, i.e. the direction of the vertical hydraulic gradient, changes from downwards in the north-east of the study area to upwards in the south and west of the study area (Figure 8.5). The line along which the head difference between the unconfined and confined aquifers is zero and hence the direction of potential flow switches is known as the Zero Head Difference (ZHD) line (Figure 8.5). The location of this line coincides approximately with the location of the Tartwaup Fault.

There have been a number of studies where evidence for inter-aquifer leakage across the Upper Tertiary Aquitard has been identified. In particular, Love et al. (1993) investigated trends in groundwater hydrochemistry, $\delta^{18}O$, $\delta^{2}H$ and ^{14}C along two transects within the study area (see Figure 8.5 for transect locations). Whilst trends in hydrochemistry data for the unconfined aquifer are dominated by local flow processes, the following could be observed in the confined aquifer for the east-west transect (AA'):

- From the eastern margin to Naracoorte, the groundwaters become progressively depleted in ^{2}H and ^{18}O, whilst the isotopic signature of the overlying unconfined groundwaters are significantly heavier. This indicates that significant downward leakage of isotopically heavier unconfined groundwaters is not occurring today. This is supported by continuously low ^{14}C activities of the confined groundwater in this region.
- Between Naracoorte and the ZHD line, the confined groundwaters become progressively more enriched in the heavy isotopes, with the signatures of the two aquifers being similar at the ZHD line. This, along with the downward hydraulic gradient suggests significant downward leakage of groundwater from the unconfined aquifer. Additional evidence for this hypothesis is a gradual increase in ^{14}C activity from background levels at Naracoorte to 31 percent modern carbon (pmC) at the ZHD line. The gradual increase in ^{14}C activity along this flow path suggests that downward leakage through the aquitard is the dominant mechanism of recharge rather than preferential flow at the Kanawinka Fault.
- To the west of the ZHD line, the stable isotopic composition of the confined groundwaters tends to decrease monotonically along the hydraulic gradient. This is consistent with lateral groundwater flow, with the stable isotopes recording temporal variations in the stable isotopic composition of the recharging water. This is supported by a monotonic decrease in ^{14}C activity along the flow path.
- Upward leakage of isotopically depleted groundwater from underlying aquifers at the western edge of the transect is suggested by a decrease in groundwater ^{2}H and ^{18}O content and this is supported by increased Cl concentrations in this area.

For the north-south transect (BB'; see Figure 8.5), although local flow cells occurred in the unconfined aquifer, these were not as well-developed as in the east-west transect (AA') due to the less undulating topography in the region (Love et al., 1993). Nevertheless, the effects of local flow processes dominate the trends in hydrochemistry and isotopes for the unconfined aquifer. The following could be observed in the trends for the confined aquifer:

- Lateral variations in chloride and ^{2}H and ^{18}O concentrations between the northern margin of the transect and the ZHD line are consistent with downward leakage from the unconfined aquifer.
- ^{14}C activities of 53.3 pmC to 77.1 pmC for the unconfined aquifer and 12.2 pmC to 61.2 pmC for the confined aquifer between the northern margin of the transect and the ZHD line suggest active recharge to both aquifers occurring in this region.
- Relatively constant chloride concentrations and decreasing ^{2}H and ^{18}O concentrations and ^{14}C activities between the ZHD line and the coast are consistent with no recharge to the confined aquifer, either from the overlying unconfined aquifer or from underlying aquifers.

As described in Section 8.3.1, Harrington et al. (1999) extended the work of Love et al. (1993) by using their ^{14}C isotopic data in a Compartmental Mixing Cell model to calibrate a two-dimensional MODFLOW groundwater flow model of the east-west transect of Love et al. (1993; 1994). One of the outcomes of this was an estimate of average recharge rates to the TCSA of 2.1 mm/yr and 8.5 mm/yr along a flow line between Naracoorte and the ZHD line.

Further evidence for the connection between the unconfined and confined aquifers in the area to the north of the Tartwaup Fault in Province 1 of the Border Designated Area is seen in the relationship between groundwater levels and groundwater extraction information for this area. These data indicate that groundwater level declines in the TCSA are not caused by groundwater extraction from that aquifer but reflect trends in the overlying TLA, suggesting interconnection of the two aquifers.

Brown et al. (2001) suggested that any downward groundwater flow across the aquitard in the Nangwarry / Tarpeena area occurs preferentially via faulting, fractures or sinkholes. Supporting this theory, ^{14}C activities of groundwater from the aquitard in the Tarpeena area measured by Brown et al. (2001) were below background levels, whilst significant concentrations of ^{14}C existed in the underlying confined aquifer. The aquitard is relatively thin in the Nangwarry / Tarpeena area (~ 2 m), which probably facilitates this inter-aquifer leakage. However, it is possible that inter-aquifer flow also occurs through the clay via similar preferential flow mechanisms in areas where the clay is significantly thicker.

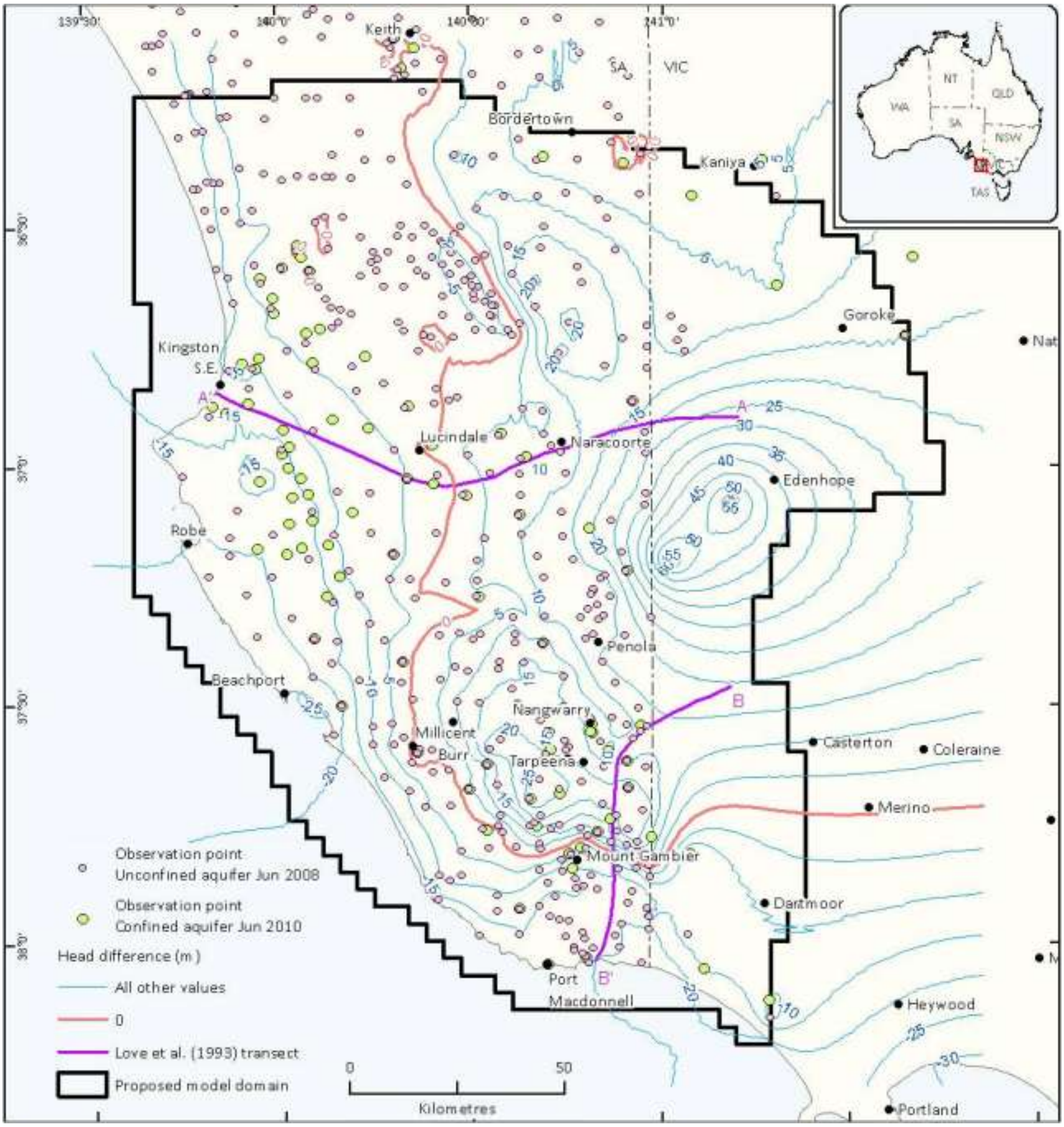


Figure 8.5 Map of head difference between the confined and unconfined aquifers (unconfined: September 2008 – confined: September 2010).

8.3.3 QUATERNARY / UPPER TERTIARY UNCONFINED AQUIFER

General Characteristics

The unconfined aquifer system in the Gambier Basin comprises predominantly the Gambier Limestone aquifer, which consists of various facies of fossiliferous limestone of Tertiary age, ranging in thickness from very thin to 300m. The Gambier Limestone is overlain and hydraulically inter-connected with the superficial Quaternary aquifers, the Padthaway, Bridgewater and Coomandook Formations. In the Murray Basin, the equivalent of the Gambier Limestone is the Murray Group Limestone and this is overlain by the aeolian Woorinen Sands and the marine Loxton-Parilla Sands.

In the Gambier Basin, the Gambier Limestone is divided into three main sub-units, the Greenways, Camelback and Green Point Members. The Green Point Member has been further sub-divided into five distinct units, forming seven units of the unconfined aquifer and these have been mapped across part of the Lower South East (Mustafa et al., 2012). Table 8.2 shows the characteristics of the seven sub-units of the Gambier Limestone, as presented in Mustafa et al. (2012). These characteristics apply in the region to the south of the Tartwaup Fault but vary to the north of this (J. Lawson, pers. comm., 2013). As shown in Table 8.2, the TLA often becomes marly and dolomitic towards the base. This marly, dolomitic unit has recently been mapped across part of the study area (Lawson et al., 2009) but its regional extent is unknown due to a lack of penetrating wells (Love, 1991).

Table 8.2 General description of the Gambier Limestone Formation sub-units in the region to the south of the Tartwaup Fault (Mustafa et al., 2012).

STRATIGRAPHIC UNIT	STRATIGRAPHIC NAME	HYDROSTRATIGRAPHIC UNIT	DESCRIPTION
Thgr	Green Point Member	U1	Off white to cream bryozoal limestone, with or without chert.
		U2	Grey marl with abundant chert.
		U3	Cream to light grey bryozoal limestone, with or without chert.
		U4	Grey limestone with abundant marl.
		U5	Cream to off white limestone
Thgc	Camelback Member		Grey to pink dolomite
Thgg	Greenways Member		Grey marl with coarse bioclastic with frequent chert band, often glauconitic near base.

Outcrops of the Gambier Limestone occur as a result of uplift and/or erosion of overlying sediments, with a major outcrop occurring to the south of the Tartwaup Fault. Rapid thinning of the entire unconfined aquifer formation to the north of Mount Gambier is due to up-warping along the Gambier Axis and transgression of the sea in the late Pleistocene, which truncated and re-worked the top part of the sequence. A groundwater divide occurs here along the Gambier Axis (Love, 1991).

Preferential Flow

The Gambier Limestone has an intrinsic primary permeability, with a secondary fracture permeability occurring in many areas along structurally weak zones (e.g. faults) in the form of karstic features. Karstic features are described to occur in Border Zone 6A and the western parts of Zones 5B and 6B (Border Groundwaters Agreement Review Committee, 2008b). Lawson et al. (1993) describe karst features in the Mount Gambier area as being oriented in the north-east to south-west direction. Despite the extensive development of karst in the South East, Holmes and Waterhouse (1983) considered that these features do not form an inter-connected system and that groundwater flow is predominantly intergranular (Love, 1991). Lawson et al. (1993) also state that the degree of connection between fractures and karst features in the Mount Gambier area, and their connection with Blue Lake (see Section 8.5.5) is unknown.

Many studies of groundwater flow in the TLA have been concentrated around Mount Gambier, due to concerns about the migration of diffuse and point source contaminants into Blue Lake via groundwater flow. The majority of groundwater flow to Blue Lake is believed to occur via the dolomitic Camelback Member of the Gambier Limestone, with the top of this unit occurring about 50 m below lake level, at approximately -39 mAHD. However, there are few observation bores completed exclusively in this dolomitic unit to enable investigation of its properties. In a study of the Mount Gambier area using a downhole flow meter, Telfer and Emmett (1994) identified a 0.5 m thick interval of aquifer tens of metres below the water table through which the majority of groundwater flow appeared to occur. However, the specific locations of the bores targeted by this investigation were not provided in their paper. Vanderzalm et al. (2009) used injection of SF_6 into the Gambier Limestone aquifer up-gradient of Blue Lake in Mount

Gambier to measure attenuation rates and travel times of groundwater as it potentially flows through karst features towards Blue Lake. They injected SF_6 into 24 bores, the majority of which were drainage bores, located 1 to 3 km to the north and north-west of Blue Lake. Some injection sites were oriented directly up-gradient of Blue Lake (to the north), but the majority were located to the north-west to enhance the opportunity to observe migration of the tracer through NW-SE oriented preferential pathways. Subsequent regular sampling for SF_6 over several years at various locations in Blue Lake indicated that the SF_6 tracer reached Blue Lake after approximately 2 years. This indicated a groundwater velocity of 0.5 to 1.5 km/year through karstic flow.

In some areas, dissolution of the limestone along the karstic features has resulted in brecciation and collapse of the limestone near the ground surface, forming numerous sinkholes. Figure 8.6 shows the mapped locations of some sinkholes (also known as 'runaway holes') obtained from DEWNR; however this map is not necessarily exhaustive. Herczeg et al. (1997) assessed the importance of localised recharge from these point-source features to the karstic groundwater system. They found that water recharging the groundwater system via these features was detectable at a local scale only (<150 m from the source) and comprised less than 10% of total recharge.

Groundwater Flow

Groundwater flow in the unconfined aquifer in the study area is generally from east to west, towards the coast in areas north of Mount Gambier (Figure 8.6). To the south of Mount Gambier, flow is to the south or south-west, with discharge occurring at the coast. Flow in this region also occurs towards the Glenelg River and, although the upper units of the aquifer are likely to be connected to the river, the nature of this interaction is yet to be determined (Border Groundwaters Agreement Review Committee, 2008a).

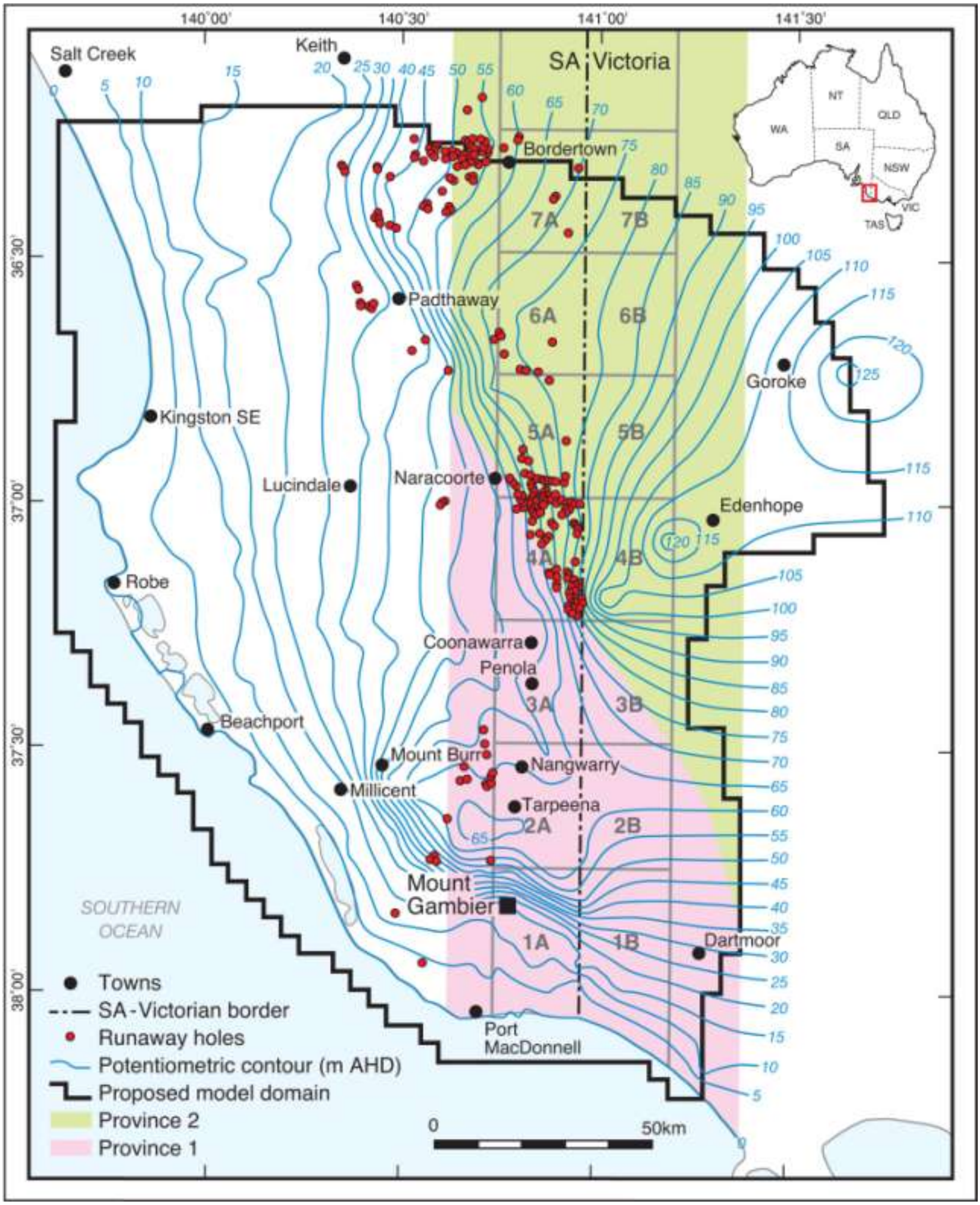


Figure 8.6 Unconfined aquifer potentiometric contours for September 2011.

The watertable generally ranges between 5 m and 25 m below ground level, but is within 2 m of the ground surface adjacent the coast and in some parts of the inter-dunal flats (Figure 8.7). A steep hydraulic gradient zone to the north of Mount Gambier coincides with the location of the Tartwaup Fault (Figure 8.6; Figure 2.1). The exact influence of the fault on groundwater flow is complex, and not yet fully understood, as described in Chapter 7. However, recent drilling investigations indicate that significant stratigraphic displacement occurs across the areas where the fault structure has been mapped. Lawson et al. (2009)

reported on drilling investigations along a transect across the Tartwaup fault north-east of Mount Gambier. They found that approximately 100 m of uplift occurred in the southern part of the transect (see Figure 7.2a). In these up-lifted sections, significant upper sub-units of the Gambier Limestone (Green Point Member sub-units) were not present. Such displacement is likely to hinder regional groundwater flow, and is likely to be the cause of the steep gradient. A groundwater divide occurs to the north of the Tartwaup fault zone, as a result of thinning and uplift of the unconfined aquifer above the structural high of the Gambier Axis, with flow to the north of the divide occurring to the north and north-west and flow to the south occurring to the south of the divide. A slight groundwater depression in the Nangwarry area is considered to act as a sink for recharge to the underlying Dilwyn aquifer and corresponds to a groundwater mound in that aquifer (see Section 8.3.1).

A similar ‘steep gradient’ zone is observed in the watertable along the base of the Naracoorte Ranges. This steep gradient zone is associated with the Kanawinka Fault line, and is thought to be caused by thinning of aquifer sediments on the eastern side of the fault (Lawson et al., 2009).

Love (1991) identified that a number of potential local flow systems occur in the unconfined aquifer in the study area, and that the fact that the watertable is close to and follows the topographic surface suggests a high importance of local recharge/discharge processes within the unconfined aquifer. Local flow cells tend to br recharged at topographic highs and discharged in the adjacent inter-dunal topographic lows (Love et al., 1993). Rapid lateral variations in groundwater chloride, ^{14}C, δ^2H and δ^{18}O support this (Love et al., 1993).

Brown et al. (2001) inferred average groundwater residence times from CFC-12 values of ~ 30–35 years for shallow groundwater (between 1.5 and 2 m below the watertable) in the Tarpeena and Nangwarry areas. Harrington et al. (1999) estimated lateral flow in the TLA to range between 4 and 38 m/year using their combined MODFLOW and Compartmental Mixing Cell approach.

Declining water levels in the TLA in Border Zone 5A, parts of Zone 5B, 6A and 6B are thought to be due to recharge being less than groundwater outflows and extraction (Border Groundwaters Agreement Review Committee, 2008b).

(a) (b)

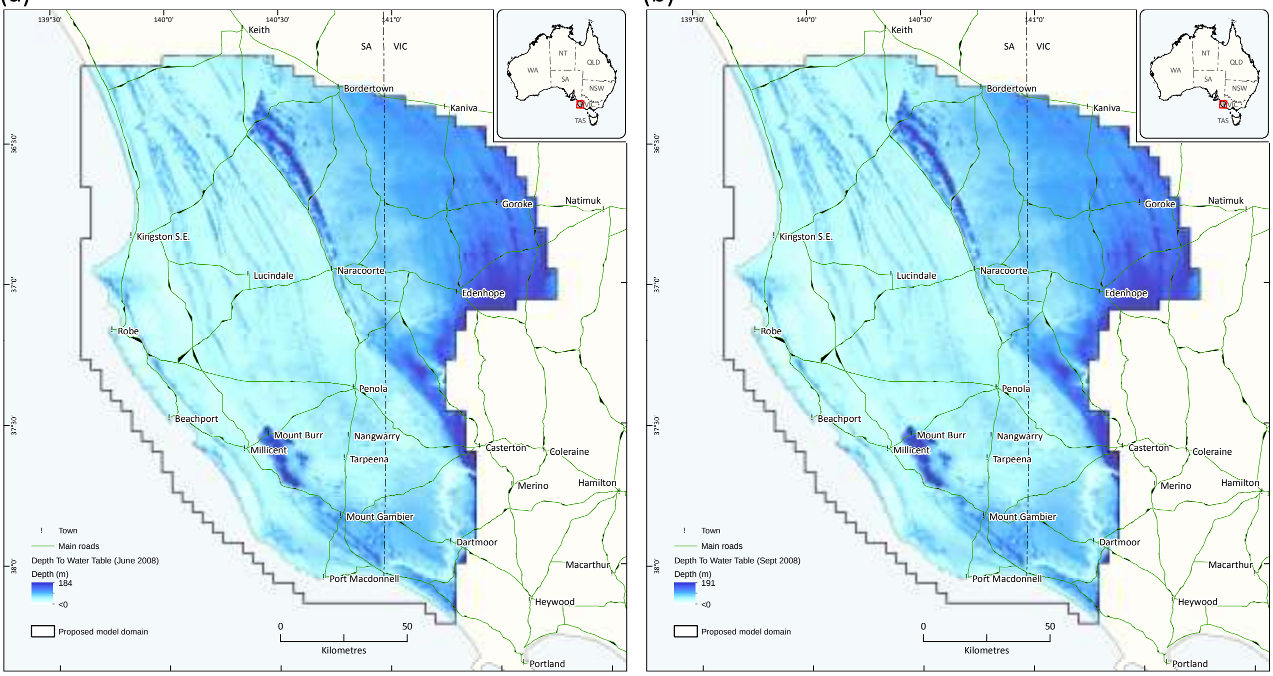


Figure 8.7 Depth to watertable map for (a) June 2008 and (b) September 2008.

Aquifer Properties

Porosity estimates for the unconfined aquifer range from 30% to 50% from borehole geophysics and 49% to 61% from measurements on outcrops (Andrews, 1974; Lawson et al., 2009; Love, 1991). This data also includes the Padthaway and Bridgewater Formations (Love, 1991). More recent estimates of porosity from borehole geophysics are in the range of 6% to 18% for the Gambier Limestone, 5% to 20% for the Bridgewater Formation and 20% to 30% for fractured rock (Lawson et al., 2009).

Mustafa and Lawson (2002) reviewed all available hydraulic data for the Gambier Limestone in the lower South East. They found that the majority of transmissivity and specific yield values estimated for that area were of low reliability, either due to the length of time over which the pump tests were carried out, the pumping rate used, or the construction or configuration of the bores used. Of the data for the entire lower South East, transmissivities ranging between 35 and 560 m^2/day were considered to be of medium or high reliability. The majority of these values were between 200–500 m^2/day. Only two specific yield estimates, both of 2×10^{-4}, from the Millicent – Tantanoola area, were considered to be of medium to high reliability. The data assessed by Mustafa and Lawson (2002) are included as Appendix B to this report.

As part of their review, Mustafa and Lawson (2002) calculated transmissivity values from specific capacity data using a variety of empirical relationships. This data is also included in Appendix B. It was found that, when plotted spatially with watertable contours, most low transmissivity values overlay the steep gradient zone to the north and north-west of Mount Gambier and high transmissivity values coincide with the flat gradient zone to the south of Mount Gambier. Most of the high transmissivity values were for wells completed in the Camelback Member of the Gambier Limestone. In the hundred of Mingbool, high transmissivity values were also associated with wells completed in the Bridgewater Formation.

Less aquifer property data exists for the Upper South East. The Padthaway Prescribed Wells Area has been a focus of numerous groundwater investigations over the past few decades and, hence, there are a few measurements of aquifer properties in this region. Groundwater extraction in the Padthaway area is predominantly from the Padthaway and Bridgewater Formations and the data focuses on these formations. The Padthaway formation ranges in thickness from 6 to 14 m and transmissivity estimates of range between 1,100 and 11,000 m^2/day, giving an approximate range of hydraulic conductivities between about 80 and 1800 m/day. Transmissivities of the Bridgewater Formation, where it underlies the Padthaway Formation on the Padthaway Flats and is approximately 20 m thick, range between 320 and 2 400 m^2/day, providing hydraulic conductivities of the order of 16 to 120 m/day. In the Naracoorte Ranges, where the Padthaway formation is absent and the most groundwater extraction is from the Bridgewater Formation, average well yields are 30 L/second but highly variable. Most of this extraction occurs from the base of the Bridgewater Formation, which is better consolidated than the upper part, or the top of the Gambier Limestone.

Aquifer Property Values Used in Previous Numerical Models

Based on data from previous reports and production test results, hydraulic conductivity values between 10 and 300 m/day, and specific yield values between 0.1 and 0.25 were considered reasonable by Stadter and Yan (2000) for their numerical model of the Gambier Limestone aquifer in the region to the south of Mount Gambier. Through the model calibration process, they also found that the use of hydraulic conductivity zones ranging between 0.5 and 90 m/day and a specific yield value of 0.1 produced optimum results.

In the original model of the Coles-Short area developed by Mustafa et al. (2006), two layers were used to represent the unconfined aquifer and different hydraulic conductivity zones delineated based on existing data. Conductivity values ranged from 15 to 55 m/day, and specific yield from 0.07 to 0.15. Aquaterra (2010a) updated this model by making it a one layer model, and assigning generally higher hydraulic conductivity values (25 to 78 m/day). These increases in hydraulic conductivity were required to adjust to other updates in the model, such as lower recharge, lower irrigation extraction, the inclusion of evapotranspiration and refined drainage.

A transmissivity of 2000 m^2/day and a specific yield of 0.1 are used routinely for modelling and management of the Border Zone Province 2 region (Border Groundwaters Agreement Review Committee, 2008b).

8.4 Water level trends

The information in this section is sourced from DFW (2011a).

8.4.1 UNCONFINED AQUIFER

Inter-dunal flats

Figure 8.8a presents the representative hydrographs for observation wells in the shallow watertable inter-dunal flats. Here, the watertable is less than three metres below the ground surface and shows a rapid response to rainfall events and high seasonal fluctuations due to losses from the aquifer by evapotranspiration during summer coupled with extraction. The long-term trends are relatively stable with the winter maximum water levels showing a broad relationship with rainfall trends.

Declining trends as a result of reduced recharge

Within the broad coastal plain portion of the study area, there are a number of processes that are affecting groundwater levels. The most widespread driver of groundwater levels in the Lower Limestone Coast PWA has been reduced recharge due to drier conditions since 1993. Figure 8.8b presents groundwater levels from throughout the Lower Limestone Coast PWA that show a consistent decline in groundwater levels since 1993, probably due to reduced recharge. It should be noted that extraction and land use change may also contribute to localised declines. Wetter conditions during recent years have led to some recovery of water levels in most areas.

Impacts of groundwater extraction

Extractions from groundwater resources in the Lower Limestone Coast PWA are used for a number of purposes, including town water supplies, irrigation, industrial purposes and stock and domestic supplies. These activities will impact on groundwater levels where extractions are concentrated. Figure 8.8c displays the response in two observation wells located in an area of intensive licensed extraction in the Donovans Management Area to the south of Mount Gambier. The hydrographs show declining in water levels due to increased extraction, with the large seasonal fluctuations also a response to extraction during summer. Figure 8.8c displays an example of the impacts of licensed extractions (HIN038). All three wells are also showing rising trends due to recent above-average rainfall.

Impacts of land use change around forest plantations

Land use change such as expansion of the plantation forest estate can have a significant effect on groundwater levels. Plantations of *Pinus radiata* and blue gums intercept rainfall and hence reduce recharge into the aquifer. They can also extract groundwater where the watertable is relatively shallow. In Figure 8.8d, observation wells SHT012 and MON035 show the typical fall of several metres in watertable levels in response to the establishment of large areas of blue gums in the late-1990s. The recent rise in both of these wells is likely due to increased rainfall and the harvesting of plantations to the north and east of SHT012. Well MON008 is located in nearby open pasture and displays a similar but smaller declining trend that is due to below-average rainfall and also a more significant response to recharge from increased rainfall during recent years. Well NAN009 is located within a pine plantation near Nangwarry. Following a slow decline in groundwater level due to recharge reduction and possibly direct extraction, water levels show a rapid rise in 1983, following the Ash Wednesday bushfires that destroyed the trees and allowed recharge to the aquifer to occur. After the area was replanted several years later, the decline in groundwater levels resumed.

Water level trends due to clearance of native vegetation

In the unconfined aquifer beneath the Naracoorte Ranges highlands where the depth to the watertable is more than 10 m, groundwater level trends are responding to widespread clearance of native vegetation, which has resulted in increased recharge rates and hence rising groundwater levels. These trends are also recorded in the Tatiara and Padthaway PWAs to the north. Figure 8.8e presents the gradual rising trends of up to 0.2 m/year for several representative observation wells. This rising trend persisted for several years after the prolonged period of below-average rainfall commenced in the mid-1990s, as shown by the cumulative deviation from mean annual rainfall graphed in orange for the nearby Frances rainfall station (26007).

Most observation wells now show stable or declining trends in a delayed response to the below-average rainfall, with the lag time varying depending on the depth to the watertable and the permeability of the sediments.

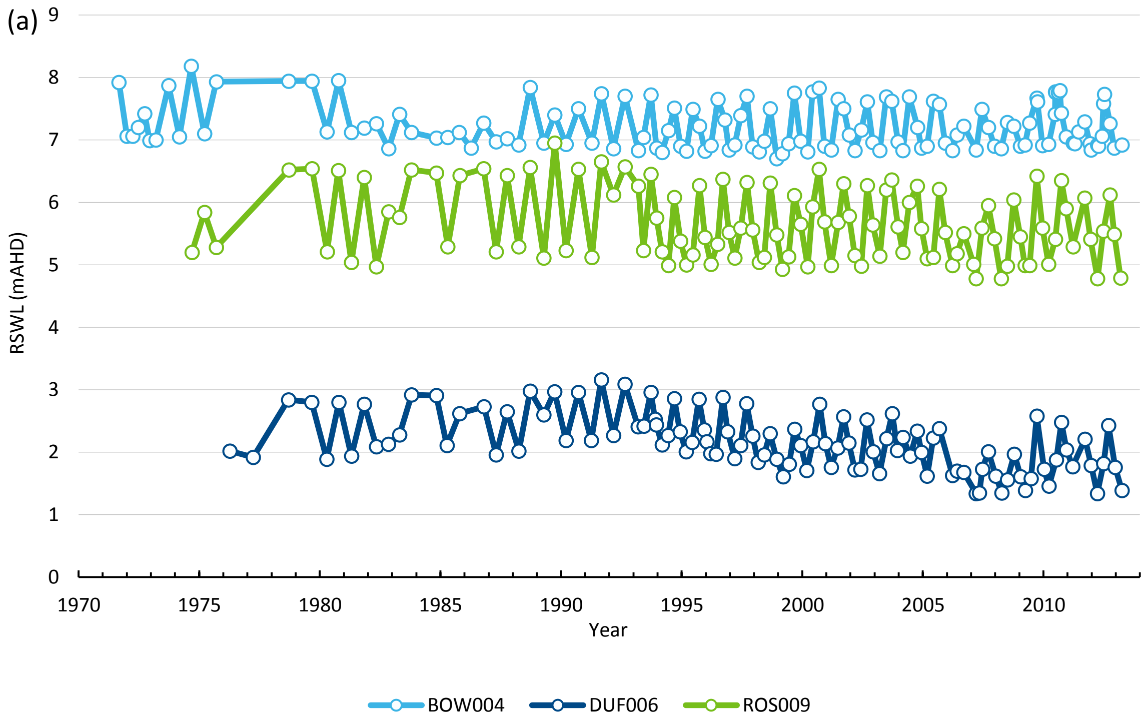
Water level below sea level

Three observation wells between Robe and Beachport near the coast have recorded groundwater levels lower than sea level (i.e. 0 mAHD). Hydrographs for the three wells are shown in Figure 8.8f. WAT012, which is the closest well to Robe, has recorded groundwater levels lower than sea level throughout the measurement period, with an average water level at -1.2 mAHD. Water levels at LKG013, which is further away from Robe, are below sea level for most of the time, with an average water level of -0.4 mAHD. BRA023 is located further inland compared to the other two wells and its groundwater levels only drop below sea level occasionally.

8.4.2 CONFINED AQUIFER

Over most of the Lower Limestone Coast PWA, outside the central artesian area (inland of Kingston to Beachport), the water level trends in the confined aquifer were relatively stable until 1993, after which declining trends are evident as shown in Figure 8.9a. There is limited extraction from the confined aquifer in this area and no direct recharge from rainfall and therefore the trends (which are identical to those recorded for the overlying unconfined aquifer in Figure 8.8b) are thought to be caused by the process of hydrostatic loading. A falling watertable results in less water being stored in the unconfined aquifer and consequently, less weight pressing down on the confining layer. This reduction in weight reduces the hydrostatic pressure on the underlying confined aquifer and causes confined water levels to also fall (Harrington and Cook, 2011). It should be noted that investigations are underway to examine the contribution of leakage between aquifers in causing these falling trends.

The hydrographs for the confined aquifer observation wells in the central artesian area (inland of Kingston to Beachport) show significant seasonal fluctuations due to high levels of irrigation use in the area (Figure 8.9b). The water level trends are consistent and show both rising and falling trends since 1990. The rise in pressure levels over the last few years is due to the South East Confined Aquifer Well Rehabilitation Scheme which has greatly reduced the number of uncontrolled flowing wells and allowed increased irrigation efficiency. The increased hydrostatic pressure from the rising watertable in the overlying unconfined aquifer may have contributed during recent years. Note that MAC077 near Port MacDonnell is very close to the coastline and its groundwater level is higher than the sea level by approximately 18 m.



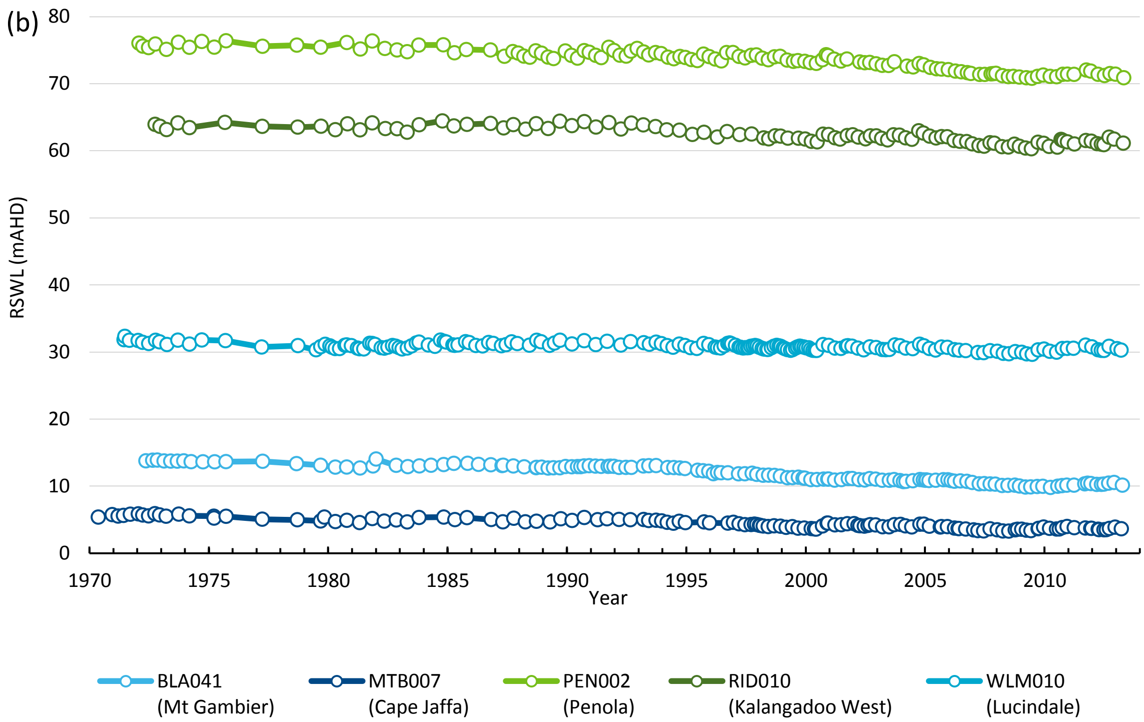
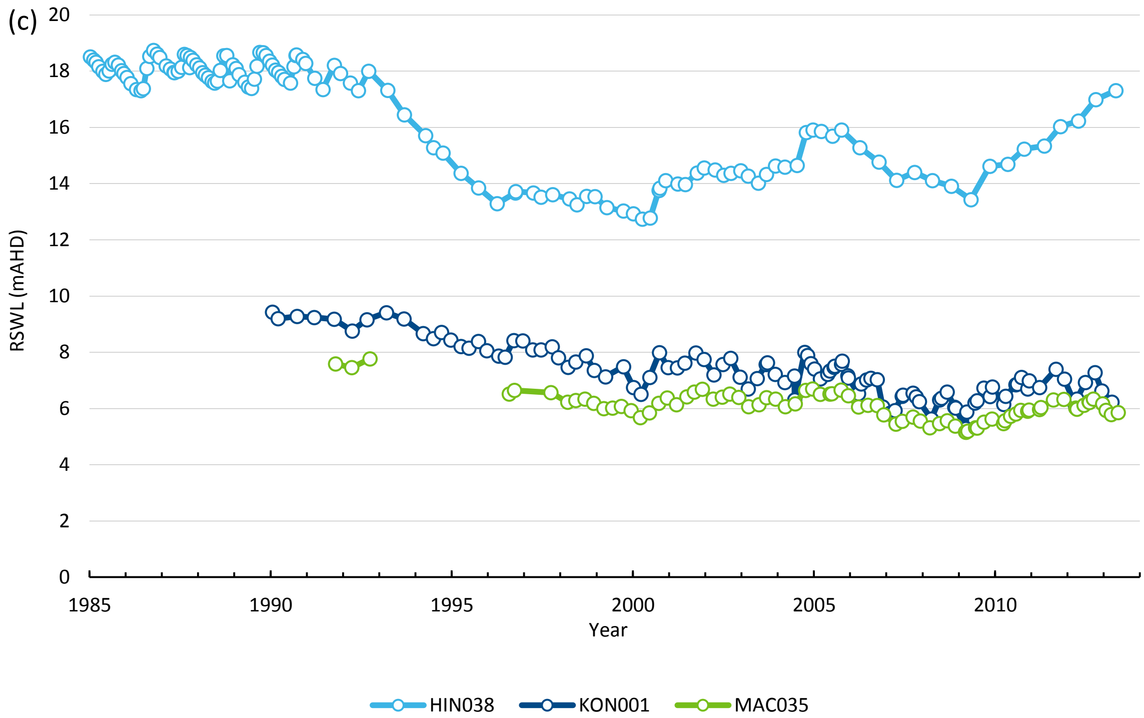


Figure 8.8 Groundwater level trends for the unconfined aquifer in the Lower Limestone Coast PWA: (a) inter-dunal flats, (b) coastal plain: regional, (c) costal plain: near extractions, (d) coastal plain: beneath forested areas, (e) highlands and (f) coastal plain: below sea level. Note that the graphs above are in different scales.



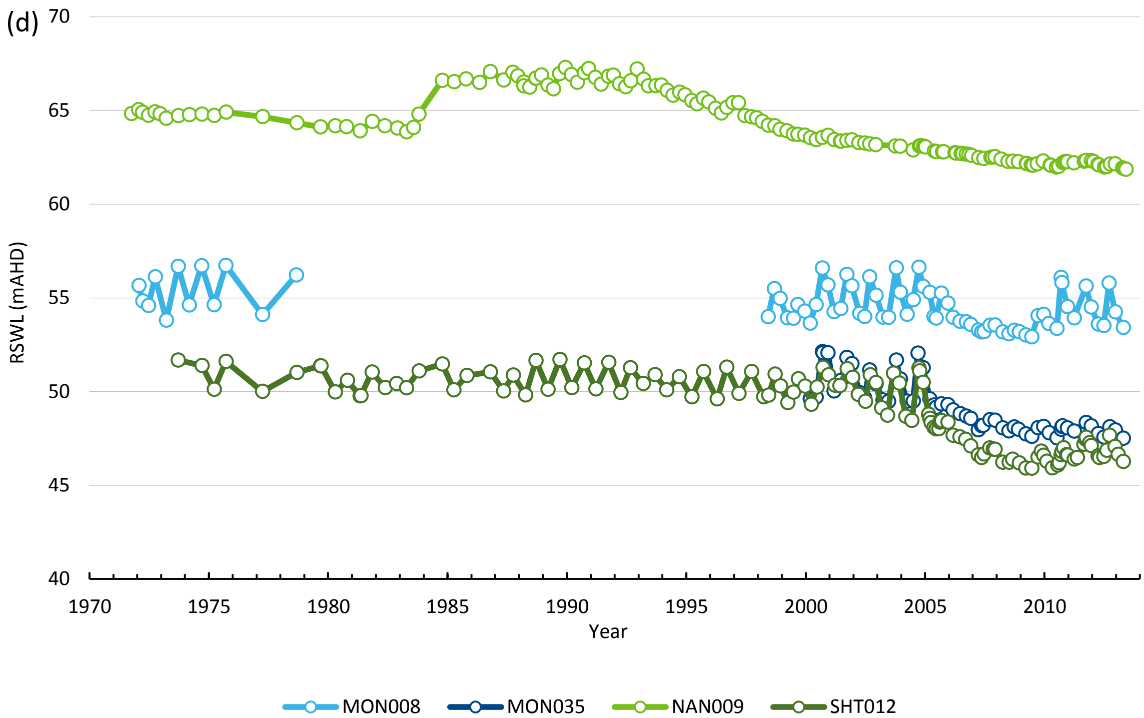
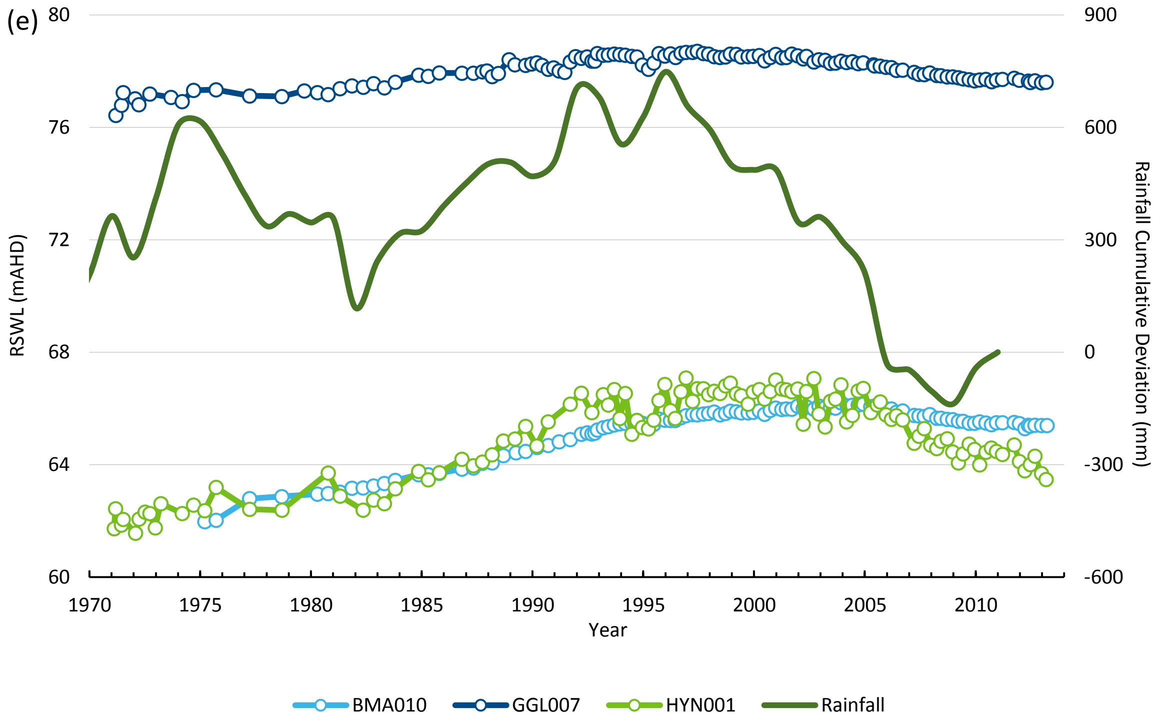
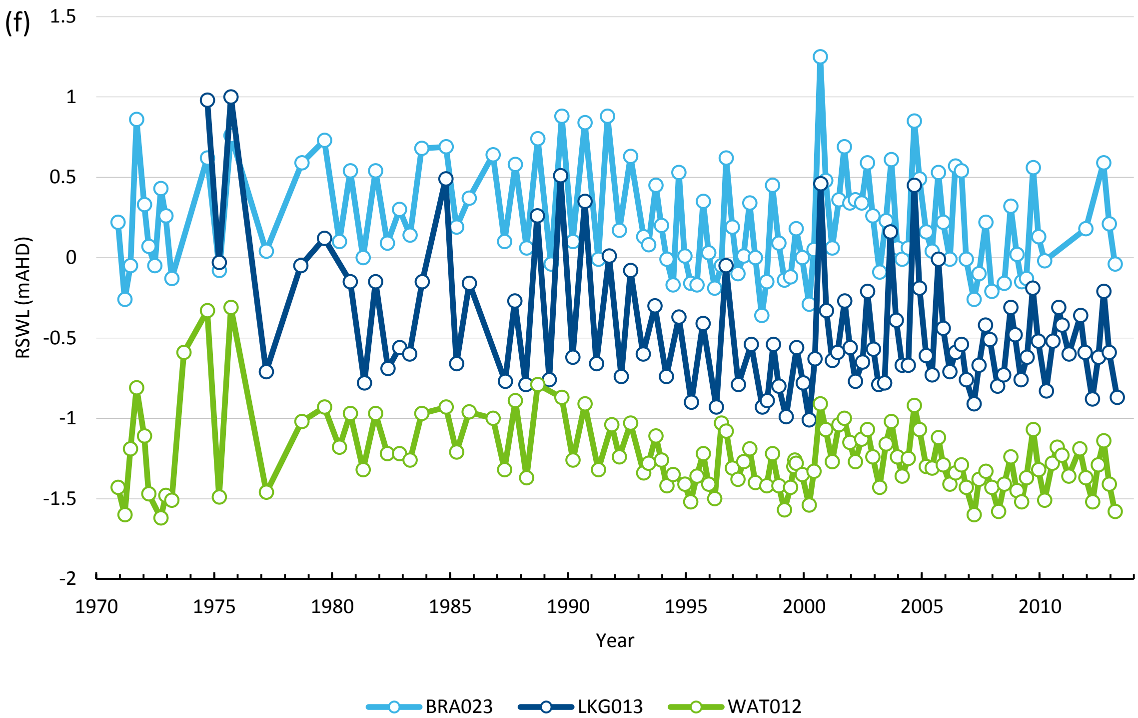


Figure 8.8 continued





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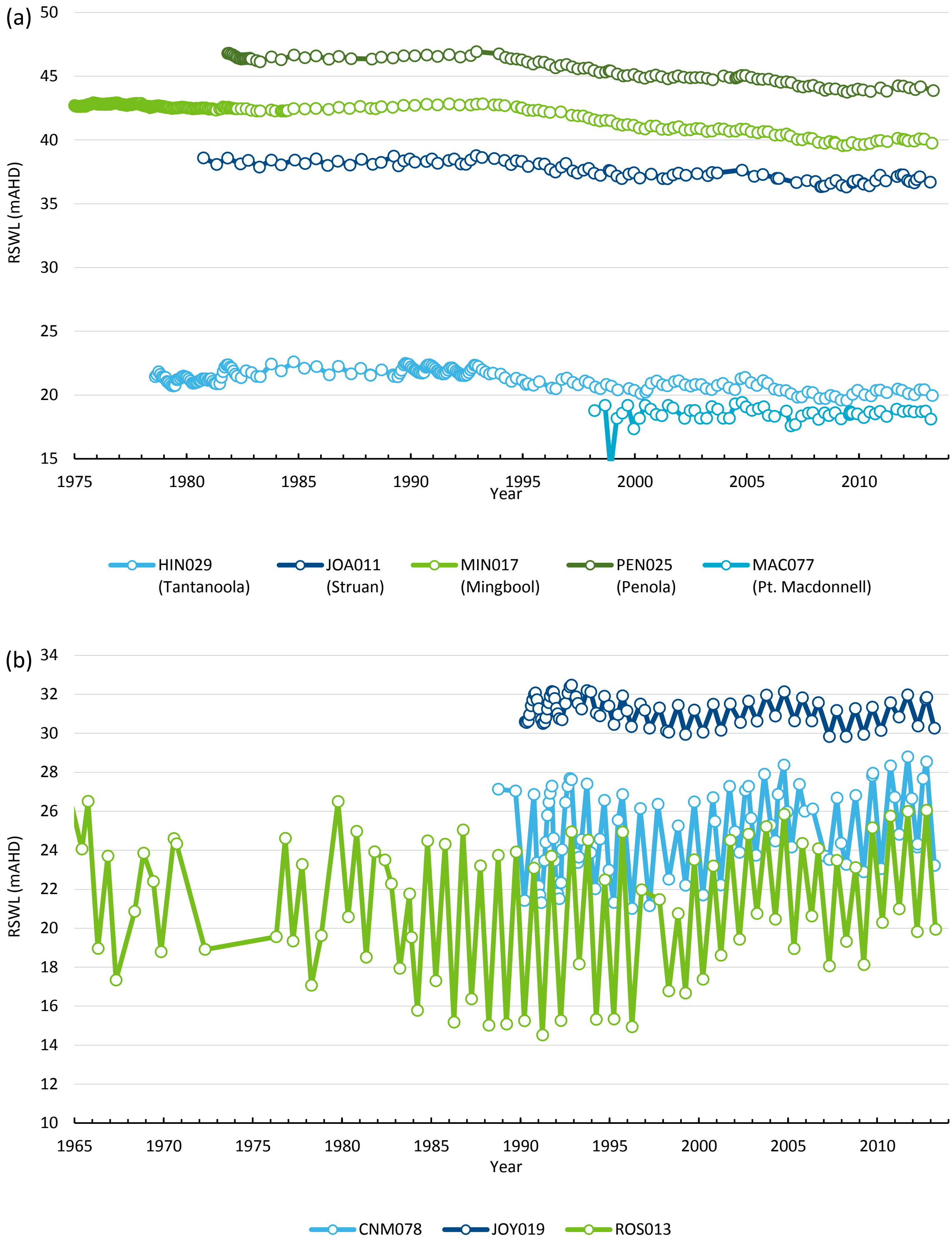


Figure 8.9 Groundwater level trends for the confined aquifer in the Lower Limestone Coast PWA: (a) regional and (b) artesian part of the confined aquifer. Note that the graphs above are in different scales.

8.5 Surface Water

Appendix C provides a summary of the available surface water gauging data and the data archived and graphed for this project.

8.5.1 NATURAL WATERCOURSES, SWAMPS AND WETLANDS

The surface water hydrology of the South East is complex and has been greatly modified since European settlement (Wood and Way, 2010). Broad scale land clearing and an extensive drainage network have converted what was once a wetland-dominated landscape into broad scale agricultural production. Historically, the South East contained a vast area of inter-connected wetlands that covered approximately 40% of the landscape. It is estimated that less than 6% of the original wetlands in the South East remain and that those that do remain are subject to a significantly altered hydrology (Brooks, 2010).

The natural hydrological pattern is for high rainfall events to flood the low gradient flats into an interconnected series of slowly draining wetlands. Flow in these is generally impeded by the low slope of the topography and the transverse dune system, resulting in the occurrence of numerous swamps and wetlands, lakes and sinkholes in inter-dunal corridors. These swamps and wetlands usually occur over shallow watertables and clay horizons during the wet winter months, as a result of clay soils holding surface water in low lying depressions, and are typically found to the north of Mount Gambier.

Most runoff is generated from the Lower South East and the cross-border catchments of the Morambro, Naracoorte and Mosquito Creeks. These creeks flow across the SA/Victorian border into the South East of South Australia (Figure 2.4). Historically, runoff from the cross-border catchments has combined with local runoff to fill wetlands and slowly drain north-westwards towards the Coorong over time scales of months (Wood and Way, 2010) (Figure 8.10). Mosquito Creek discharges into Bool Lagoon, a RAMSAR listed wetland complex south-west of Naracoorte. Morambro Creek discharges into Cockatoo Lake north-west of Naracoorte, and is the only prescribed surface watercourse in the South East. Flow in all of these creeks is ephemeral, and highly dependent upon winter rainfall. In wet years, the northward flowing water would provide freshening flows to the Coorong via Salt Creek.

Other springs feed creeks such as Deep Creek, Jerusalem Creek and Cress Creek, which discharge to the coast south of Mount Gambier. Cress Creek and Jerusalem Creek are ephemeral streams fed by shallow spring discharge sourced from groundwater with an apparently low residence time in the unconfined Tertiary Limestone Aquifer (Wood, 2011). Wood (2011) provides a good description of the coastal springs and creeks to the south of Mount Gambier. Flow has been periodically gauged in these creeks since the 1970s, and mean annual discharge to the coast from all these sites is ~ 97 GL/year (Figure 8.11).

Piccaninnie Ponds and Ewens Ponds are karst spring complexes that receive groundwater from the unconfined Tertiary Limestone Aquifer. Piccaninnie Ponds was RAMSAR listed in 2012 (M. Gibbs, pers. comm., 2013). Parts of Piccaninnie Ponds are believed to be in excess of 100 m deep and hydrochemical evidence suggests that Piccaninnie and Ewens Ponds receive at least some of their inflow from deeper units of the unconfined aquifer (Wood, 2011). Water from Piccaninnie Ponds discharges to the coast via an outlet drain. Water from Ewens Ponds discharges to the coast via Eight Mile Creek. Some water flows seasonally from Piccaninnie Ponds into Pick Swamp, a wetland site on the western side of Piccaninnie Ponds Conservation Park at a rate of about 1 to 5 ML/day, eventually evaporating or discharging to the coast via another outlet (Wood, 2011). Pick Swamp is also fed by another smaller spring, Crescent Pond, which is 4 to 6 m deep and located up-gradient of Pick Swamp.

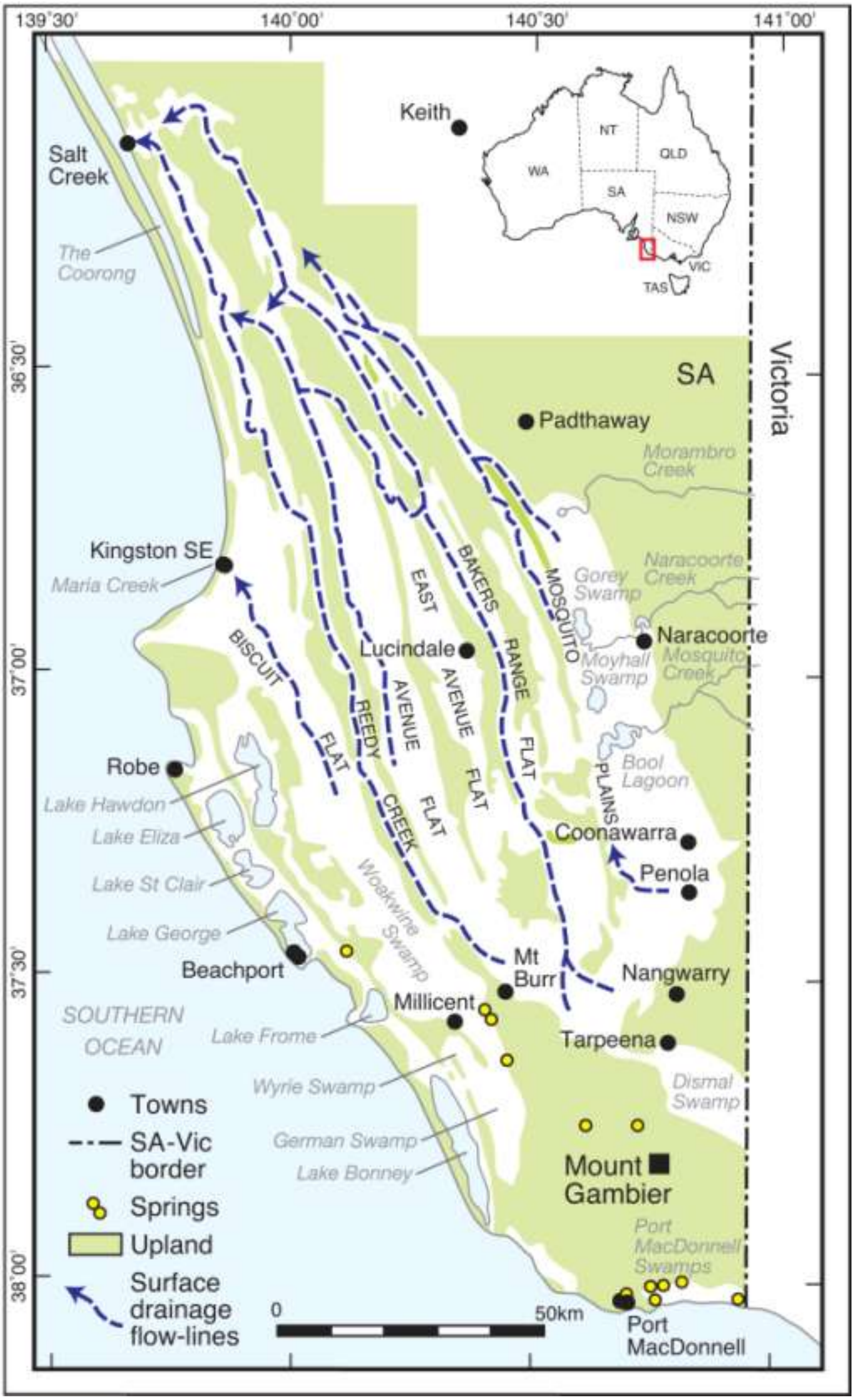
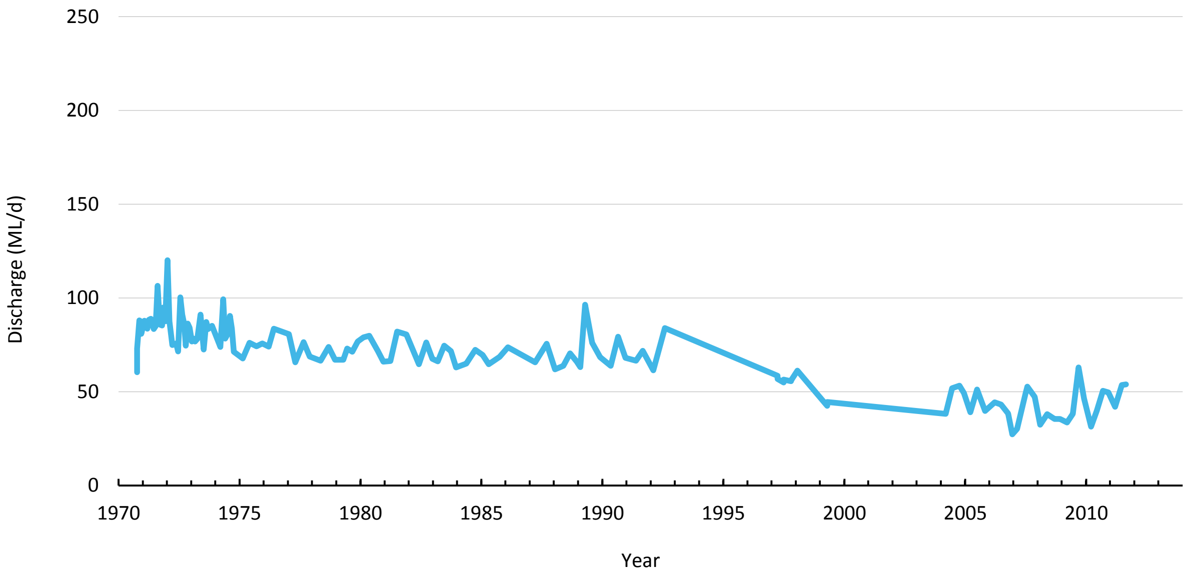


Figure 8.10 Pre-European drainage patterns and spring locations (reproduced from Williams (1964)).

(a)



(b)

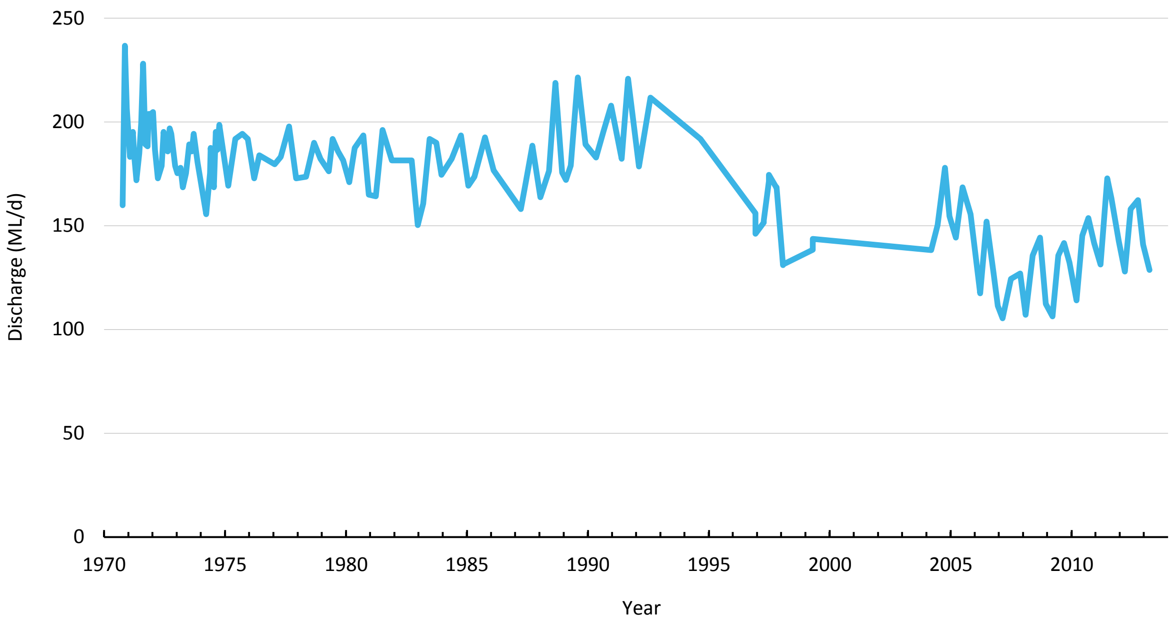
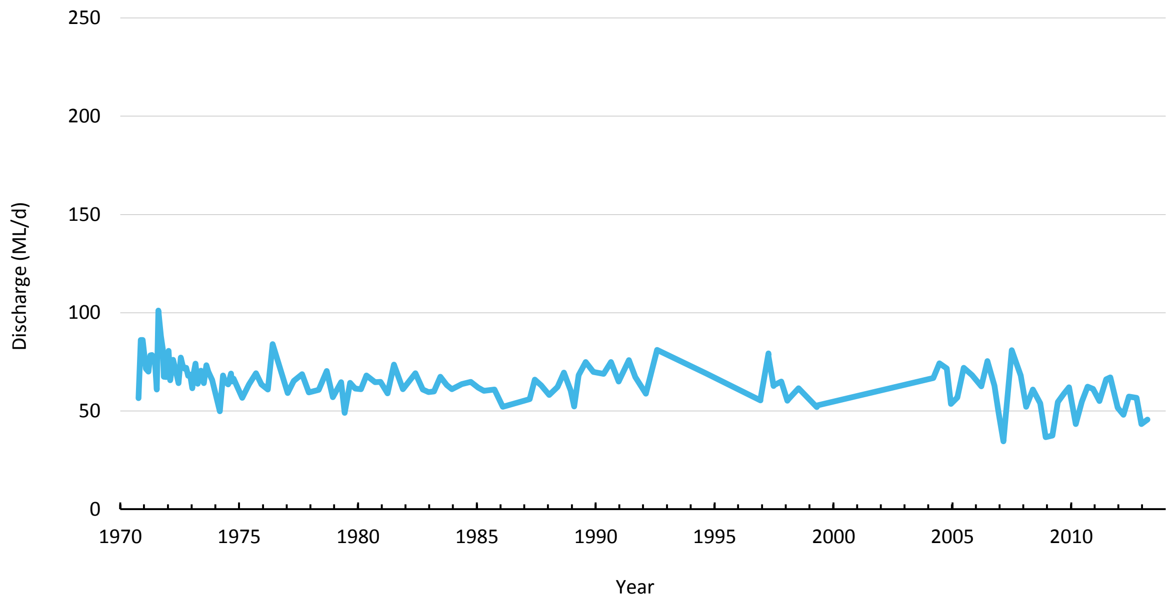


Figure 8.11 Measured outflows at the coastal outlets: (a) Piccaninnie Ponds Spring Discharge, (b) Eight Mile Creek, (c) Deep Creek and (d) Cress Creek.

(c)



(d)

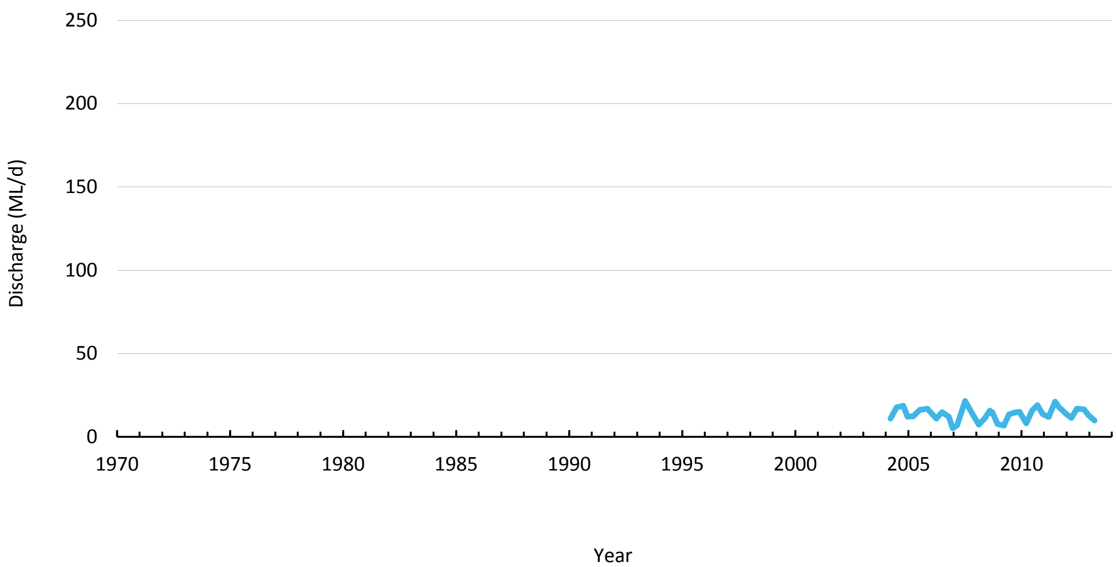


Figure 8.11 continued

Mean daily flows at gauging stations on the cross-border creeks, Morambro Creek, Mosquito Creek and Naracoorte Creek are shown in Figure 8.12. Figure 8.12 shows the ephemeral nature of these creeks, with flows only occurring during winter. Mosquito Creek, which discharges into Bool Lagoon, has the highest flows and flows most years, whilst Morambro and Naracoorte Creeks are more intermittent (Figure 8.12). These gauging stations also record water levels and EC.

The Glenelg River flows through the Victorian portion of the study area and is the only major watercourse in that region. There is little information available on the hydrological characteristics of the river. There are gauging stations located at Dartmoor, for which gauging data is available, and at Sandford, just south-east of Casterton, for which there is 58 years of flow data.

The upper units of the Tertiary Limestone Aquifer are likely to be connected to the Glenelg River. Although the nature of this interaction has not yet been determined, it is likely that groundwater discharges into the river (Border Groundwaters Agreement Review Committee, 2008a). In addition, the TCSA outcrops near the river and may be recharged by the river (Border Groundwaters Agreement Review Committee, 2008a). A transect of observation wells occurs perpendicular to the Glenelg River, where it crosses into South Australia (Figure 8.13). The details of these wells are presented in Table 8.3.

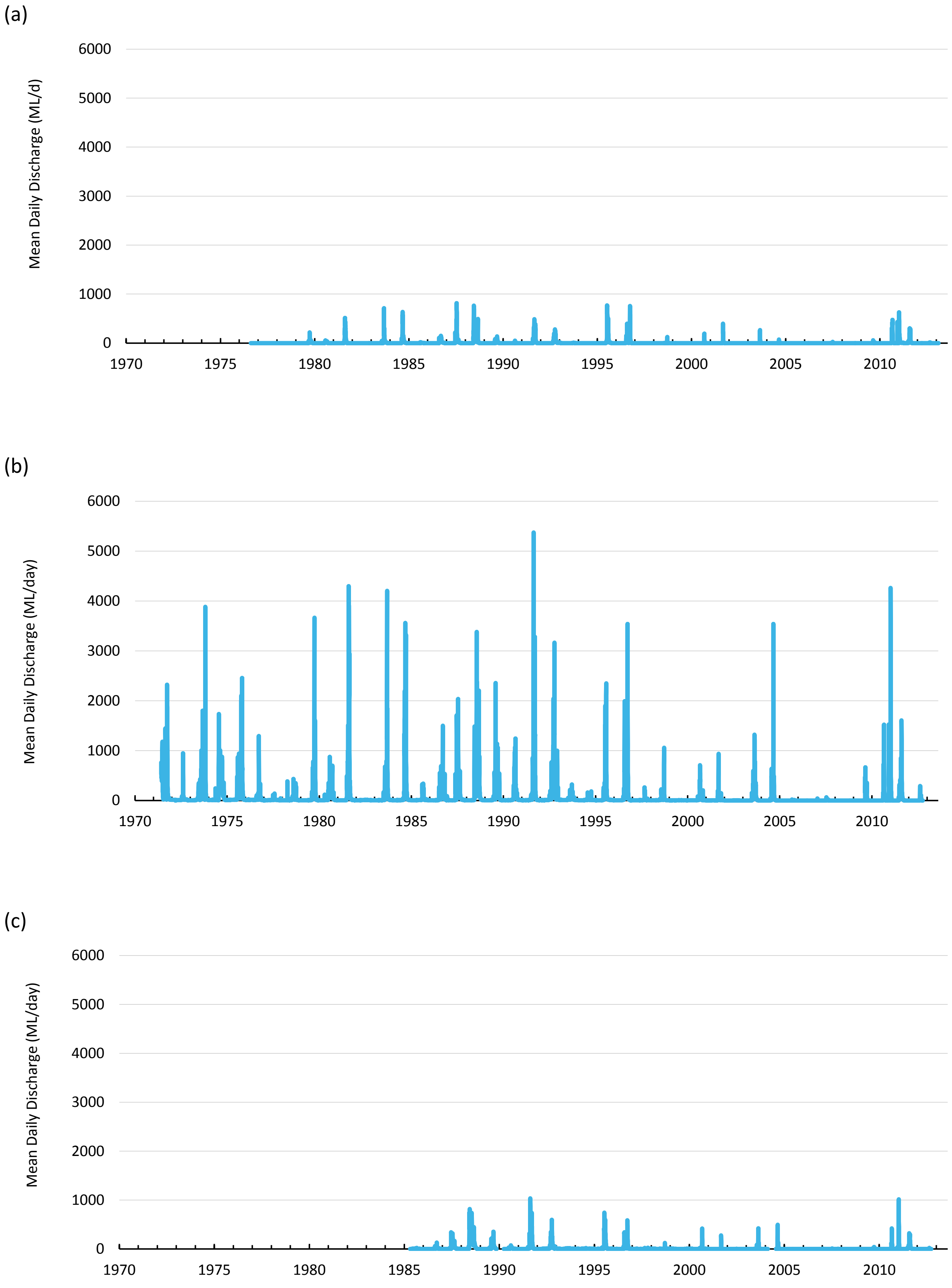


Figure 8.12 Mean Daily Flows at gauging stations on the cross-border creeks: (a) Morambro Creek, (b) Mosquito Creek and (c) Naracoorte Creek.

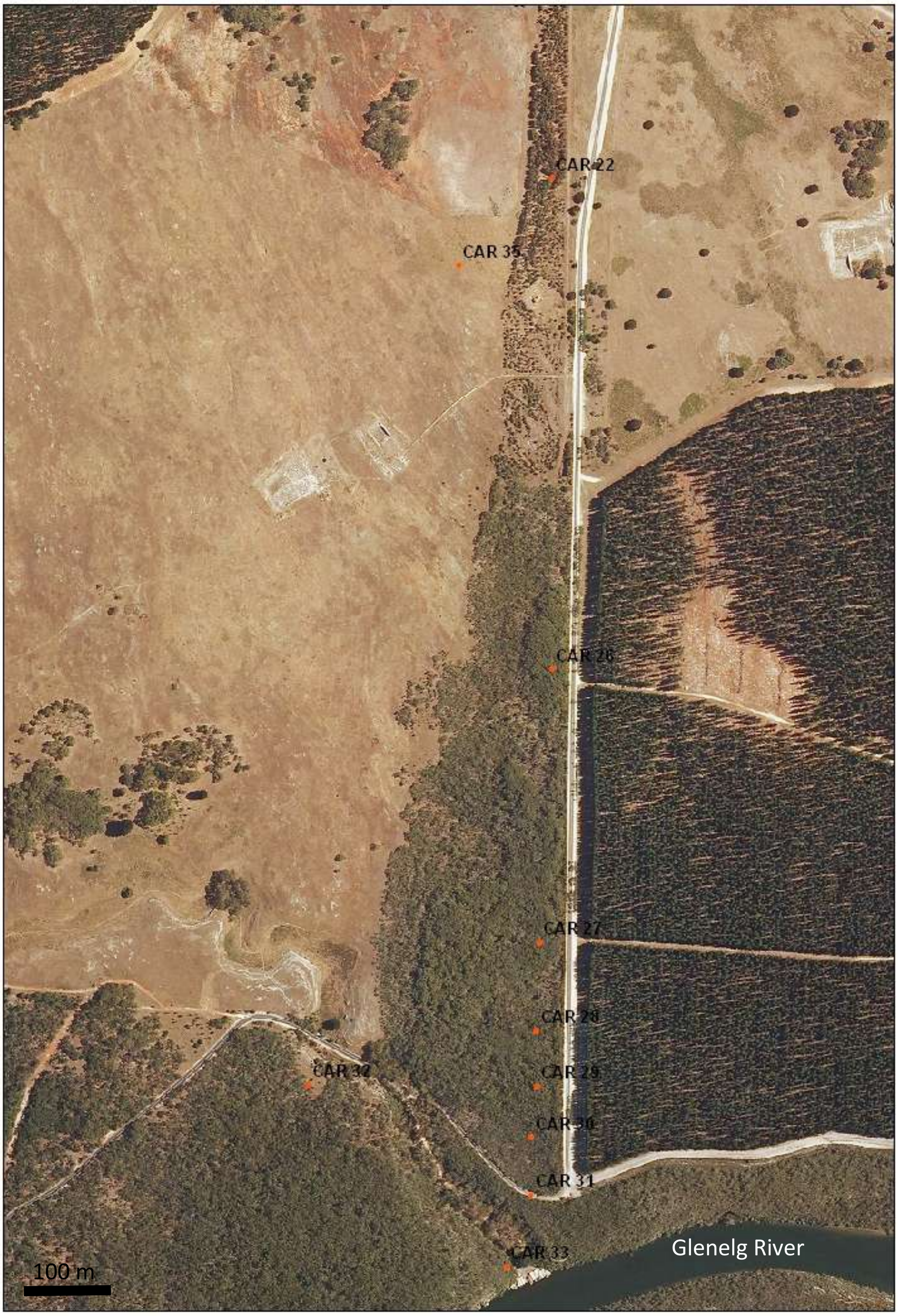


Figure 8.13 Locations of observation wells in transect perpendicular to Glenelg River.

Table 8.3 Details of observation well transect located perpendicular to the Glenelg River.

Obs No.	Easting	Northing	Distance from river (m)	Screen depth (m bgl)	Ref elev. (m AHD)	Latest RSWL (m AHD)	Latest EC (µS/cm)	SWL Record	EC record
CAR033	496983	5794881	30	na	0.89	0.26	23 300	1974-1993 2011-2013	1981 only
CAR031	497023	5794997	100	30-36	26.18	0.55	805	1974-1976 2011-2013	1974 only
CAR030	497023	5795089	200	39-45	30.82	0.64	831	1974-1976 2011-2013	1974 only
CAR029	497033	5795172	300	40-46	31.15	0.73	726	1974-1976 1982,1996 2011-2013	1981 only
CAR028	497031	5795261	420	44-50	34.12	0.85	776	1974-1976 2011-2013	1974 only
CAR032	496665	5795174	470	13.5-26	11.93	1.62	482	1974-1976 1996-1998	1973
CAR027	497036	5795403	500	34-40	23.63	2.09	828	1974-1975	1974 only
CAR026	497057	5795843	940	37-43	28.82	1.78	673	1974-1982	1981 only
CAR035	496907	5796492	2200	24-31	22.28	3.08	636	1980,2001,2003	1975 only
CAR022	497057	5796632	1760	22.2-28.1	21.78	3.18	520	Constant between 1971-2013	1981,2008

A summary of the gauging station data available for other natural watercourses in the study area is provided in Appendix C . Locations of all current gauging stations are shown in Figure 2.4.

Harding (2012) provides a map, included in this report as Appendix D , of wetland extent prior to European settlement compared with current extents. Wetland inventories have mapped over 16,000 wetlands in the South East of SA and have identified 45 ecologically significant groundwater-dependent wetland complexes including the RAMSAR listed Bool and Hacks Lagoon and internationally renowned Piccaninnie Ponds (Harding, 2012). The South Australian Wetland Inventory Database (SAWID) for the South East region, previously managed by DENR (now DEWNR), provides detailed mapping of wetland ecosystems completed for wetland inventories in the Lower South East (Taylor, 2006) and Upper South East (Harding, 2007) regions. The wetlands spatial layer identifies 16,695 wetland polygons across the South east, and incorporates Microsoft Access ® related tables, including biological, physical and chemical attributes for inventoried wetlands (Harding, 2012). Harding (2012) provides maps of environmental significance, national and international significance of wetlands for the South East of SA.

Fass and Cook (2005) carried out a reconnaissance survey of the groundwater dependency of wetlands in the South East using steady state mass balances of chloride and radon to calculate volumes of surface water and groundwater inflow. Their results indicated that, of the 70 samples collected from 38 sites, 63% had negligible groundwater input, 26% had low groundwater input, 1% had moderate groundwater input and 10% had high groundwater input. In a detailed radon mass balance study of a shallow wetland in the Honan Native Forest Reserve, approximately 16 km west-north-west of Mount Gambier, Cook et al. (2008) estimated the groundwater inflow to vary between 12 and 18 m^3/day.

Coastal lakes occur along the majority of the coast in the study area. These represent a special type of surface water feature. The base elevations of these lakes are captured in the DEM and many of them receive surface water inflows from drains (Figure 2.4).

8.5.2 DRAINS

Historical Development

Approximately 2000 km of drains have been constructed throughout the South East since the 1860s. The network now consists of a combination of shallow drains (<2 m deep), and deeper drains (>2 m deep) designed to intercept groundwater (Figure 2.4). Historically, they were constructed to drain the valuable agricultural land on the flats and make it more agriculturally viable. In the early stages of settlement, drainage schemes were small and their impacts localised (Figure 8.14). However, as regional flooding problems persisted, the drainage became more extensive and a series of cross-country drains were built to convey floodwaters directly to the ocean, fulfilling the vision of the Surveyor-General at the time, George W. Goyder. Drain M is the largest of these cross-country drains. Figure 8.14 shows the development of the drainage network over time.

Recent Developments: the Upper South East Dryland Salinity and Flood Management Program

Whilst the drainage network has been very effective at draining flood waters out to the ocean, there is now widespread recognition that the water should also be used to maintain wetlands in the region. The Upper South East Dryland Salinity and Flood Management Program (USE Program), carried out over the past few decades has been designed partly to facilitate this. It was also a response to a history of flooding and salinity issues in the USE region. It has been estimated that, prior to the Program, 250,000 hectares or 40% of productive agricultural land in the USE region was degraded by salinisation caused by high groundwater levels and flooding. A further 200,000 hectares, including 40,000 hectares of high value wetlands and native vegetation were also at risk. This was a long-standing problem in the USE, but was brought to the forefront when aphid infestations in 1978 ruined lucerne crops with the resulting increase in recharge causing widespread flooding during the 1980s and early 1990s.

The USE Program has included the construction of a network of approximately 714 km of saline and freshwater drains, and floodways connected to natural watercourses and wetlands (Figure 8.14). The study area for the Regional Water Balance Model includes part of the USE Program network. The USE Program has sought to satisfy multiple, and sometimes competing objectives, including (DFW, 2011b):

- Protecting agricultural and environmental lands from dryland salinity;
- Mitigating widespread and prolonged flooding
- Providing environmental flows to protect and enhance wetland and watercourse ecological values; and
- Protecting and enhancing ecological values of remnant natural areas (terrestrial and wetland) through management agreements with private landholders.

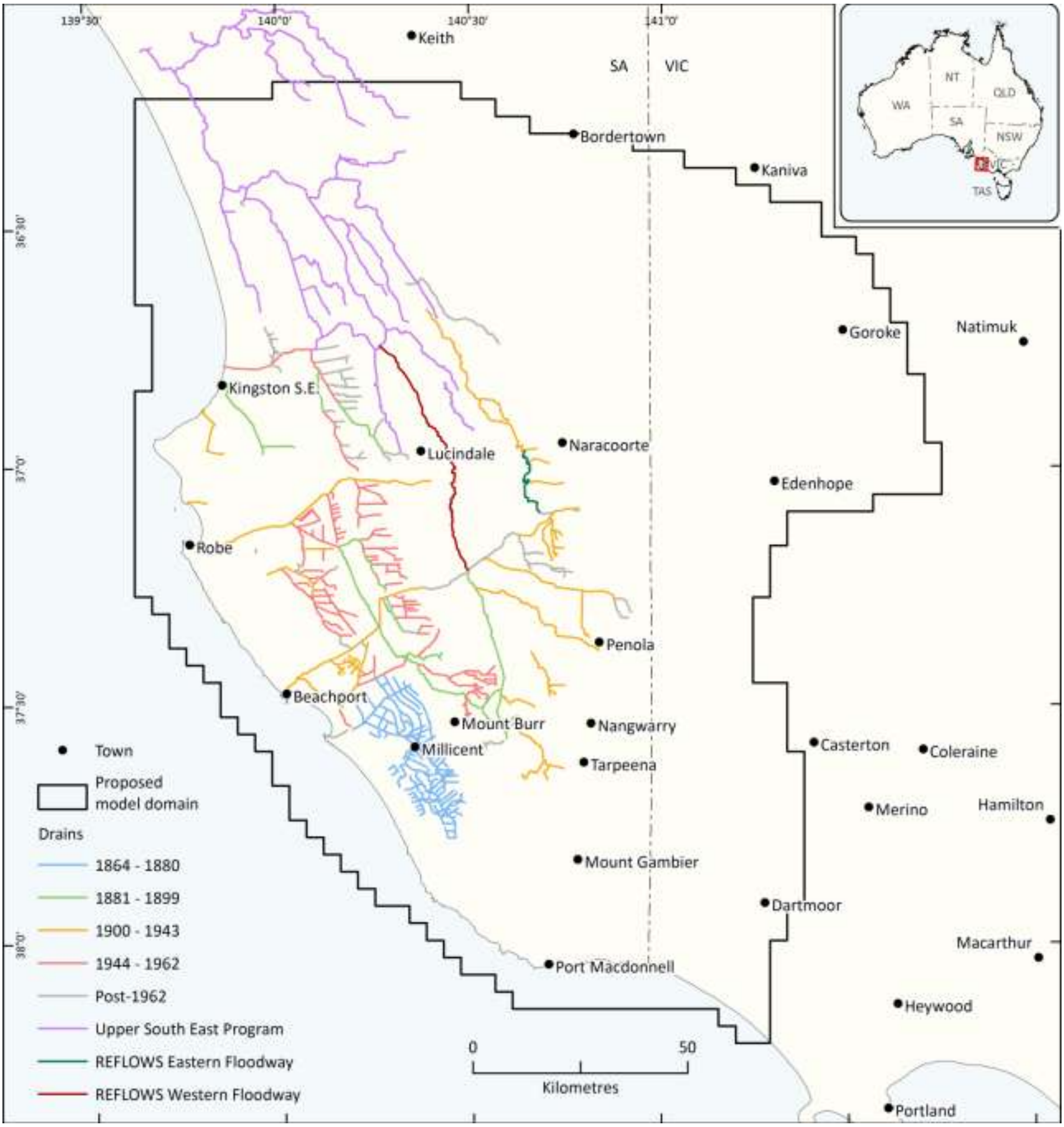


Figure 8.14 Development of the South East drainage network over time (reproduced from Williams 1964)). Note: REFLOWS Eastern Floodway was proposed but has not yet been completed.

The final engineering component of the USE Program, which was establishment of the REFLOWS Western floodway to reconnect historical environmental flow paths from catchments in the Lower South East to the wetlands of the USE, was completed in May 2011. The REFLOWS initiative provides the capacity to capture some of the surface water that is currently drained to sea and use it to supplement environmental flows to wetlands of the USE. In periods of high rainfall/runoff, it aims to deliver environmental flows to the south lagoon of the Coorong.

Flows along the USE network are manipulated by 140 flow regulating structures, including regulators and weirs. A decision support system is currently being developed to optimise the control of surface water flows for the benefit of high value environmental assets and productivity of agricultural land. Feeding into this is information on the region's wetlands, captured in the regional SA Wetland Inventory Database (SAWID), which then provides environmental flow objectives to an Adaptive Flows Management System.

8.5.3 RECORDS OF WATER MOVEMENT

There is little historical record of the operation of control structures to move water around the landscape, besides the gauging station data described above. The Decision Support System for the drainage network provides a record of the operation of control structures and became operational in 2011, however this is a relatively short period of time to ascertain the behaviour of the drains, particularly for model calibration. Anecdotal records may also provide some insight. For example, DFW (2011b) describes recent filling of wetlands:

- 2004 and 2005 – wetlands along major watercourses in the USE received reasonable environmental flows. However, these did not fill the large wetland areas of the Northern Bakers Range, Gum Lagoon/Duck Island Complex, or Tilley Swamp.
- 2006 to 2008 – almost no catchment runoff.
- Winter 2009 – many wetlands along the Marcollat, Bakers Range, West Avenue and Taratap watercourses received refreshing flows, however flows were insufficient to fill or flush through to the large northern wetlands.
- 2010 – wet winter conditions provided significant system flows through the USE, allowing multiple opportunities for the diversion of water into wetlands. This included sustained release from the Morella Basin into the Coorong (outside study area), inundation of Lochaber Swamp from Drain E, inundation of the Taratap Swamps from the Taratap Drain, delivery of environmental flows to the West Avenue Watercourse, and filling of Willalooka Wetlands and Mandina Marshes.
- 2010 – an unseasonal rainfall event in December enabled water to be diverted to the West Avenue watercourse.

8.5.4 SURFACE WATER – GROUNDWATER INTERACTIONS

The majority of the surface water – groundwater interactions occurring around drains are of the gaining type (groundwater discharge to drains). Comparison of a depth to watertable map with the locations of the drains supports this (Figure 8.7). However, the spatial and temporal variability of fluxes of this discharge is not well understood. Wood and Way (2010) estimated groundwater flows to drains for a series of six east-west cross-sections, each intersecting between two and four north-south trending drains. The estimates were made for September 2004 and inflows ranged between 0.3 and 2 ML/km/day. Harrington et al. (2012) carried out a preliminary reconnaissance of ^{222}Rn concentrations and electrical conductivity (EC) of drain waters across the South East drainage network to evaluate the usefulness of these tracers in quantifying surface water – groundwater interactions. The results, included as Appendix E , provided semi-quantitative assessments of the contribution of groundwater to drain flows could be made for the sampling periods.

8.5.5 BLUE LAKE

One of the most significant surface water bodies in the South East is the Blue Lake, located at Mount Gambier and acting as the primary water supply for the rural city. Blue Lake is a volcanic crater lake, thought to have been formed at least 28,000 years ago (Leaney et al., 1995). It covers an area of 6.03 x 10^5 m^2, has a volume of ~ 30 GL, and a depth of 74 m (Figure 8.15). It is fed almost exclusively by groundwater discharge. Due to the steep sides of the lake, its catchment is only 10% greater than the lake surface itself.

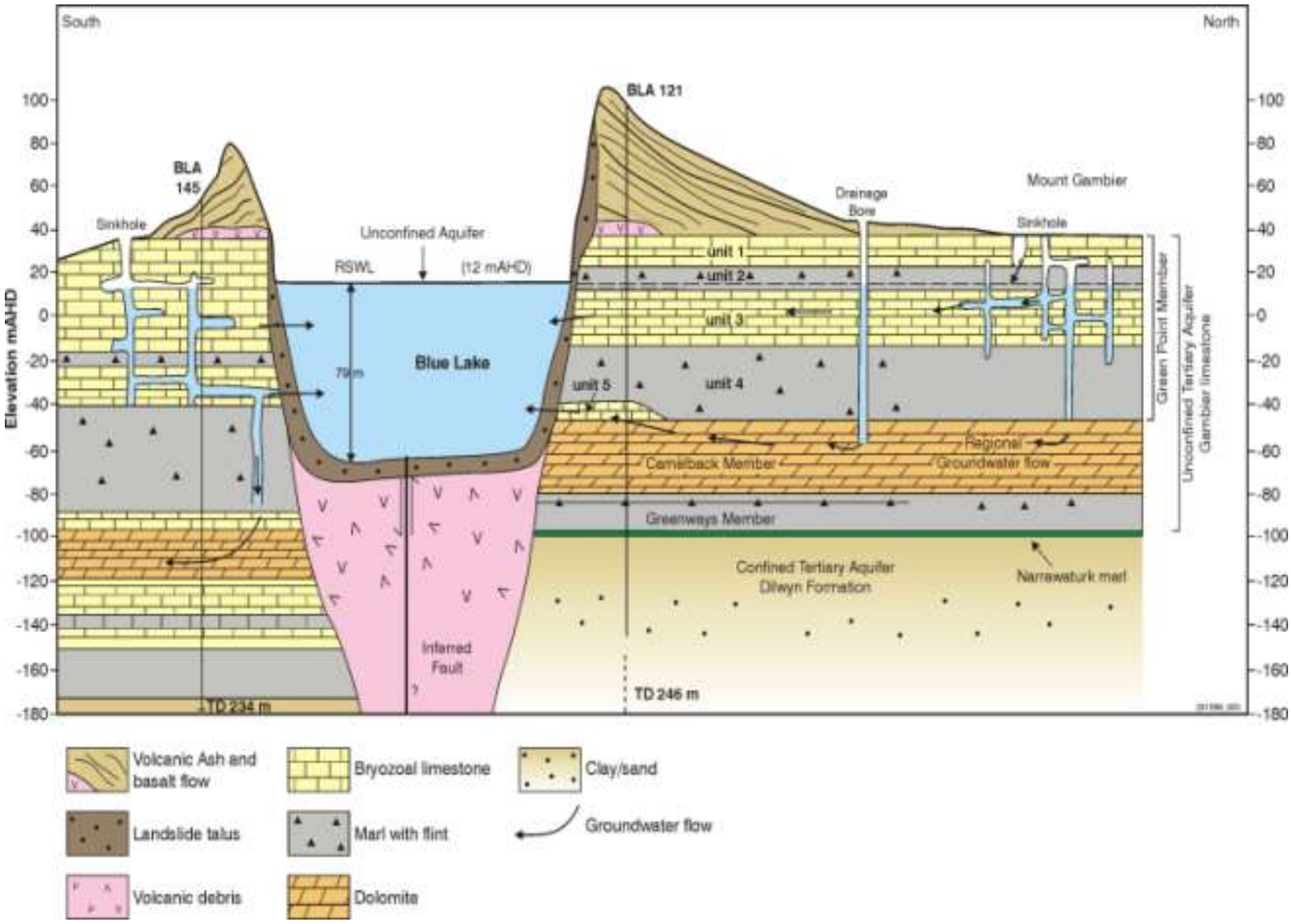


Figure 8.15 Conceptual diagram of the Blue Lake (Lawson and Hill, in prep).

Lake inflow occurs at around 50 m below the lake surface (-39 mAHD), which coincides with the location of the dolomitic Camelback Member of the Gambier Limestone Fm. To the south of the lake, it is possible that Unit 1 of the Green Point Member provides inflow to the lake, whilst some outflow occurs via the Camelback Member (J. Lawson, pers. comm., 2013).

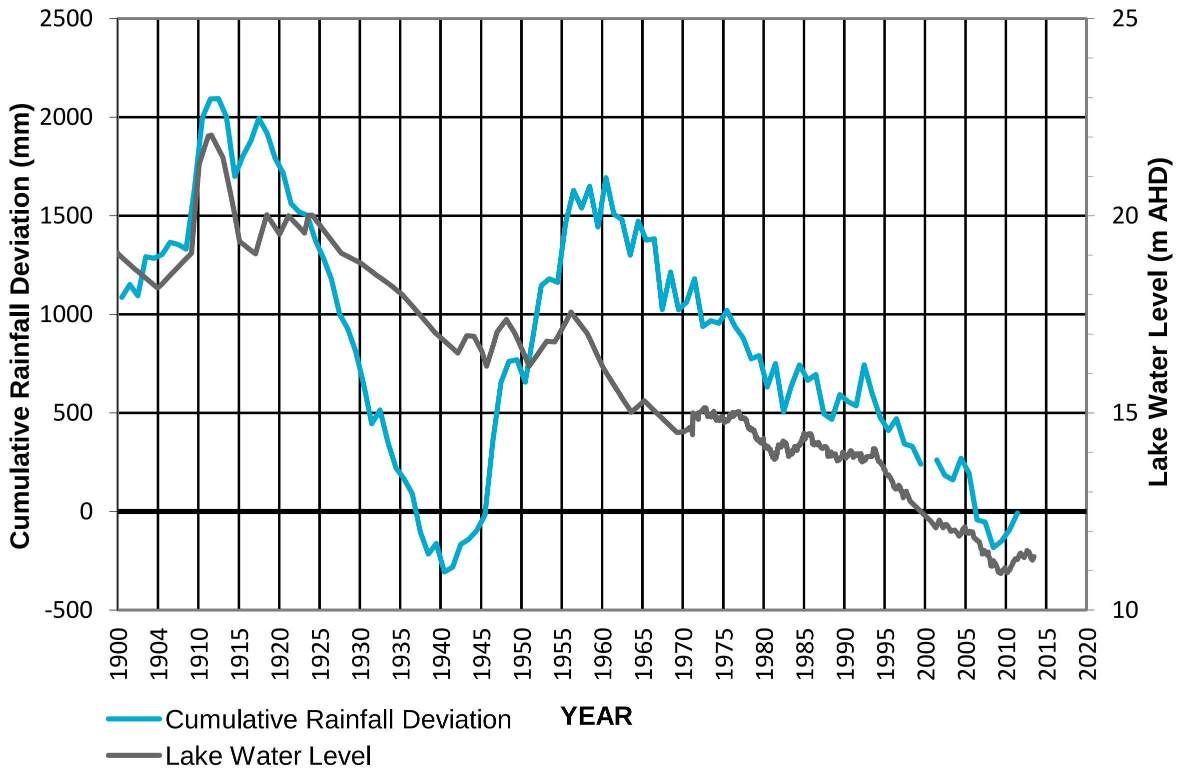
A geochemical mass balance of the Blue Lake, performed by Ramamurthy et al. (1985) suggested that groundwater discharges at a rate of ~ 5000 ML/y, 85% to 100% of which is sourced from the unconfined aquifer (between 0 and 15% comes from the underlying confined aquifer). Due to the fault inferred to occur through Blue Lake, there is potential for underflow from the Gambier Limestone to the Dilwyn Formation, which could then move upwards into Blue Lake (Vanderzalm et al., 2009). Vanderzalm et al. (2009) present the following water balance for the Blue Lake (Table 8.4):

Table 8.4 Estimated water balance of the Blue Lake (Barr et al., 2000; Herczeg et al., 2003; Lamontagne and Herczeg, 2002; Vanderzalm et al., 2009).

PARAMETER	ESTIMATE (ML/Y)
Groundwater inflow	3500–4500
Groundwater outflow	0–1000
Precipitation	500
Evaporation	700
Pumping Extraction	3600

The historical water level data for the Blue Lake, shown in Figure 8.16, was collected manually until 1997. A data logger was installed in 1997 and the data collected by this is now available from DEWNR's Obswell database, using Observation Well number BLA106.

(a)



(b)

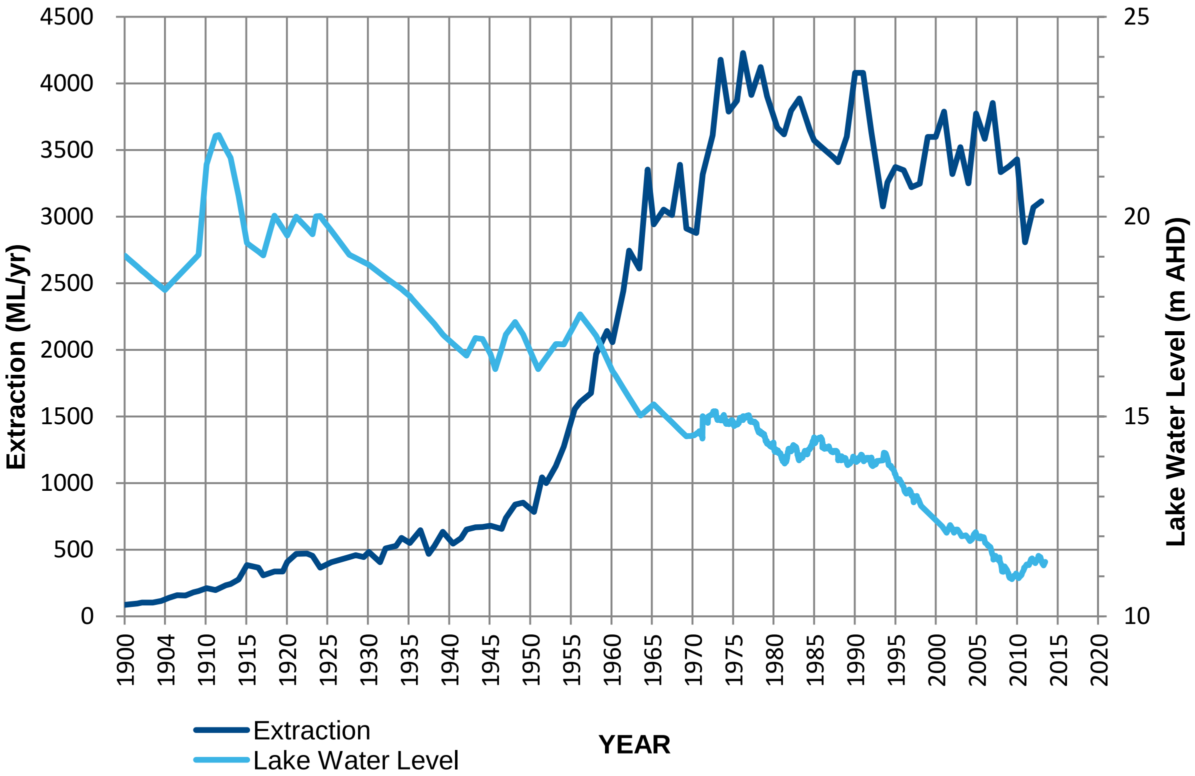


Figure 8.16 Historical water levels of Blue Lake plotted against (a) cumulative rainfall deviation and (b) extraction from the lake. Note that historical water level, rainfall and extraction records extend back to 1882, 1862 and 1891 respectively, but are shown from 1900 here to allow graphing in Excel.

8.5.6 SURFACE WATER MODELS FOR THE SOUTH EAST

As part of the Regional Flow Management Strategy project for the South East, the regional DEM was used to define stream networks and catchment boundaries for the surface water systems of the South East (Wood and Way, 2010). Wood and Way (2010) then developed a series of rainfall-runoff models for these catchments to simulate regional flow through the drainage system and natural watercourses, with special attention given to simulation of water inflow to high value wetlands. A reference period of simulation from 1971 to 2000 was used for all models, and they were calibrated to observed data (i.e. measured flow) where that data was available. However, the lack of monitoring data in some areas – particularly in areas where interactions between surface water and groundwater may be significant – was identified as a limitation in validating the models and such catchments were generally omitted from the study.

Going forward, surface water models for the region will be developed as the need arises. For example, a model for the Drain L catchment using the Source platform was developed for a project investigating the ability to meet environmental water requirements for Lake Hawdon and the Robe Lakes. This model incorporated a simple analytical relationship for surface-water groundwater interaction, and was used to investigate volumes of water that may be able to be diverted from these catchments while still meeting the downstream environmental water requirements.

8.6 Land use

Knowledge of land use changes over time is important for understanding the temporal trends in rainfall recharge, ET and plantation forestry impacts. It can also be used as a surrogate for estimating temporal changes to groundwater extraction when more accurate data is absent.

8.6.1 SUMMARY OF HISTORICAL LAND USE CHANGES IN THE STUDY AREA

Most of the information presented below is sourced from the time-line presented in Table 2.1 or comes from anecdotal evidence gathered during the course of the project.

Settlement in the South East occurred in 1839. Limited grazing and cropping would have occurred from this time, but agricultural land was of limited productivity due to complete inundation of the inter-dunal areas during winter. Establishment of the drainage network gradually opened up agricultural land to increased productivity. The first drains were established in 1864 to 1880 around the Millicent area (Figure 8.14), so presumably this was one of the first low-lying areas to become agriculturally viable. The major cross-country drains were installed between 1900 and 1943 and this would have allowed agriculture to expand into the inter-dunal areas that had previously been seriously affected by inundation. Dryland cropping and pasture has been a dominant land use in the study area. Of note were the severe aphid infestations, which occurred in 1978, ruining many Lucerne crops with the resulting reduction in evapotranspiration causing watertables to rise and widespread flooding during the 1980s and early-1990s.

The establishment of the forestry industry in the South East of SA commenced in 1879, when Forestry SA established the first plantations at Leg of Mutton Lake in Mt. Gambier due to a shortage of timber in the rapidly developing colony. Forestry plantations in the region have expanded steadily since then, although this expansion slowed during the periods of the two World Wars (1914 to 1918 and 1939 to 1945). Further expansion occurred in the 1960s, which led to large scale native vegetation clearing and planting of commercial forests.

The Ash Wednesday bushfires occurred in 1983, burning large areas of forestry plantations and native vegetation. Maps of the areas affected by the bushfires are available from DEWNR. The impact on groundwater of the fires, which effectively removed the deep-rooted plantations and native vegetation, increasing recharge, can be readily observed as water level increases in the hydrographs from the affected area. The first blue gum plantations were planted in 1987 to 88, with major expansion of this plantation type occurring in 1990 to 95/96. Blue gums were favourable at this time due to their short rotations.

Vineyards were first trialled at Padthaway in 1964 and proved to be successful. Prior to this, the only land use in the Padthaway area was native vegetation and, to a lesser extent, improved pastures. Since then there had been a continuous vineyard development in the Padthaway area until the Padthaway Prescribed Wells Area (PWA) was proclaimed in 1976, due to concerns over rising groundwater salinities. Anecdotal evidence suggests that the major expansion of vineyards in the Coonawarra area (north of Penola) occurred in the 1980s.

Tatiara PWA was proclaimed in 1984 due to concerns over deteriorating groundwater quality. Prior to the prescription, some of the irrigation areas were increasing in size by 20% per year.

Large centre pivots became important in 1992. The driver for the expansion of centre pivot irrigation was the dairy companies offering premium milk prices if supply could be provided through the summer months. This change coincided with the purchase of the first rotary rig in the Mount Gambier area, which allowed a bore to be drilled to the Camelback Formation in one or two days. In comparison, a cable tool drilling rig would take between one and two weeks to reach the same depth.

8.6.2 RECENT GIS-BASED LAND USE DATA

GIS-based land use data for the South Australian part of the study area is available for 1998, 2002, 2008-2012 from DEWNR. These maps are shown in Figure 8.17. The datasets were derived from aerial images and the accuracy was improved through field validation. Different datasets contain various levels of details (i.e. number of land use classes) and label classes differently. Therefore an effort was made to name the classes consistently across the datasets so that they can be comparable.

Some key features of the land use dataset are:

- There were few hardwood plantations present in 1998.
- Considerable expansion of hardwood plantations occurred to the west of Penola in 2002 and the plantations expanded further to the north in 2008.
- Since 2009 the area under hardwood plantations appears to have reduced and remained at a size similar to that at 2002. Currently, after harvesting, some hardwood plantations are being replanted with softwood. However, since the sale of Forestry SA, it is not understood whether this practice will continue.
- The area under softwood plantations is relatively large and has remained relatively constant since 1998.
- The spatial extents of native vegetation and irrigation areas appear to decrease significantly from 2008 to 2009 but this is likely to be an artefact of the 2009 to 2012 datasets being coarser than the earlier datasets.

In addition to the datasets shown in Figure 8.17, land use data at a national scale and covering both the South Australian and the Victorian parts of the study area is available for approximately 1992 to 2005 from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES). However, its resolution may be too coarse for the purpose of this study and hence has not been included in this report.

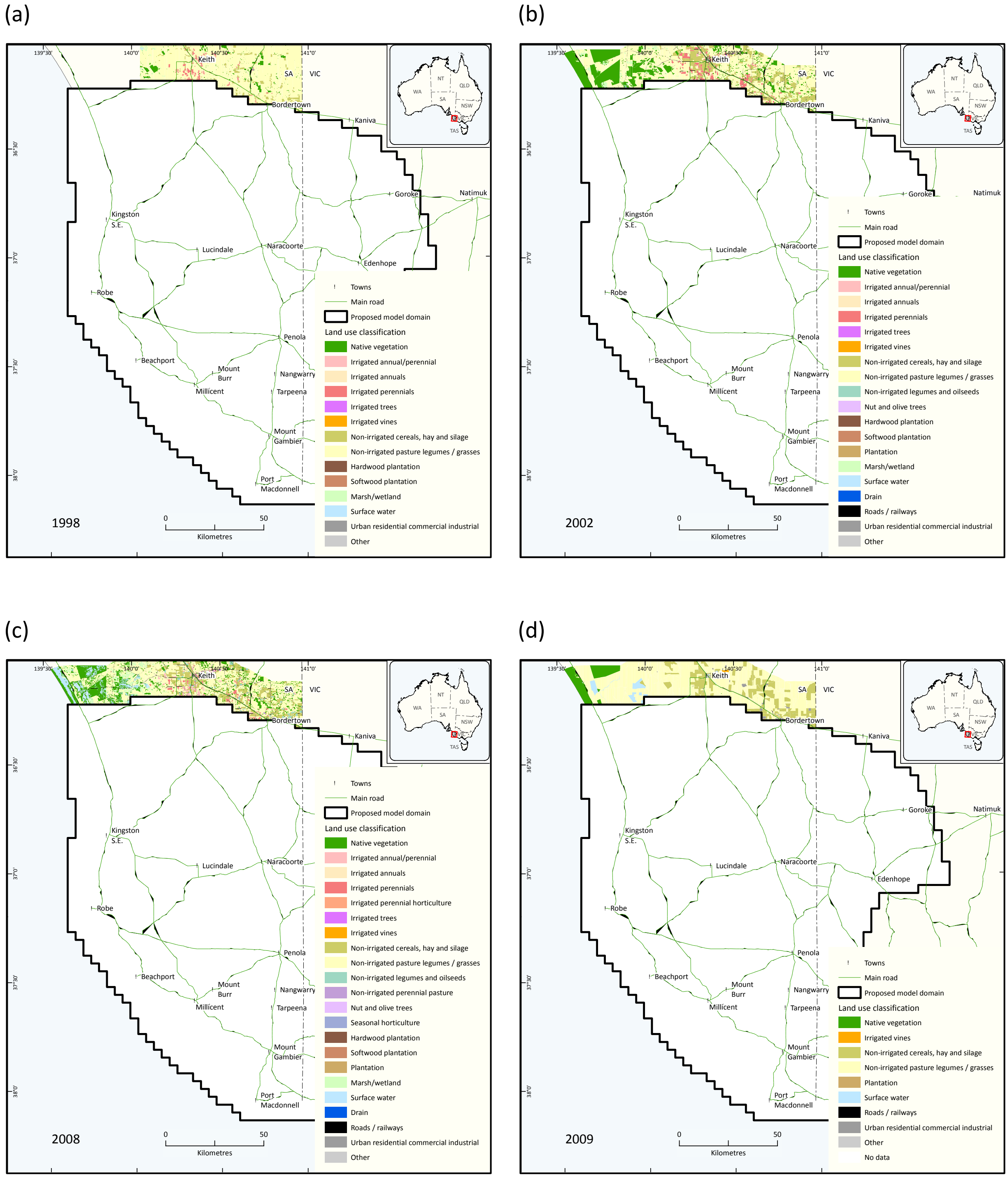
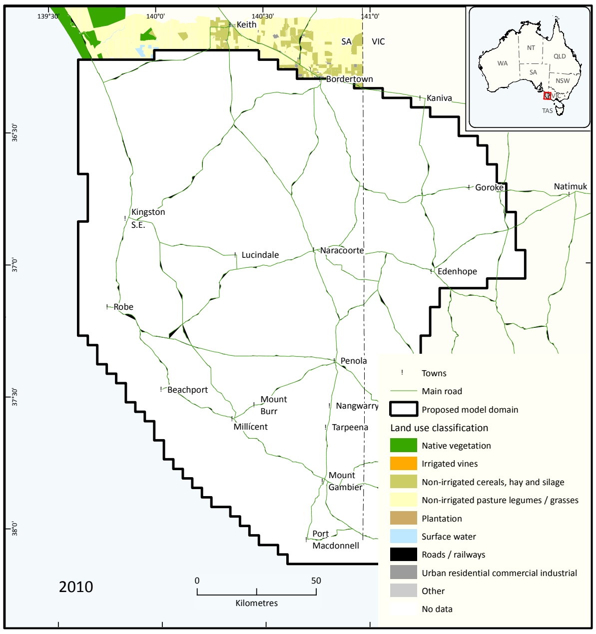
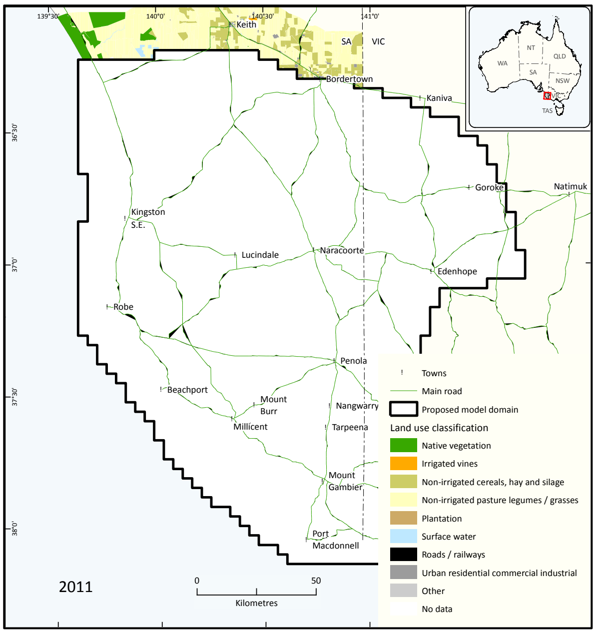


Figure 8.17 Land use changes for the South Australian portion of the study area at (a) 1998, (b) 2002, (c) 2008, (d) 2009, (e) 2010, (f) 2011 and (g) 2012.

(e)



(f)



(g)

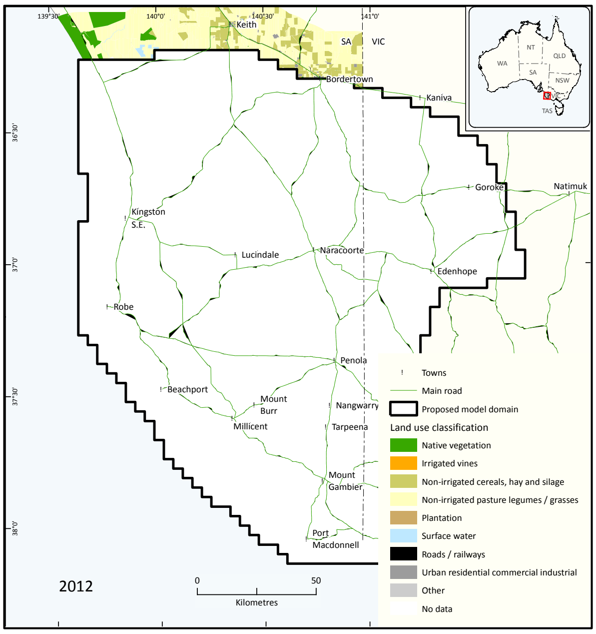


Figure 8.17 continued

8.7 Rainfall recharge and evapotranspiration

The status of knowledge on rainfall recharge is described in detail in Chapter 5.

8.7.1 AVERAGE ANNUAL EVAPOTRANSPIRATION

Potential evapotranspiration (PET) and actual evapotranspiration (AET) for the study area are shown in Figure 8.18. The PET is a Penman Formulation using data from 1981 to 2006 from Donohue et al. (2010) at a 0.05° resolution. The AET is derived from MODIS using CMRSET for the period 2001 to 2010 as described by Guerschman et al. (2009). The spatial trend of PET is opposite to AET, where PET decreases from the north-east at ~ 1700 mm/year to the south at ~ 1300 mm/year, while AET increases from the north-east at ~ 400 mm/year to the south at ~ 800 mm/year. This is because AET is limited by water availability and hence it is lower in the north-eastern part of the study area where the rainfall is below 500 mm /year, while PET is driven by temperature and humidity and therefore will increase away from the coast.

(a) (b)

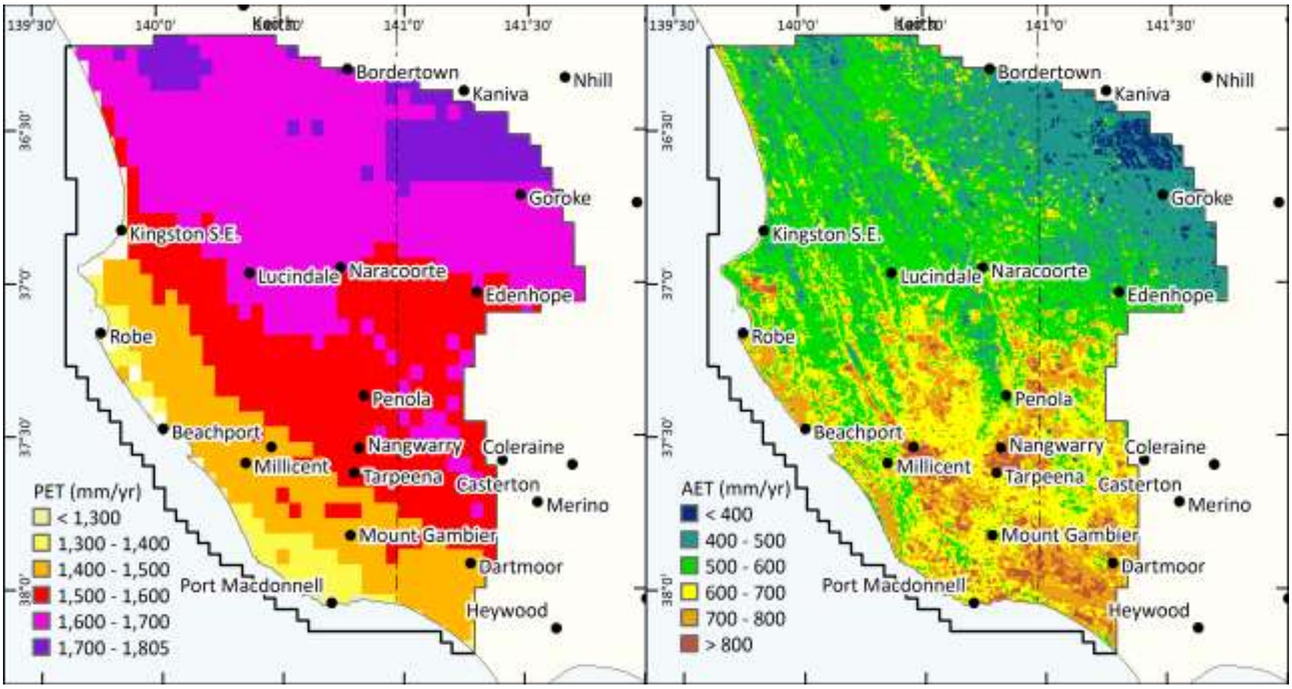


Figure 8.18 (a) Potential evapotranspiration (Donohue et al., 2010) and (b) actual evapotranspiration (Guerschman et al., 2009)

Figure 8.19 shows the average monthly potential ET for Padthaway South (Station 026100) and Mt. Gambier (Station 026021)(BOM, 2013). The Padthaway South station is located in the northern part of the study area and covers a period of 10 years (2000 to 2011), whilst the Mount Gambier station is located in the southern part of the study area and covers a period of 40 years (1967 to 2013). ET recorded at the Padthaway South station is consistently higher than the Mount Gambier station throughout the year. The annual total ET is 1580 mm/year for the Padthaway South station and 1282 mm/year for the Mount Gambier station. These values agree well with the PET in Figure 8.18.

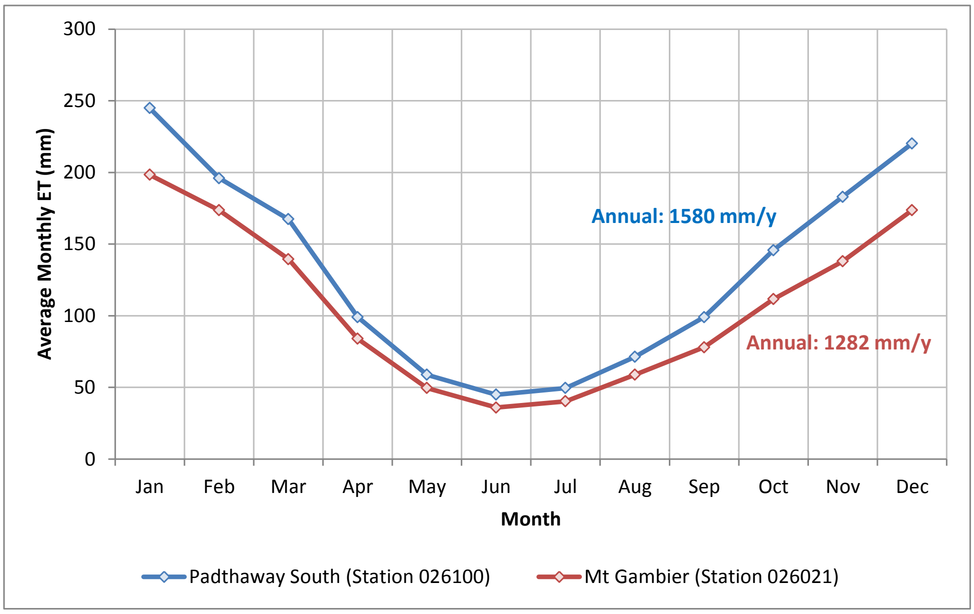


Figure 8.19 Average monthly potential ET at the Padthaway South and Mount Gambier stations (BOM, 2013)

8.7.2 EVAPOTRANSPIRATION BY PLANTATION FORESTRY

A number of field studies have been undertaken to investigate the interactions between forestry plantations and groundwater in the South East. In particular, Benyon and Doody (2004) and Benyon et al. (2006) estimated ET from groundwater by mature (i.e. after canopy closure) blue gum and pine plantations using a water balance approach, and their results are summarised in Table 8.5 below.

Table 8.5 Literature review summary for ET by mature forest plantations in the South East

STUDY	VEGETATION	DEPTH TO WATERTABLE (M)	ET (MM/Y)	ET FROM GROUNDWATER (%)
Benyon and Doody (2004)	Blue gums	< 3.5	847 - 1193	13 - 53% (avg. 34%)
		10.3	713	0%
	Pines	1.9	484	36%
		20.9	447	34%
Benyon et al. (2006)	Blue gums	4.4	1167	37%
		> 7	488 - 713	0%
	Pines	<= 6	560 - 1343	0 - 62% (avg. 35%)
		>8	635 - 795	0 - 14% (avg. 6%)

Holmes and Colville (1970) used neutron moisture meters (to approximately 8 m depth) and tensiometers to analyse soil water content changes at two forest sites near Mt. Gambier and Penola over a three-year period. They concluded that no infiltration to the watertable occurred under the forested sites.

Benyon and Doody (2009) estimated groundwater recharge in the period between harvest and growth of blue gum seedlings to one year and pine seedlings to two years old. Their results show that recharge can range between 86–428 mm/year for the pine seedlings and 276 mm/year for the blue gum seedlings, while

ET can range between 296–371 mm/year for the pine seedlings and 439 mm/year for the blue gum seedlings.

For management purposes, plantation forests are currently considered to extract groundwater directly from the watertable in areas where the median depth to watertable is less than 6 m. During the SENRMB facilitated negotiation process between stakeholders, including the forestry industry and DWLBC (now DEWNR), an accurate depth to watertable map was developed by DWLBC and the South East Resource Information Centre (SERIC). This new map revealed that approximately 70% of the blue gum estate and approximately 20% of the pine estate occurred above watertables with median depth less than 6 m.

Based upon revised plantation areas (December 2006), direct extraction rates and depth to watertable maps were used to recalculate impacts of plantation groundwater extraction at both regional and management area scales (Latcham et al., 2007).

Brown et al. (2006) estimated groundwater extraction by softwood plantations to be 2.34 and 2.59 ML/ha/year for hardwood (blue gums). Subsequent negotiations with forest industry revised these values to: softwood = 1.66 ML/ha/year; hardwood = 1.82 ML/ha/year to reflect current forest management practices (Latcham et al., 2007).

8.8 Groundwater extraction

8.8.1 LICENCED GROUNDWATER EXTRACTION IN THE SOUTH EAST OF SA

Records of groundwater extraction for irrigation prior to 2007

Anyone extracting groundwater in Prescribed Areas in South Australia must hold a licence to do so, with the exception of bores used exclusively for stock and domestic purposes. Each licence has a groundwater allocation associated with it. The first groundwater allocations, prior to Volumetric Conversion in 2007, were based on the Irrigation Equivalent (IE) system, an area-based water allocation system that was developed for use in Prescribed Wells Areas of South Australia where non-metered groundwater supplies are used for irrigation. The unit of allocation is the Irrigation Equivalent (IE), which is defined as the irrigation requirement for 1 ha of Reference Crop (IR_0). Irrigators held water licences specifying the number of IEs they could irrigate. Crop Area Ratios (CAR) have been determined as the ratio of Irrigation Requirement for the Reference Crop (IR_0) to the irrigation requirement for the range of crops being irrigated. The total area of each crop being irrigated divided by the relevant CARs could not exceed the value of IEs held on the licence. This allocation system managed irrigation extraction by controlling the area of crops grown, rather than the amount of water applied. The total volume allocated to each management area was then calculated by multiplying the number of IEs allocated by the IR_0.

To determine the annual water use within a management area, under the area-based system, Annual Water Use Reports (AWURs) compiled by licensees were collected, the data entered into the water licensing system, and assessed to determine the area of each crop type irrigated. Completion of the AWURs was a condition of the licence and hence return of the reports was generally above 90%. A large amount of detail was requested on the AWURs including the areas of crops irrigated, irrigation period, number of irrigations, irrigation method, and a spatial plan of the irrigation development. Instructions were also given for how to estimate volumes of water pumped, using a range of methods. However, the fact that the estimates of water pumped rely on individual landholders completing the forms correctly, mean that the accuracy of the data should be treated with caution. The data from the AWURs was used to calculate total areas of crops and irrigation plantings for each irrigation season. From this, the total number of IEs used and a total (theoretical) water use for the management area could be calculated.

A number of assumptions were inherent in the area-based allocation system (and hence the system for estimating groundwater use):

- All irrigation results in maximum crop water use according to the Irrigation Requirement of the crop.
- Extraction in excess of Irrigation Requirements returns to the aquifer with no evaporative loss.

The Prescribed Wells Areas that are included in the study area are (Figure 2.1):

- The Lower Limestone Coast PWA (formerly Lacepede-Kongorong PWA, Comaum-Caroline PWA and Naracoorte Ranges PWA)
- The Padthaway PWA
- Part of the Tatiara PWA

The unconfined aquifer management areas included in the study area are shown in Figure 2.7. The Confined Aquifer Management Areas that are included in the study area are: Millicent, Kalangadoo, Lucindale, Kingston, Taratap, Fairview, Wirrega and Border Zones 1A to 6A and part of Keith and Zone 7A (Figure 2.8).

As the Padthaway and Tatiara PWAs were proclaimed (prescribed) in 1976 and 1984 respectively, AWUR data for these areas should be available for as early as the 1980s. Data for other areas should then be available following the timetable of prescriptions shown below:

1986 Naracoorte Ranges and Comaum Caroline PWAs (now part of LLC PWA)

1993 Naracoorte Ranges PWA expanded to include Naracoorte Flats (now part of LLC PWA)

1997 Lacepede Kongorong PWA (now part of LLC PWA)

2003 Tintinara Coonalpyn PWA

Annual Water Use Reports are held in hard copy form in the DEWNR Mount Gambier Office, filed by irrigation licence. It is assumed that this data is also available in electronic form in the water licensing system but this had not been made available to this project at the time of preparation of this report.

For this project, we have been able to obtain an Irrigation Activity Report document for 1997 to 1998 (Smith, 2000), which provides information on groundwater allocation and use by Management Area for the Tatiara, Padthaway, Naracoorte Ranges, Comaum Caroline and Lacepede Kongorong PWAs. This is the earliest record of groundwater extraction by Management Area that has been obtained so far. The report also includes areas of irrigated crops and total water use by crop type for each PWA. Subsequent report documents obtained and the data extracted are summarised in Table 8.6. These generally also contain information on groundwater extraction from the confined aquifer. Information from an additional report on earlier groundwater use for the Padthaway PWA is also summarised in Table 8.5. The datasets extracted from these reports have been collated and archived in an Excel spreadsheet. Note that all groundwater use values included in these datasets were estimated based on crop water requirements only, not volumes pumped, unless otherwise specified.

Table 8.6 Summary of pre-2007 irrigation data collated from Annual Water Use Reports and archived for this project.

IRRIGATION SEASON(S)	REFERENCE	DATA EXTRACTED
1985/86–1993/94	Cobb and Brown (2000)	• Padthaway PWA total irrigation use (IE)
1994/95–1996/97	Cobb and Brown (2000)	• Padthaway PWA total irrigation use (IE) • Padthaway PWA total industrial and recreation use (all zero) • Padthaway PWA –estimated stock water use for each hundred in 1996/97
1997/98	Smith (2000)	• Irrigation water use for each Management Area • Number of licences in each Management Area • Area of each crop type irrigated in each PWA • Total water use of each crop type in each PWA • Padthaway PWA total industrial and recreation use (zero)

IRRIGATION SEASON(S)	REFERENCE	DATA EXTRACTED
1998/99	Smith (2000)	• Padthaway PWA total irrigation use (IE) • Padthaway PWA total industrial and recreation use (zero)
1999	Binks (2000)	• Various data on crop types, irrigation types and gross irrigation extraction estimates
2002/03	Kelly and Laslett (2003)	• Irrigation water use for each Management Area • Area of each crop type irrigated in each PWA • Water use of each crop type in each PWA • Each irrigation method as a percentage of total irrigation area for each PWA
2003/2004	Kelly and McIntyre (2005)	• Irrigation water use for each Management Area • Allocations for Public Use for each Management Area • Area of each crop type irrigated in each PWA • Total water use of each crop type in each PWA • Each irrigation method as a percentage of total irrigation area for each PWA
2003/2004	Latcham et al. (2007)	• Indicative irrigation use, as calculated by the Volumetric Conversion Project*
2004/05	DWLBC (2006)	• Irrigation water use for each Management Area • Allocations for Public Use, Aquaculture, etc for each Management Area • Area of each crop type irrigated in each PWA • Water use of each crop type in each PWA • Each irrigation method as a percentage of total irrigation area for each PWA
2004/05	Latcham et al. (2007)	• Indicative irrigation use, as calculated by the Volumetric Conversion Project*
2005/06	Smith and McIntyre (2007)	• Irrigation water use for each Management Area • Allocations for Public Use, Aquaculture, etc for each Management Area • Area of each crop type irrigated in each PWA • Water use of each crop type in each PWA • Each irrigation method as a percentage of total irrigation area for each PWA

*This includes an estimate of crop water use, calculated using the traditional area based system (updated crop area ratios), but with the addition of (a) a crop adjustment factor where it was considered that the area based system did not allocate enough water (b) a delivery component, calculated based on field trials of different irrigation systems to account for water required in excess of crop requirements to account for irrigation system losses or deep drainage (c) specialised production requirements for other irrigation related activities, e.g. frost control on vines.

For the purpose of calculating groundwater extraction using the pre-2007 data, which only provides data by the Management Area, it is assumed that the Willalooka, Wirrega and Tatiara Management Areas of the Tatiara PWA are entirely included in the study area and that the Stirling Management Area is not. In reality, the study area boundary cuts across all of these Management Areas (see Figure 2.7). The Shaugh, Cannawigara, Zone 8A and North Pendleton Management Areas of the Tatiara PWA are not included in the Study Area (see Figure 2.7).

Figure 8.20 shows graphs of groundwater extraction volumes for each Management Area within each Prescribed Wells Area for selected years from 1997/98. The Volumetric Conversion Project calculated 'Indicative Uses ' for the 2003/04 and 2004/05 irrigation seasons, which included allowances for irrigation system inefficiencies, extra delivery requirements and specialised production requirements (Carruthers et al., 2006b).

(a)

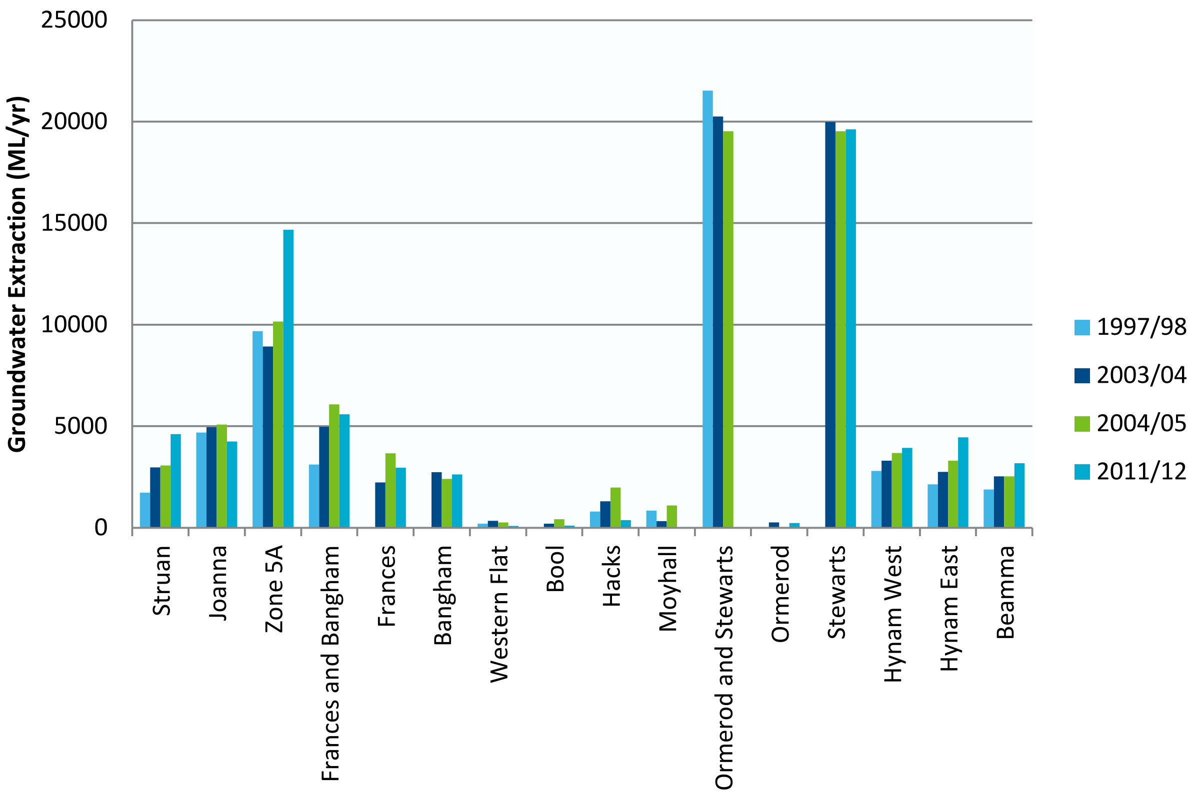
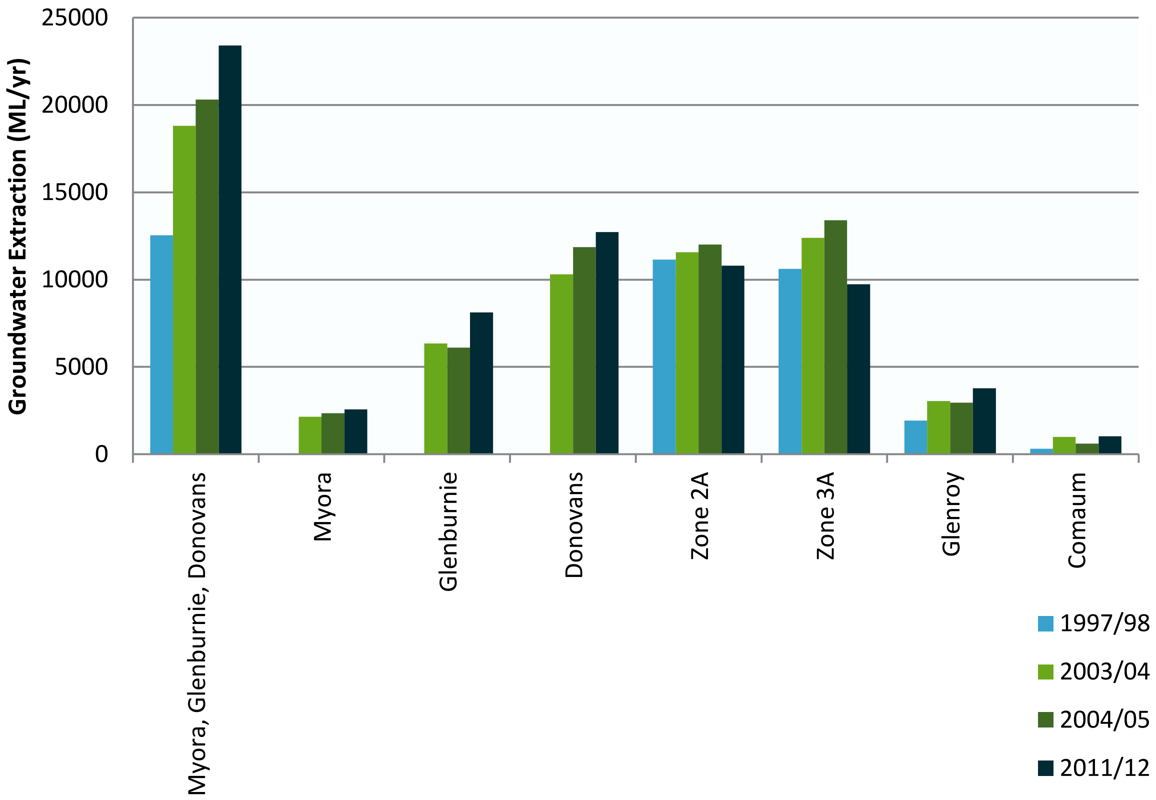


Figure 8.20 Graphs of estimated groundwater extractions for 1997/98, 2003/04, 2004/05 and 20011/12 for the (a) Naracoorte Ranges PWA (unconfined), (b) Comaum-Caroline PWA (unconfined), (c) Lacepede Kongorong PWA (unconfined), (d) the Padthaway PWA (unconfined) and the management areas of the Tintinara Coonalpyn PWA included in the study area and (e) all confined aquifer management areas. See text for methodology used to estimate groundwater extraction for each year.

(b)



(c)

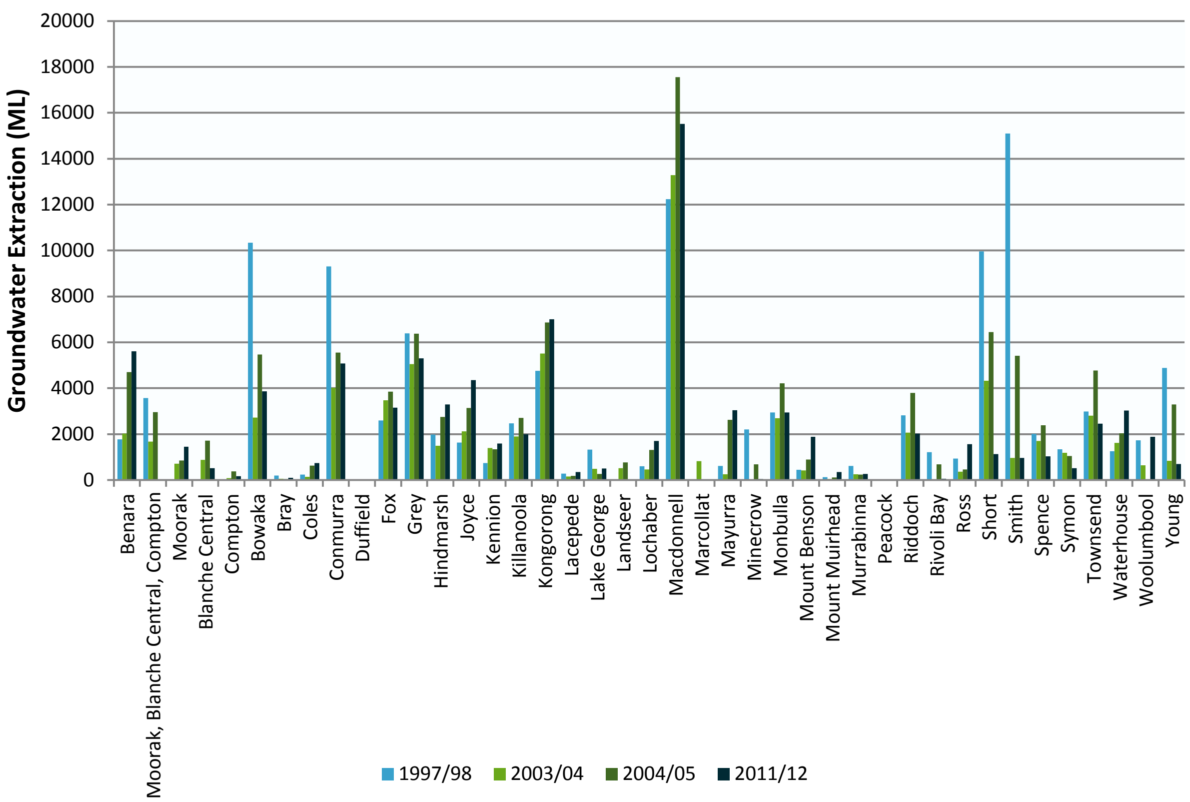
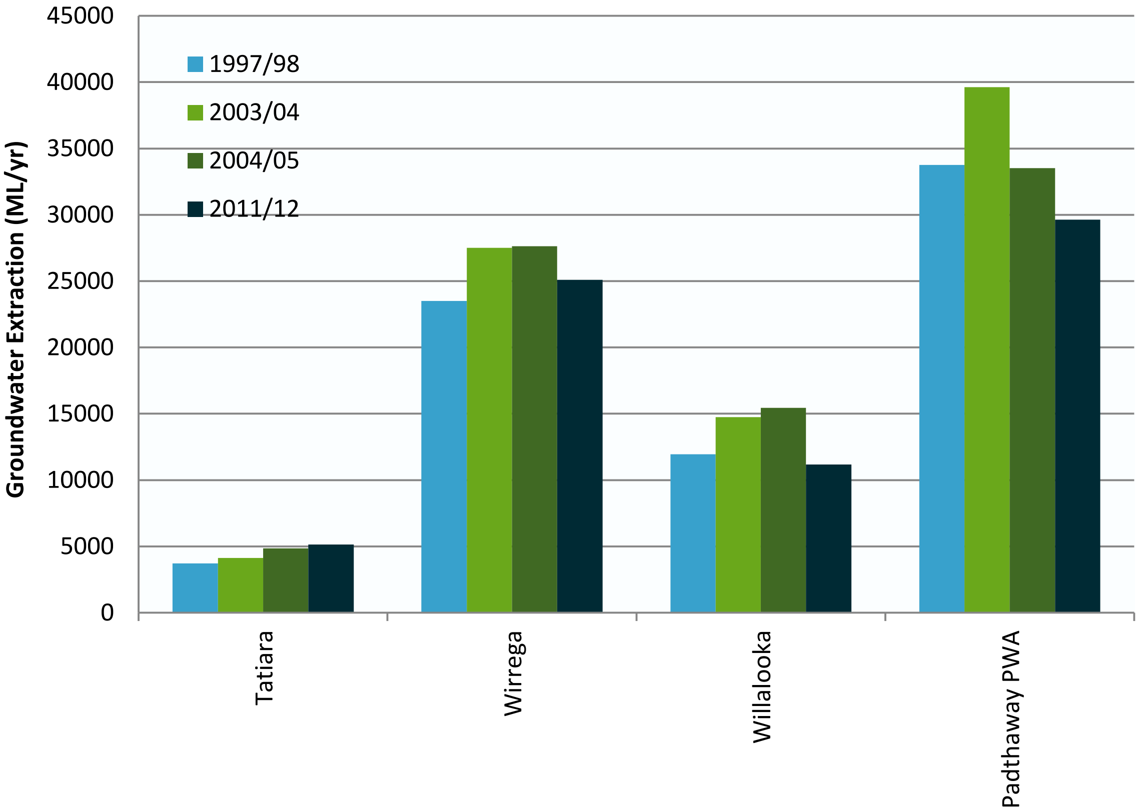


Figure 8.20 continued

(d)



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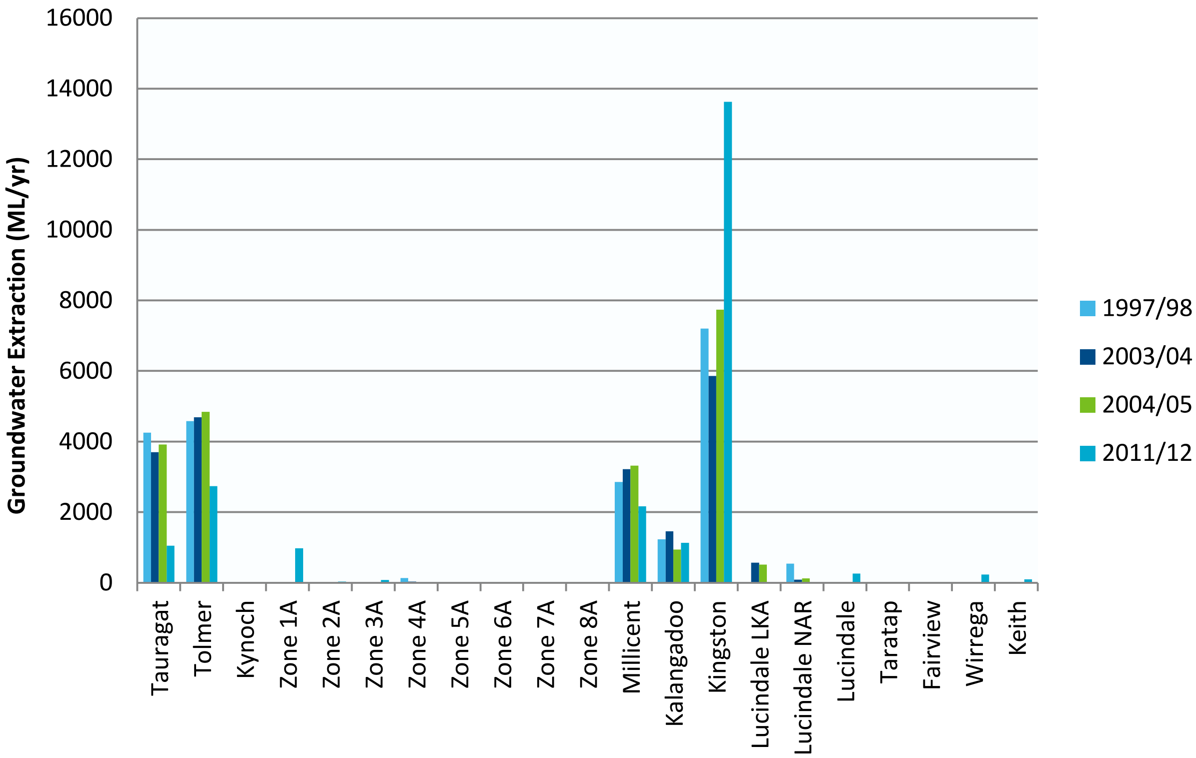


Figure 8.20 continued

The earlier data are based only upon the old IE system, which estimates crop water use only and does not include any allowance for irrigation system inefficiencies, extra delivery requirements or specialised production requirements. The earlier IE values also use earlier crop factors which have now been updated through the Volumetric Conversion project. The 'indicative use' values were compared with the IE-based estimates for the same years. Ratios of Indicative Use / IE-based use for each management area were generally fairly constant across the two years. Given the small changes in the proportions of crop and irrigation types between 1997/98 and 2003, this ratio has been applied as a rough correction to the 1997/98 data to provide more comparable groundwater use values.

Volumetric conversion and the installation of meters: 2002 to 2009

The Volumetric Conversion Project was initiated in 2002 to facilitate the process of converting the area-based water licenses in the South East to a volumetric basis. The project ran between 2002 and 2006 and included comprehensive field investigations to determine the volumes of water required to grow irrigated crops in the South East, as well as the collection of a trial suite of metered groundwater extraction data (Carruthers et al., 2006a; Carruthers et al., 2006b; Pudney, 2006). The requirement to install, maintain and submit records from meters on all irrigation bores then came into force in 2007.

Metered extraction data 2009 to 2012

The first full set of metered data is available for the 2009/10 financial year, with 2007/08 and 2008/09 data considered to be ‘transitional‘ and of low quality. Although quality checked metered extraction data is now available for 2009/10, 2010/11 and 2011/12, only the dataset for the latter year has been obtained from DEWNR to date. This dataset includes groundwater extraction data by well, with details of well co-ordinates and the groundwater Management Area in which it is located. A summary of the 2011/12 data by Management Area is included on Figure 8.20.

Kimberley Clark

The Kimberley Clark pulp mill is located approximately 10 km south east of Millicent. The mill was built in 1960. Groundwater extraction for the mill is currently 10 to 12 ML/day, although this has been up to 60 ML/day in the past (J. Lawson, pers. comm.). There was a large cone of drawdown around the pulp and main mill operations, monitored via specific observation wells by DEWNR. The watertable within this cone of drawdown, at the maximum extraction rate, dropped below sea level. With the extraction rate now about a third of what it was prior to the closure of the pulp mill (30 ML/day) the drawdown cone has and still is reducing significantly (J. Lawson, pers. comm., 2013). Groundwater level data and groundwater extraction data for the Kimberley Clark mill are available from DEWNR.

8.8.2 VICTORIAN GROUNDWATER USE DATA

Spreadsheets of metered groundwater extraction data collated by the SAFE program are available, but have not yet been received. These will represent point-scale metered groundwater use for the most recent measurement period, considered to be the most accurate. Rasters of groundwater use density created from these data sets have been provided by DSE.

Victorian Water Accounts reports for 2003/04 to 2010/11 obtained from the internet provide estimates of groundwater use by Groundwater Management Area (GMA) or Water Supply Protection Area (WSPA) for these years.

Historical datasets have not been obtained for the Victorian portion of the study area and it is considered that major patterns of land use change (i.e. conversions to irrigated land uses) could be used to create some simple temporal variation in groundwater extraction for this portion of the study area, which is outside the main area of interest for the current project. Future applications of the regional water balance model could incorporate more detailed temporal datasets if required.

8.9 Processes occurring at the coastal boundary

8.9.1 SUMMARY OF PREVIOUS STUDIES OF THE SEAWATER – FRESHWATER INTERFACE

Most of the knowledge of processes occurring at the coastal boundary of the study area is focused on the position fo the seawater-freshwater interface in the region to the south of Mount Gambier.

There has recently been concern over the impacts of increased irrigation development on the position of the seawater interface and hence the risk of salinisation of ecologically sensitive karst rising springs in the area to the south of Mount Gambier. Seawater intrusion also poses a significant risk to the highly developed dairy industry reliant on groundwater in this area. Knowledge of the position of the seawater interface, and the hydrostratigraphy in the coastal areas, is essential in the conceptualisation and modelling of the coastal boundary and determining the likely position and flux of groundwater discharge at the coast.

The earliest identification of the seawater interface was at Carpenter's Rocks in 1976, where salt water was intercepted at a depth of 25 m below ground level at a distance of 350 m inland from the coast during drilling of the town water supply well (Barnett, 1976). The well was abandoned and a second production well drilled a further 500 m inland to a depth of 25 m obtained sufficient fresh water, although it was never used (J. Lawson pers. comm., 2013). Since then, two key investigations have been carried out to identify the location of the seawater interface, both focusing on the area of coastline to the south of Mount Gambier.

King and Dodds (2002) used transient electromagnetic method (TEM) over five transects perpendicular to the coast to identify conductive bodies at depth that were considered likely to be salt water (Figure 8.21). The results appeared to indicate the position of the salt water interface, although this required confirmation with drilling and groundwater salinity testing (Figure 8.22). They found considerable irregularity in the assumed saltwater interface, probably caused by variations in the permeability of the aquifer. The occurrence of volcanic intrusions was also suggested although this has never been identified in any of the deep wells drilled in the area (J. Lawson, pers. comm., 2013). Where present, the depth to the saltwater interface increased rapidly inland, but appeared to flatten off at a depth of approximately 200 m. King and Dodds (2002) also carried out salinity profiling on wells CAR11 and CAR10, located on Transect Lines 1 and 2 respectively (Figure 8.22a,b). The results of the TEM surveys and salinity profiling are discussed below for each transect.

Figure 8.22a-e have been re-drawn from the King and Dodds (2002) report to include annotations of the interpretations of the data made by those authors. These are discussed individually below. King and Dodds (2002) made a three main recommendations for drilling on Lines 1, 2 and 4 to confirm the interpretations of the geophysical data. Following this, the Department of Water, Land and Biodiversity Conservation (now DEWNR) drilled three observation wells targeting different units of the TLA and Tertiary Confined Sand Aquifer (TCSA) at Eight Mile Creek, about 1.5 km inland from the coast (Mustafa et al., 2012). The site was chosen to coincide with Transect Line 2 (Figure 8.22b), as suggested by King and Dodds (2002), in order to ground truth the location of the seawater interface. Mustafa et al. (2012) also drilled a number of wells and then carried out salinity profiling and hydrochemical sampling of a range of observation wells in the coastal area south of Mount Gambier. The results of this sampling program are discussed below in relation to the TEM transects of King and Dodds (2002).

8.9.2 KING AND DODDS (2002) TRANSECT LINE 1: PICCANINNIE PONDS

The 40 layer inversion model of the TEM survey of Transect Line 1 is shown in Figure 8.22a, although a 5 layer inversion model was also presented by King and Dodds (2002). The 40 layer model provides more detail in the top 100 m of the profile but can be deceptive below 150 m depth, where any apparent layering should be treated cautiously. The TEM surveys carried out in this study are considered to penetrate to about 200 m below the surface, so again any detail provided below this should be treated qualitatively. Transect Line 1 runs north, through the Piccaninnie Ponds Conservation Park for the first 500 m of the transect (Figure 8.21). Stratigraphic information suggests that the resistivity profile penetrates the limestone and marl layers of the Tertiary Limestone Aquifer to perhaps a depth of 250 m, although there is no stratigraphic information below 150 m depth to the north of about the 750 mark (distance from the coast). It is possible that the confined aquifer approaches a depth of 150 m in this region due to uplift or faulting.

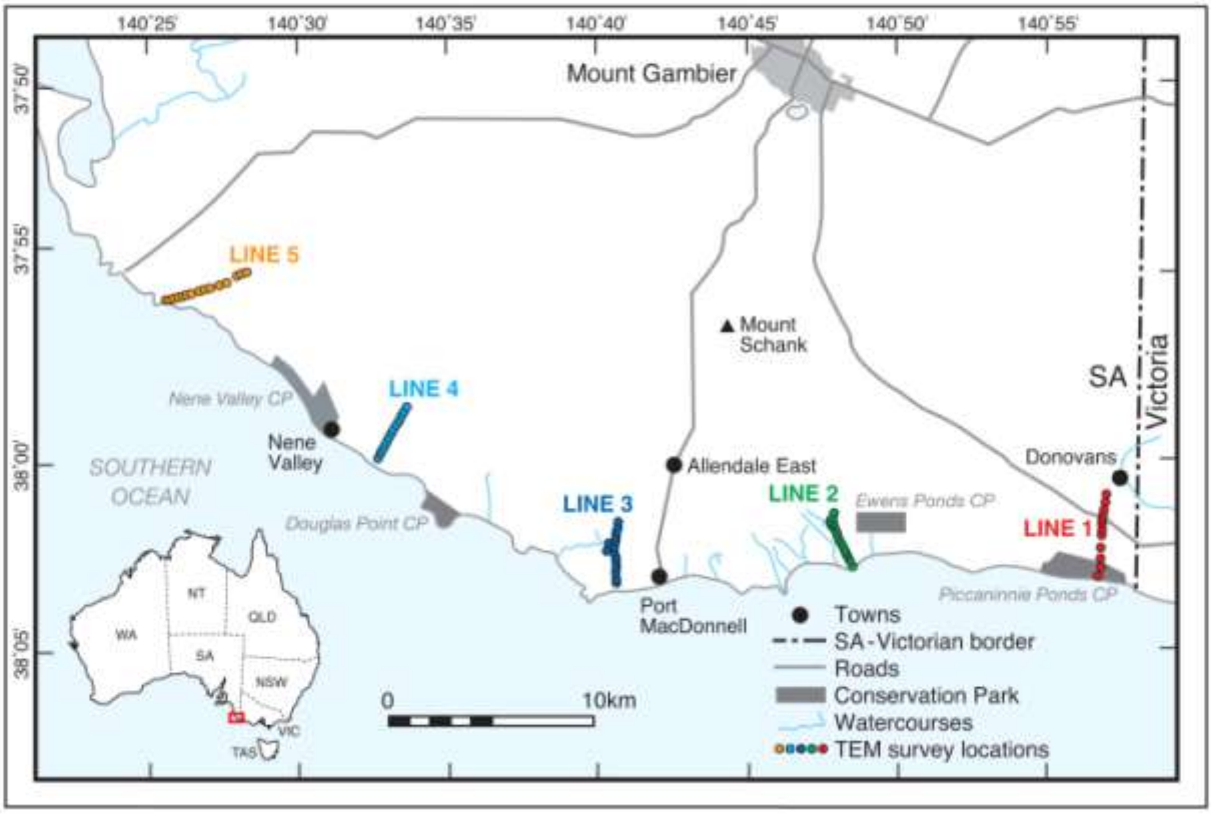


Figure 8.21 The TEM transect lines investigated by King and Dodds (2002).

(a)

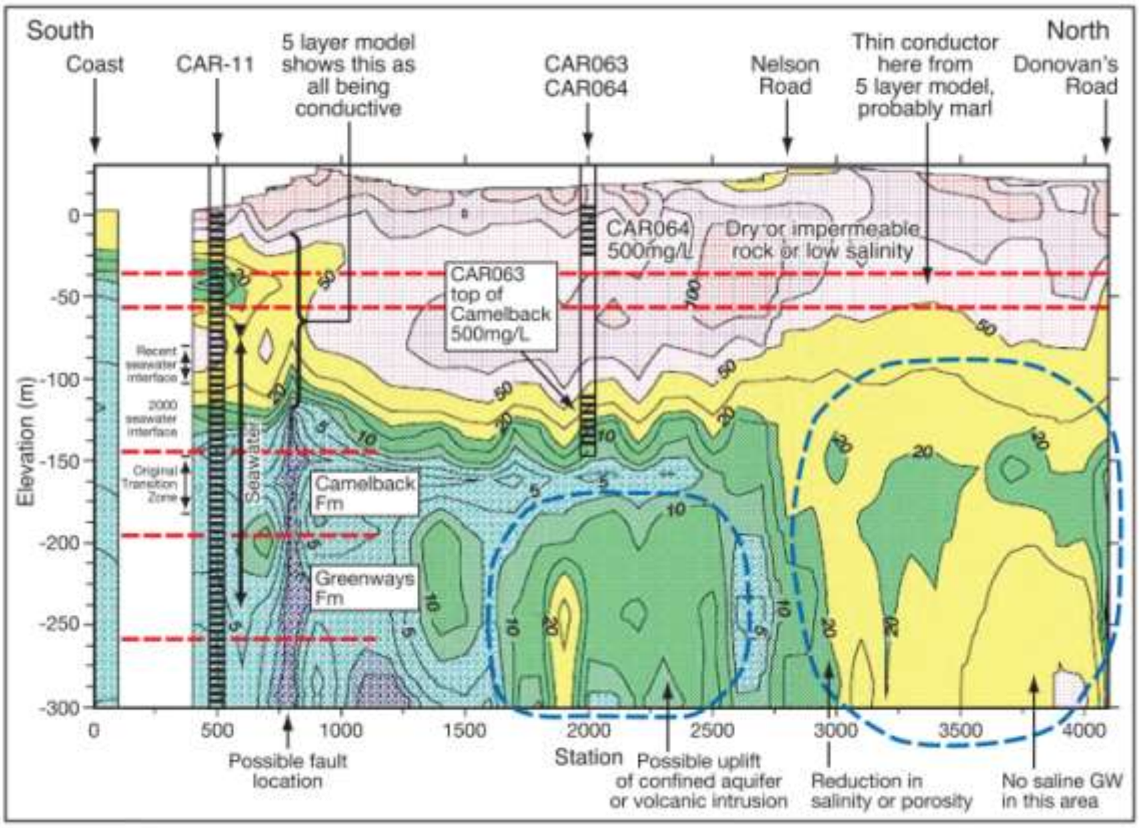
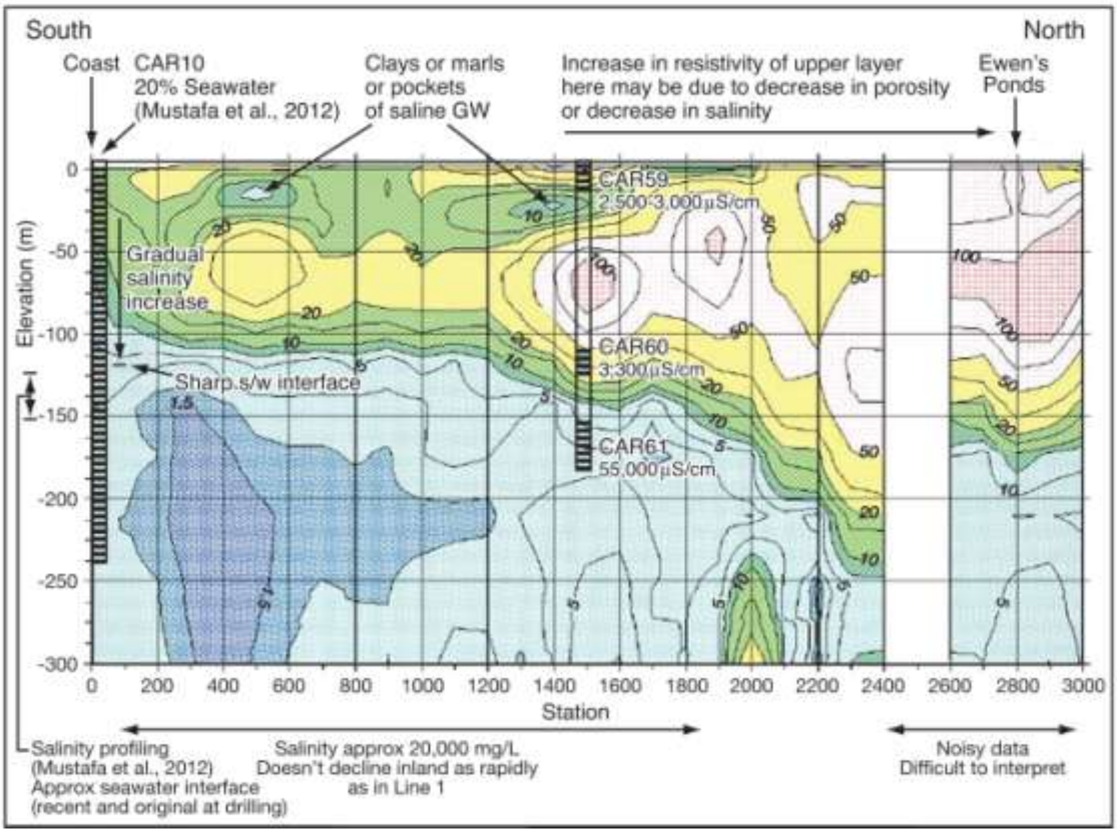


Figure 8.22 King and Dodds (2002) TEM Transects with interpretive comments; (a) Line 1 (with observation well locations), (b) Line 2 (with observation well locations), (c) Line 3, (d) Line 4 and (e) Line 5.

(b)



(c)

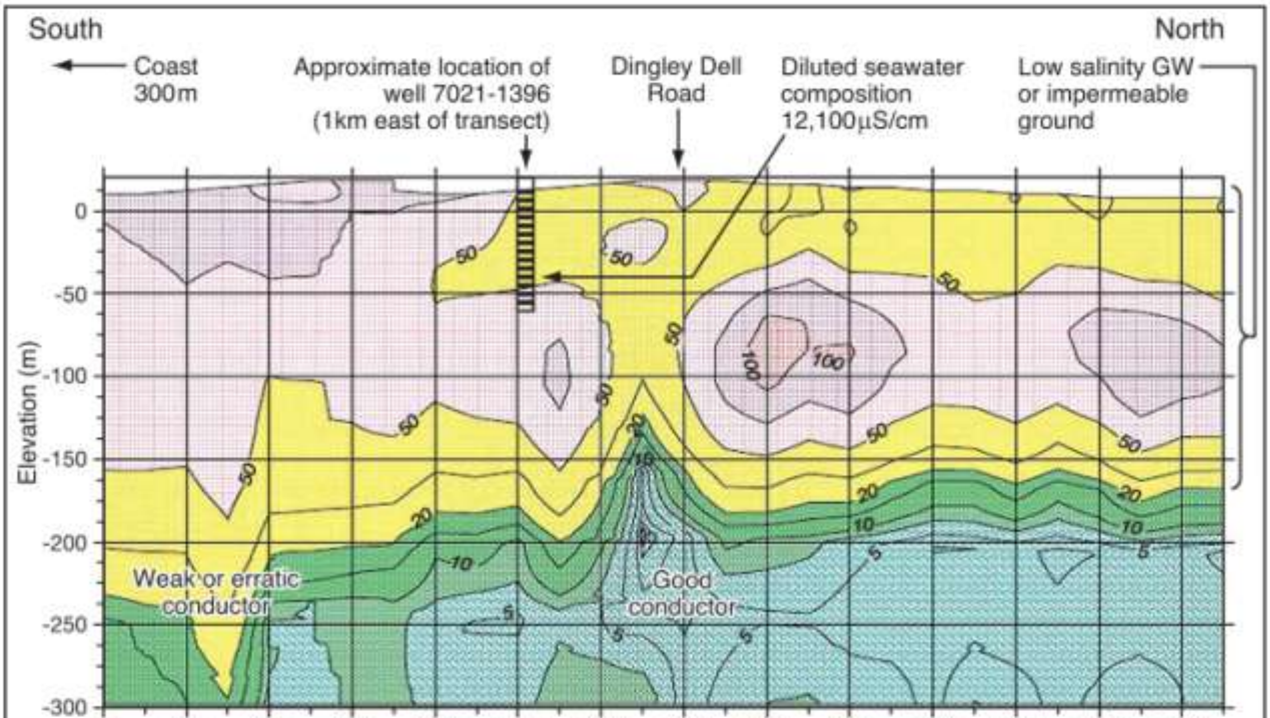
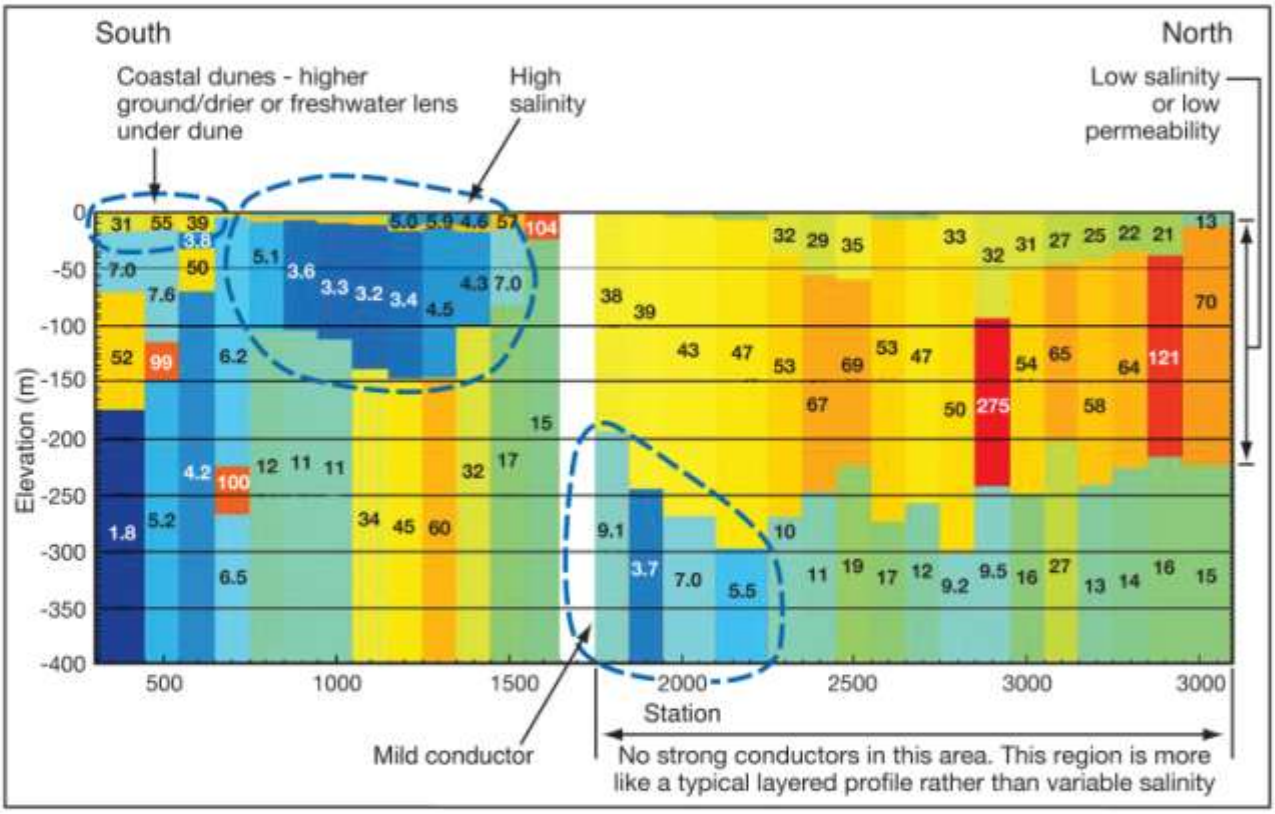


Figure 8.22 continued

(d)



(e)

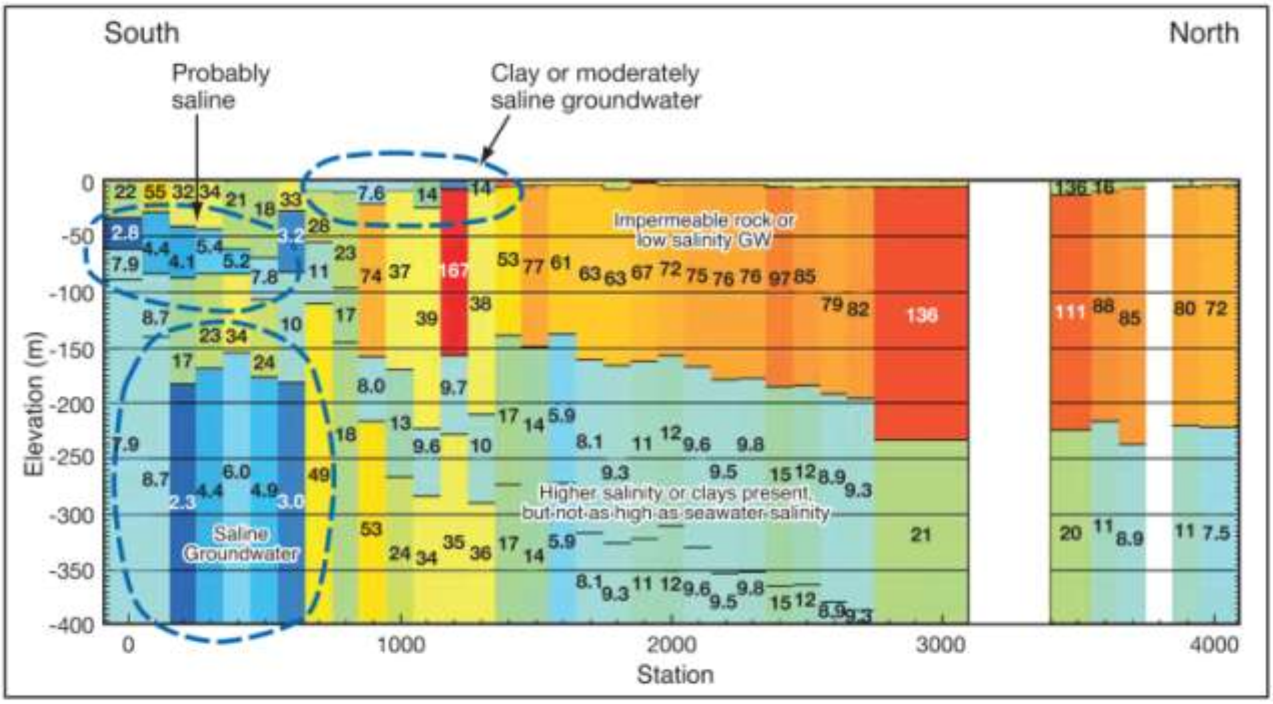


Figure 8.22 continued

The resistivity section for Transect Line 1 shows a conductive body coming to within 25 m of the surface at the coast. The lower portion of this, below 70 m, is interpreted to be seawater, with the upper portion between 25 and 70 m depth interpreted as likely to be a mixture of seawater and fresh water. This conductive body was more obvious on the 5 layer inversion model and doesn't appear continuous with depth in the 40 layer model. Observation well CAR011 is located 2 km inland of the coast, but to the east of this transect (Figure 8.22a). Salinity profiling of CAR011 was carried out as part of the King and Dodds (2002) study and showed a sharp interface occurring between 120 m and 123 m, in remarkable agreement with the resistivity profile. Here, groundwater salinity increased from 3,000 mg/L to 17,000 mg/L, remaining constant to the bottom of the profile at 140 m. In the zone above this, salinity was consistent at 1500 mg/L from the watertable to a depth of 114 m, below which it increased gradually to 3000 mg/L just above the sharp interface.

Mustafa et al. (2012) present additional salinity profiles for CAR011. The well was drilled in 1972 and completed as an open hole, fully penetrating the TLA (Figure 8.22a). Discrete water sampling during drilling placed the salinity interface between 150 m and 170 m depth, where it reached a peak of 48,000 EC. This depth corresponded to the Camelback Member at 146 m to 182 m. Another salinity peak was associated with the Greenways Member at 182 m to 256 m depth. More recent salinity profiling of CAR11 between 2008 and 2011 has placed the seawater interface between approximately 80 m and 100 m depth (Mustafa et al., 2012).

Other key features of the resistivity section are:

- A thick conductor at variable depth between 110 m and 160 m. This is most conductive near the coast, indicative of saline groundwater either in clays or marls or mobile within the aquifer. This becomes gradually more resistive inland, with an abrupt increase in resistivity at about 2 700 m. This variability could be due to changes in salinity (likely) or porosity of the aquifer.
- From 500 m inland the top approximately 110 m of the profile is resistive, consistent with unsaturated conditions or low salinity water in porous medium. Observation wells CAR063 and CAR064 are located near station 2000 and both intersect fresh water of about 500 mg/L (Mustafa et al., 2012). Periodic measurements of electrical conductivity of groundwater from CAR063 has shown constant ECs of 750 µS/cm – 800 µS/cm since 2009.
- A thin conductor occurs between 40 and 70 m depth in the 5 layer model (not shown), probably corresponding to a marl layer.
- A narrow vertical zone of low resistivity at station 800 may be caused by a high porosity feature such as a fault zone.
- Indications of layering below 250 m should be considered qualitatively and may be due to the confined aquifer coming close to the surface or volcanic intrusions.

8.9.3 KING AND DODDS (2002) TRANSECT LINE 2: EWENS PONDS

Resistivity transect line 2 of King and Dodds (2002) is shown in Figure 8.22b along with its major interpretive features and the locations of the observation wells for which salinity profiling and hydrochemical sampling have been carried out. Transect Line 2 runs north-northwest from the coast towards Ewens Ponds Conservation Park, running adjacent Eight Mile Creek between the 1500 m and 2100 m marks and stopping approximately 500 m south-east of the conservation park. The stratigraphy was interpreted to consist of layered limestone and marl of the Tertiary Limestone Aquifer to a depth of 150 m, but there was no stratigraphic information to interpret below that depth. Again, the result of the 40 layer inversion model is shown, although a 4 layer model was also interpreted. In this case, the 40 layer model identified certain resistivity features more clearly. The key features of the resistivity section are:

- Similarly to Line 1, a large conductive body occurs at depth, starting at about 70 m depth at the coast, dipping sharply within the first 100 m of the transect and then more gradually to about 240 m at 2400 m from the coast. Again, note that this method is expected to penetrate to a depth of around 200 m and any information below this should be interpreted cautiously. This conductor was interpreted as likely to be due to the presence of water with salinity of around 20,000 mg/L. The salinity declines away from the coast, but not as rapidly as in transect line 1.
- Some shallow conductors within about 25 m of the surface were interpreted to be the result of clay or marls or pockets of saline groundwater.
- An increase in resistivity of the upper layer away from the coast could be due to either a decrease in aquifer porosity or a decrease in groundwater salinity.

Observation well CAR10 lies right at the coastal end of this transect. A salinity profile of this well by King and Dodds (2002) showed a more gradual seawater interface than in CAR11, with a gradual increase in salinity from 6,000 mg/L to 12,000 mg/L between 50 m depth and 110 m depth and then a sharp increase to 25,000 mg/L between this depth and about 115 m depth. CAR10 was also drilled in 1972 and completed as an open whole across the whole TLA. Discrete groundwater sampling during drilling identified a salinity change from about 7,000 to 42,000 µS/cm between 125 and 150 m depth. Subsequent salinity profiling between 2008 and 2011 generally didn't penetrate below 120 m and hence didn't intercept the seawater interface. The exceptions were June 2009 and November 2011 when the interface was identified at 125 m (approx. 37,000 µS/cm) and 130 m (approx. 48,000 µS/cm)(Mustafa et al., 2012). Calculation of a mixing ratio between seawater and fresh groundwater by Mustafa et al. (2012) based on a groundwater sample from the well suggested that the sample consisted of 20% seawater. However, as the well fully penetrates the aquifer and therefore probably samples water from above the seawater interface, this probably under-estimates the mixing ratio for the seawater wedge.

Observation wells CAR59, CAR60 and CAR61 were drilled at Eight Mile Creek, at the 1500 m point of the King and Dodds (2002) resistivity transect by Mustafa et al. (2012). The results of salinity profiling and groundwater sampling of these wells, carried out by Mustafa et al. (2012) can be summarised as follows:

- CAR059 is a shallow well completed to 12 m and displays groundwater salinities increasing gradually from 2500 µS/cm to 3000 µS/cm with depth.
- CAR060 is completed as open hole between 116 m and 124 metres below ground level (mbgl). This well shows relatively constant salinities with depth of about 3300 µS/cm.
- CAR061 is completed as an open hole in the Camelback Member, between 154 m and 180 m. The salinity profile for this well was only of water sitting in the casing to a depth of 120 m, but the salinity of this was measured at about 55,000 µS/cm. Periodic measurements of groundwater electrical conductivity in this well have shown EC remaining relatively constant at approximately 50 000 µS/cm since it stabilized post-drilling in 2004 (DEWNR, 2013).
- The seawater mixing ratio of water sampled from well CAR061 was calculated as 98% seawater.

The significant finding at the Eight Mile Creek site was that the saline groundwater was contained by a very hard dolomitic capping at the top of the Camelback Member (J. Lawson, pers. comm., 2013). This is also the formation supplying the majority of irrigation water to the centre pivots in the region. Inland migration of seawater can be observed in the salinity graph for observation well CAR61.

8.9.4 KING AND DODDS (2002) TRANSECT LINE 3: SMITH ROAD

Resistivity transect line 3 of King and Dodds (2002) is shown in Figure 8.22c along with its major interpretive features. Again, the result of the 40 layer inversion model is shown, although a 3 layer model was also interpreted. In this case, the 40 layer model identified certain resistivity features more clearly. Line 3 is located just over 1 km to the west of Port MacDonnell (Figure 8.21) and was interpreted from stratigraphic information to intersect the Tertiary Limestone Aquifer. The key features of the resistivity section are(King and Dodds, 2002):

- Above about 200 m the resistivity profile is uniformly resistive, indicating the presence of low salinity groundwater or impermeable ground.
- There is a good conductor under the northern part of the line, extending about 500 m south of Dingley Dell Road. The depth of this varies between about 200 and 240 m to the north of Dingley Dell Road, but gets deeper to the south.
- In the southern part of the line, there are indications of more conductive ground at depth, but the signal from this is weak and erratic.
- The interpretation of the data suggested that extensive areas of saline water were unlikely in the region of Transect Line 3, although minor pockets may exist.

It should also be noted for the conceptual model of the area that an aeromagnetic survey of the area in which Line 3 is located picked up a high magnetic anomaly in the area that may correspond to a volcanic plug (King and Dodds, 2002). Seismic lines through this line also indicate the presence of shallow basement at a depth of approximately 200 m (King and Dodds, 2002).

Groundwater chemistry information from one observation well could be interpreted in conjunction with this resistivity profile. The information is reported in Mustafa et al. (2012). Well 7021-1396 was constructed at the Port MacDonnell Football Club in 1984 to a depth of 64 m. This is just over a kilometre to the east of Transect Line 3, but the approximate location of the well relative to the transect is indicated on Figure 8.22c. The routine sample collected from the well at the time of drilling indicated a groundwater EC of 7000 µS/cm, too high for irrigation of the turf area. In September 2009, before abandonment of the well, three discrete samples were collected from depths of 2.5, 25 and 40 m within the well, all with relatively high salinities. The chemical composition of the water sampled from 40 m was similar to that of diluted seawater, with an EC of 12 100 µS/cm.

8.9.5 KING AND DODDS (2002) TRANSECT LINE 4: NENE VALLEY

Resistivity Transect Line 4 of King and Dodds (2002) is shown in Figure 8.22d along with its major interpretive features. Only a 3 layer inversion model was presented for this transect. Transect Line 4 lies roughly half way between Cape Douglas and the township of Nene Valley and was interpreted from stratigraphic information to intersect the Tertiary Limestone Aquifer. Key features of the resistivity section are (King and Dodds, 2002):

- In the southern part of the transect (between the coast and 1 500 m), there is conductive material indicative of high salinity above 100 m depth.
- A higher resistivity layer occurs below the coastal dunes, possibly due to higher ground, higher, and lower salinity groundwater or just drier ground.
- The resistivity decreases at a depth of 15 m to 20 m, indicating a considerable rise in groundwater salinity.
- The thickness of the conductor is variable between 15 m to over 100 m, being very thick at a distance between 800 m and 1400 m from the coast.
- Between 1500 m and 1800 m from the coast, there is a resistor over a mild conductor, with the depth of the conductor increasing steeply from 20 m to over 200 m depth. There are no strong conductors in this area and hence there is not likely to be saline groundwater present.

There were no observation wells in the vicinity of Transect Line 4 that were sampled in the Mustafa et al. (2012) study.

8.9.6 KING AND DODDS (2002) TRANSECT LINE 5: CARPENTERS ROCKS

Resistivity Transect Line 5 of King and Dodds (2002) is shown in Figure 8.22e along with its major interpretive features. A 4 layer inversion model was presented for this transect. Transect Line 5 runs roughly north-east of the township of Carpenters Rocks and was interpreted from stratigraphic information to intersect the TLA. Key features of the resistivity section are(King and Dodds, 2002):

- Resistive ground in the top 100 m to 200 m of the transect, overlying a more conductive layer.
- The resistive upper layer is compatible with either impermeable rock or low salinity groundwater.
- The more conductive lower layer is interpreted to represent aquifer material saturated with higher salinity groundwater, and possibly the presence of clays. However, seawater salinities were not interpreted, other than in small pockets.
- At the south end of the transect, between the coast and a distance of 700 m, there is a conductor at a depth of 30 to 40 m that is probably saline. The maximum thickness is about 50 m.
- This upper conductor is underlain by more resistive material, which may represent a decrease in porosity or slightly less saline water.
- Between the upper conductor and the surface, the resistivity is relatively high and this part of the profile was interpreted to contain little salt.
- Below 150 m, near the coast, low resistivities indicate saline groundwater.

- Between 800 m and 1 300 m from the coast, there is a shallow conductor, which could be clay or moderately saline groundwater. This extends from the surface to a depth of 10 m to 20 m.
- In the northern part of the transect, the same resistivity layering exists as in Transect Line 4, where there is a moderate conductor below a depth of 215 m to 220 m.

None of the wells sampled by the Mustafa et al. (2012) study were located in the vicinity of Transect Line 5.

8.9.7 SUMMARY OF KNOWLEDGE OF PROCESSES OCCURRING AT THE COASTAL BOUNDARY

As described above, most of the knowledge of processes occurring at the coastal boundary of the study area is focused around the seawater-freshwater interface in the region to the south of Mount Gambier. We have summarised the results and interpretation of the resistivity profiles, observation well groundwater salinity analyses and salinity versus depth profiles of King and Dodds (2002) and Mustafa et al. (2012) on the original resistivity profiles of King and Dodds (2002) in Figure 8.22. These figures show a seawater wedge, which can extend more than 2 km inland in some places but in others appears to be constrained by hydrogeological features. In general, where seawater or a mixture of seawater or freshwater was interpreted from the resistivity data, observation well groundwater salinity or salinity vs depth profile data, where available, is in agreement with this. The information presented on Figure 8.22(a-e) could be used as a basis for “exploratory” cross-sectional models of the coastal boundary as described in Section 9.7.2. Unfortunately, such information does not exist for the majority of the coastline in the study area and, due to differences in physical characteristics along the coastline, for example the presence of coastal lakes, this information cannot be readily up-scaled.

9 Model design

Juliette Woods, Adrian Werner and Nikki Harrington

The Lower South East Groundwater Flow Model is intended to be a regional MODFLOW model focusing on the Lower Limestone Coast region of South Australia (the area of interest), but with a model domain that is governed by hydrogeological boundaries where possible and reduces boundary effects on model performance in the area of interest. This chapter makes recommendations for the model design and construction, based on the project objective, data review and research work presented in the rest of this report.

It may be desirable that the model consider Province 1 of the Border Designated Area in Victoria (see Figure 8.4). If so, this would lead to changes in model design to that presented in this chapter. These have been noted where needed.

As a regional-scale model, the model will not simulate the numerous small-scale processes that occur. It is a fundamental assumption of regional-scale models that the properties, boundary conditions and outputs of any given grid cell are representative of the cell as a whole. The inflows, outflows and storage changes within a cell are conceptually the sum of many smaller, local-scale behaviours, but model inputs and outputs on one scale cannot easily be meaningfully downscaled. If smaller-scale models are developed of regions within the regional model domain, it would be useful to compare the water balances of the small-scale and regional models as a check on whether the regional-scale parameters are appropriate.

When modelling a field site, modellers usually face the problem of non-uniqueness: it may be possible to obtain a good calibration to observed potentiometric heads with different sets of parameters. Generally speaking, to calibrate a steady-state model uniquely, one needs to know either transmissivity or a major flux (e.g. recharge, inter-aquifer leakage, lateral inflow or outflow). Transient observations can reduce the likelihood of a non-representative calibration if a flux known (e.g. pumping) as well as change in potentiometric head over time.

In the Lower South East, the hydraulic conductivities of the both the unconfined and Tertiary confined aquifers are observed to vary by one or two orders of magnitude. Few estimates of major fluxes are available. Due to the uncertainties in both aquifer parameters and groundwater flux, the problem of non-uniqueness is one of the major challenges of modelling the study area. The problem can be reduced if the net recharge can be estimated robustly. Model outputs should be compared with as many other sources of data as possible.

Data limitations (Section 3.1) and gaps in the conceptual model (Section 3.2) are challenges for the design of the numerical model. The conceptual model and its supporting data must be represented in the numerical model in terms of domain, time period, discretization, governing equations, boundary conditions and aquifer properties. The numerous simplifications and assumptions made during model design and construction must be logical and defensible, given the model aim.

Once the model has been designed, the resulting discretized equations are solved numerically. As the project area is large and the hydrology, geology and hydrogeology are complex, there may be difficulties in numerical simulation. In some circumstances, the model design, including grid size, timesteps, processes and parameters, may need to be altered to achieve numerical convergence. This is more likely to occur if there are cells which may become dry during the simulation, e.g. where the saturated thickness is low and the aquifer is stressed by pumping or ET.

The construction and calibration of a numerical groundwater model are necessarily an iterative process. It is highly likely that some of the design recommendations presented here will need to be revised as the model is developed due to further analysis of the data, enhancements to the conceptualisation of the study area, and based on initial results from model testing.

9.1 Model objectives

9.1.1 DEVELOPMENT OF AN OVERALL MODELLING STRATEGY

It is intended that the regional water balance model be developed with careful consideration of how it will support and interact with other modelling activities carried out to address the many varied policy questions arising in the Lower Limestone Coast Water Allocation Planning process. Prior to inception of the current the project, the model objectives were developed in consultation with stakeholders in this process (Harrington et al., 2011). A need was identified in Phase 1 of this project to review these objectives in the context of the current water policy landscape and ensure that all stakeholders had a clear understanding of the objectives of and outcomes from a regional scale model. A workshop was held, including the major stakeholders, i.e. representatives of DEWNR and members of the project team for the current Goyder Wetlands project, and external modelling experts. The objectives of the workshop were to:

a. clarify the objectives and likely outcomes of the regional water balance model for stakeholders
b. identify the range of policy questions that require input from other models, so that an overall modelling approach can be developed with the regional water balance model effectively feeding into this.

The outcomes of the workshop were:

a. Stakeholders had a clear idea of which policy questions the regional water balance model would answer.
b. Stakeholders were introduced to the concepts and likely outcomes of a Wetland Connectivity project proposed for Phase 2 of this project, which will provide the connection between the regional water balance model and the Goyder Wetlands project.
c. Stakeholders had a clearer idea of which policy questions would require other smaller-scale modelling approaches.
d. The project team was able to appreciate and develop an up to date list of modelling objectives and issues for consideration in both the regional water balance model and any future smaller scale models.

9.1.2 REGIONAL GROUNDWATER FLOW MODEL

The primary objectives of the regional water balance model, which will be a regional groundwater flow model, are to:

- Assess and improve knowledge of the regional water balance, including recharge, groundwater extraction, groundwater inflows and outflows across the boundaries of the study area, and outflows at the coast.
- Quantify available surface water and groundwater volumes at a regional scale.
- Identify critical knowledge gaps.
- Secondary objectives are to:
- Estimate water balances of groundwater management areas.
- Assess the current groundwater allocation approach in which 90% of estimated recharge is allocated for extraction.
- Determine the regional distribution of recharge.
- Identify possible interaction between the unconfined and Tertiary confined aquifers.
- Evaluate whether the faults impact groundwater flow at the regional scale.
- Provide a basis for more detailed localised models.

The regional groundwater model will be the first to span the Lower South East (LSE) and include both the unconfined and Tertiary confined aquifers. It will apply a consistent approach and region-wide datasets to the entire LSE , rather than the differing assumptions made by previous localised models.

The outputs, to be delivered in Phase 2 of this project, will be:

1. A calibrated MODFLOW model, with input files and key output files.
2. A model report adhering to the *Australian Groundwater Modelling Guidelines*, including a discussion of model capabilities, limitations and suggestions for further work, and that is detailed enough that the model could be reconstructed from its descriptions plus key datasets. New aspects of the conceptualisation that are revealed through the modelling process will also be discussed.

9.1.3 INTERACTIONS WITH FUTURE SMALLER-SCALE MODELS

It is intended that the regional water balance model will provide a basis for future local-scale groundwater models, which would be developed to answer hydrogeological questions that a regional model cannot. The large spatial scale of the study area, and potentially long simulation periods will require the regional-scale model to have relatively coarse levels of spatial and temporal discretisation (i.e. large model cells and long time-steps). Hence, the regional model will represent groundwater heads and flow rates that are averages over significant areas and periods, whereas in some cases, more detailed, fine-scale predictions may be beneficial for management decision-making and process understanding. In cases where local-scale ‘telescoped’ models are considered necessary to more accurately simulate focused areas (and times), the regional model can be used as the foundation for the telescoping process. Regional model surface elevations, boundary conditions, aquifer and aquitard parameters, and aquifer stresses can be applied to local-scale models, which could then be refined using more detailed local data. The simulation of smaller-scale processes using higher resolution datasets, which are not included in the larger model, may provide insights and form the basis for updates and refinements of the regional model.

The recent introduction of MODFLOW-USG (Panday et al., 2013) allows for local grid refinement, such that local-scale regions of interest can be more accurately simulated within the regional-scale model domain, without the need for building separate smaller models.

Based upon the discussions at the stakeholder workshop, some objectives for future local-scale models could include:

1. Detailed (quantitative) assessments of proposed management scenarios or developments (e.g. irrigation, forestry, industry) where local-scale model predictions are needed at higher spatial or temporal resolutions, including the impacts of land use and land use change on groundwater levels and aquifer throughflow.
2. Better understanding of localised flow processes, e.g. flow between the confined and unconfined aquifers, surface water-groundwater interactions (including groundwater-dependent ecosystems).
3. Assessment of the validity of current resource condition triggers.
4. Detailed assessments of the water balances for current individual management areas and the implications of changing to hydrogeology-based management areas, where local-scale processes are important.
5. Contaminant transport modelling or investigation of groundwater salinity issues such as seawater intrusion, which will require additional information about solute distributions, solute boundary and initial conditions, and transport parameters.
6. Modelling surface water – groundwater interactions and unconfined – confined aquifer interactions to minimize the risk of double accounting of these water types - defining what is a groundwater impact and a surface water impact (e.g. accurately accounting for forestry impacts – for both surface and ground water) – and to assist with revising management area boundaries
7. Understanding surface water-groundwater interactions to manage risks of holding water up in the landscape and identify and quantify the losses from the drainage and flow management network (man-made and natural).
8. Investigating whether our knowledge is adequate for decision making about local scale processes.

9. Identification and prioritisation of critical knowledge and data gaps at local scales.
10. Testing of technical assessment tools – e.g. forest hydro.

9.2 Modelling process

Model development will conform to three documents: the National Water Commission *Australian Groundwater Modelling Guidelines* (Barnett et al., 2012), the DEWNR Model Warehouse specifications for data and model storage and reporting, and Goyder Institute recommendations on making data and outputs publicly available.

At the start of model development, an advisory committee will be assembled that includes members with expertise on the hydrogeology of the Lower Limestone Coast (LLC) and, if desired, the Border Designated area. The committee should also include an experienced groundwater modeller and South East policy staff.

It is also recommended that two independent reviewers be engaged, one to participate during the model development and calibration, and one to review the end product.

There is a need for feedback from the advisory committee at key stages of model development process, whereby significant elements of the conceptual and numerical models are evaluated and agreed upon, to enable the model to progress to subsequent stages, including calibration, uncertainty analyses and scenario testing. A staged approach to model development, providing for input to the model construction, will ensure that the final set of modelling tools are fit for purpose and capture existing data (i.e. field observations) and the extensive hydrogeological conceptualisation knowledge of LLC experts.

Meetings should be arranged for the following stages:

1. Project inception
2. Data review and model conceptualisation
3. Model design, including preliminary calibration and sensitivity analysis
4. Final model calibration; scenario design
5. Scenario results and uncertainty analysis
6. Reporting
7. Project close; discussion on recommendations for further work

As detailed in the following sections, model development may depend on the outcomes of:

- Further historical land use mapping
- Net recharge modelling
- Any further data acquisition
- Small-scale models to test how drains and the coastal boundary should be represented in the regional model
- Outcomes of proposed Phase 2 investigations into wetland-groundwater connectivity that are expected to include the development of local-scale modelling.

Any hydrological investigations (e.g. wetland-groundwater connectivity, drain-aquifer interactions, etc.) of the LSE that are undertaken concurrently with regional-scale modelling, should be developed interdependently with the regional model to optimise the outcomes from these activities. This will ensure that new knowledge pertaining to important groundwater and surface water systems are incorporated into the regional-scale representation of the system, and that the role of local-scale features in controlling basin-scale functioning is adequately captured. The milestones for local-scale investigations need to be scoped and integrated into the plan for regional model development, so that key outcomes from all activities are coordinated appropriately.

9.3 Model platform

MODFLOW (Harbaugh et al., 2000) is selected as the numerical groundwater model code. It is an industry-standard code that has been well tested in the scientific and technical literature. MODFLOW has a range of optional packages that are capable of simulating the key hydrogeological processes of the study area. For example, the Horizontal Flow Barrier package may be used to represent the role of faults in potentially restricting flow. The developers (United States Geological Survey) have made the FORTRAN source code publicly available, so it can be altered to meet specialist needs. This may be required to implement recharge calculations based on the outputs of Chapter 5. MODFLOW is also the code preferred by DEWNR, who are the most likely custodians, end-users and adaptors of the South East Regional Model.

Various versions of MODFLOW have been developed since it was first released in 1988. DEWNR is currently using MODFLOW-2000 (Harbaugh et al., 2000), so this may be the version that is adopted. Alternatively, there is the recently-released MODFLOW-USG, which allows for an unstructured grid: this may expedite significantly sub-model telescoping to simulate some areas in closer detail. MODFLOW USG has not been applied previously in S.A., and decisions about its use will need to be made during the course of the proposed project. The decision will be based on whether there is adequate support in commonly used Graphical User Interfaces, amongst other factors. MODFLOW-USG documentation will be reviewed and a final decision on the code version will be made in discussion with DEWNR.

Groundwater Vistas (Rumbaugh and Rumbaugh, 2011) will be used to create the input files for MODFLOW and to examine the output files. It imports and exports GIS file formats, allowing for rapid model development, and supports both MODFLOW-2000 and MODFLOW-USG. It is one of the modelling platforms used by DEWNR.

Note that the regional model will simulate only saturated groundwater flow. There are alternative codes which can simulate fully-coupled surface water-groundwater interaction and unsaturated zone flow. These have significantly greater data requirements, much longer simulation times and are often more susceptible to numerical instabilities (i.e. the calculations required for the simulation may fail). A fully coupled surface water-groundwater model is presently beyond the scope of the current proposal and is not supported by the currently available data. Such an undertaking in the future would require a strategic focus on data acquisition over the preceding five years.

9.4 Model Domain and Spatial Discretisation

The preliminary model domain, selected as the study area of this project, is shown in Figure 2.1 and is identical to that used for the Tertiary Confined Sand Aquifer Model (Brown, 2000). The domain is based on the location of the area of interest (the LLC PWA), the geology, the hydrogeology, and the need for efficient model construction (i.e. the domain should be no larger than necessary). The area of interest is the Lower Limestone Coast Prescribed Wells Area, although the Padthaway Prescribed Wells Area is naturally included in the proposed model domain. This South Australian region is underlain by the Gambier Basin of the Otway Basin and the south-western margin of the Murray Basin.

The model domain should ideally be larger than the study area “to ensure that the limits of the model domain are sufficiently remote to reduce the impact of the assumed boundary conditions on the model outcomes” (Barnett et al., 2012). For this reason, the selected domain extends approximately 20 km north of the study area and also includes the Victorian portion of the Gambier Basin to the east (Figure 2.1).

The model domain is also based on maps of the water table elevation and potentiometric head for both the Quaternary/ Upper Tertiary Unconfined Aquifer and the Lower Tertiary Confined Aquifer respectively. The maps include those produced for this study (Figures 8.4 and 8.6) and also the Murray Basin Hydrogeological Map Series for Horsham, Hamilton, and Naracoorte (Cobb and Barnett, 1994; Mann et al., 1994; McAuley et al., 1992). The latter have water table elevation and potentiometric contours based on substantially more information than is available in the current Victorian observation network, providing significantly more detail. Some of the features described below are not clear in the Chapter 8 figures. Localities mentioned in this section can be found on Figure 8.5.

The northern boundary is selected as follows: the model boundary is oriented so that the watertable and potentiometric contours are roughly perpendicular, and hence there is minimal flow in or out of the model domain there. The unconfined aquifers (Quaternary aquifers, Bridgewater Formation, Padthaway Formation, Murray Group Limestone, Loxton-Parilla Sands) and the confined Renmark Group aquifer extend further northwards from the model edge (Figures 8.4 and 8.6). Between Bordertown and the coast (i.e. just south of Salt Creek), groundwater flows are generally east to west, except where a unit is absent due to basement outcropping (for example), and therefore the model boundary runs east-west. From Bordertown east to near Little Desert National Park, north of Goroke, flows are from southeast to northwest, so the model boundary curves so that it remains perpendicular to the watertable and potentiometric contours.

The eastern boundary is less straightforward to define. There is a hydrogeologically complicated region south of Little Desert National Park, near Goroke, Natimuk (Mount Arapiles) and Edenhope, where the potentiometric head contours have no simple trend, due to the influence of the Gerang-Gerung Fault and the Dimboola High (McAuley et al., 1992). This is close to the edge of the Mallee-Limestone hydrogeological province described by Evans and Kellet (1989), where the Murray Group Limestone reaches its eastern extent and where the Geera Clay, Winnambool Formation and Bookpurnong Beds divide the Renmark Group laterally (McAuley et al., 1992). An alternative model boundary could be considered during model development, where the domain extends to the edge of the Mallee-Limestone province.

South of Edenhope to Casterton, the model boundary follows the edge of the pre-Cainozoic outcrop of the Dundas Plateau, where the Murray Group and Renmark Group are absent and the watertable is within the fractured bedrock.

South of Casterton to Dartmoor is another complicated region, where the model boundary should be reviewed. In this location are Quaternary and Tertiary volcanics, and a groundwater divide which could become the revised boundary (Mann et al., 1994).

From Dartmoor to the coast, it is unclear how the model domain of Brown (2000) was selected. It may represent the boundary between the Gambier and Tyrendarra Embayments of the Otway Basin. The division between the embayments is not well defined. It is described in Ryan et al. (1995) as the Lake Condah High but is not clear-cut in the cross-section of Mann *et al.* (1994).

If the Border Designated Area of Victoria is to be part of the area of interest, then the model boundary should be extended eastwards south of Casterton to ensure that the model boundary is sufficiently distant from the area of interest. The revised boundary could follow the edge of the pre-Cainozoic basement plateau. South of the plateau, it should extend as far as the groundwater divide near Condah Swamp shown in Mann et al. (1994).

The final location of the coastal boundaries to the south and west will depend on the coastal exploratory models described in Section 9.7.2. The model domain will extend beyond the coast.

The preliminary domain is approximately 175 km east-west and 225 km north-south, aligned north-south and east-west. The maximum grid size will be 1000 m x 1000 m, so the minimum number of modelled cells per layer will be 39,375, not all of which will be active. This grid size is selected because the domain is large and a denser grid would increase computational time. A relatively coarse grid will allow for the application of automated calibration software, which requires a significant number of repeated simulations in order to achieve a calibrated model. It may be necessary to refine the grid during model development in order to simulate key regional hydrogeological features.

9.5 Temporal scales and discretisation

9.5.1 SIMULATION PERIOD

Generally speaking, most regional groundwater flow models simulate a steady-state condition, followed by a transient historical period. The steady-state simulation is used to predict an initial condition, often the pre-development situation, or at least some representation of the conditions a number of decades prior to the present time. The short run times (in the order of seconds) of the steady-state simulation allow for a rigorous calibration of hydraulic conductivity and model boundary conditions. The transient historical period, involving considerably longer run times, is commonly adopted in calibrating storage parameters and aspects of recharge. If the model is to simulate highly seasonal dynamics, the earliest part of the transient historical simulation may act as a "warm-up" transition between the steady-state condition and typical seasonal conditions prior to the transient calibration period. Some modellers also have a verification/validation period (Barnett *et al.,* 2012) but in practice this becomes an extended part of the calibration period, so it will not be discussed further here.

The modeller must decide on the steady-state conditions, the starting date of the transient period, the length of any 'warm-up' period, and the calibration period. It is not simple to make these decisions for the Lower South East due to its long and complex history has involved significant change to the hydrology and hydrogeology since the first drains were constructed in 1864 and subsequent changes in land use, e.g. land clearance and replanting in 1860s and 1870s, and forestry since the 1870s.

The choice of steady-state conditions will depend on how quickly the system responds to changes induced by drain construction, land clearance and forestry. A simple analytical equation such as the Unit Response Equation (Knight *et al.,* 2005) can estimate this, or the numerical model could be used for a type of sensitivity testing. An initial steady-state model could be set up with constant native-vegetation recharge and no drains, using initial estimates of aquifer properties. Three separate transient simulations could then be run to determine the length of time before the system reaches equilibrium, as determined from modelled hydrographs, with the simulations as follows:

- All current drains
- All current land clearance
- Maximum historical extent of forestry

The choice of steady-state conditions and the starting date of the transient simulation will be based on the test results. For example, if the system responds rapidly to all three, the following could be used:

- Steady-state conditions based on the data available for the early 1960s, i.e. the 1962 extent of drains and the 1965 extent of forestry and land clearance.
- Transient seasonal "warm-up" period from 1955 to 1964 .
- Transient calibration period of 1965 to 2012 (as some water table level and potentiometric head observations are available from the mid-1960s).
- Transient future scenarios with the simulation period to be determined through stakeholder consultation.

9.5.2 STRESS PERIOD LENGTHS

Watertable elevations in the unconfined aquifer are highly seasonal in areas where the watertable is shallow or where there is significant groundwater extraction for irrigation. It is therefore suggested that transient simulation periods adopt quarterly stress periods to capture this behaviour. Quarterly stress periods are computationally efficient and should be sufficient for the primary model objective of estimating the regional water balance. Monthly stress periods will increase the computational time, and are unlikely to improve the calibration to hydrographs. While monthly stress periods may provide more detailed model results to compare to observed potentiometric heads, the model results are "averaged" over a large grid area, while a hydrograph may be representative of only a much smaller area. Monthly stress periods would improve estimation of maximum and minimum potentiometric head over the year, which is important in assessing flow to GDEs and creeks; however, this level of detail will not be possible in a regional scale model.

9.6 Model layers

The hydrostratigraphy of the Lower South East is complex. It involves two major sedimentary basins: the Otway Basin and the Murray Basin. Various units become very thin or are absent in different parts of the model domain and the watertable passes through a large number of different formations. An aquifer within a particular formation may be confined in one area and unconfined in another. Also, the extent and thickness of the formations are not mapped in detail everywhere across the domain. The interactions between the various aquifers are not always known.

It is good modelling practice to start simply and add complexity as needed. Given the initial aims of the regional model, it is suggested that the hydrogeology be characterised in three layers: a Lower Tertiary Confined Aquifer system, an Upper-Mid Tertiary Aquitard and a Quaternary/Upper Mid-Tertiary Unconfined Aquifer. Within the Otway Basin, there is a deeper Cretaceous aquifer system but this is not to be included as it is highly saline and too deep for economic utilisation (Love et al., 1993). Earlier modelling studies, listed in Harrington et al. (2011), have presumed that the Cretaceous aquifer is hydrologically insignificant relative to the overlying aquifer systems, but this has not yet been conclusively demonstrated.

It is recommended that this choice of layers be reviewed as the model is developed. Locations where the three-layer characterisation is inexact should be noted. Any subsequent telescoped models based on the regional model may need to incorporate more layers and more detail. Where enough data exist, it may be possible to use the Hydrogeologic-Unit Flow (HUF) package (Anderman and Hill, 2000) that varies layer properties with saturated thickness, reflecting which unit the watertable is in. The Lower Tertiary Confined Aquifer system includes the aquifers within the Dilwyn Formation and Renmark Group. The formations include both sand and clay units, so in some areas there may be multiple aquifer layers within the aquifer system, but this is unlikely to have a significant impact on the regional water balance.

The aquitard layer will represent various stratigraphic units that act as a confining layer over the Lower Tertiary Confined Aquifer. In the Otway Basin, this includes the Gellibrand Marl, Narrawaturk Marl, Mepunga Formation and Dilwyn Clay. In the Murray Basin, this includes the Ettrick Formation, Renmark Clay and Geera Clay.

The Quaternary/Upper Mid-Tertiary Unconfined Aquifer will represent a combination of units which will be treated as a single unconfined aquifer: the Gambier Limestone, Padthaway Formation and volcanic units in the Otway Basin, the Murray Group Limestone and Loxton-Parilla Sands in the Murray Group and the Bridgewater Formation in both regions. Note that this simplifies the complexity of these aquifer units. For example, there are locations where two or more of these units are saturated and separated by an aquitard, and hence there are locally confined aquifers which will be treated as part of the regionally unconfined aquifer.

As defined above, the three layers are not continuous. In the north-west, there are outcroppings from the Padthaway Ridge and the Renmark Group and unconfined aquifers are not always present. Nor is the aquitard present everywhere in the model domain. Where an aquifer or aquitard is not present, the absence will be represented by adopting aquifer/aquitard properties from those of the unit below. In this way, all three layers will be continuous and avoid issues with internal inactive zones.

Section 8.2 describes the construction of the model layer surfaces.

9.7 Boundary conditions

9.7.1 REGIONAL FLOW BOUNDARIES

Boundary conditions are based on maps of water table elevation and potentiometric head. As discussed in Section 9.4, more detail is available in the Murray Basin Hydrogeological Map Series than in the current Victorian observation network, hence they are used in preference in Victoria.

As also discussed in Section 9.4, the northern model boundary is selected so that it is roughly perpendicular to the watertable potentiometric contours. Hence no-flow boundary conditions can be applied for Layer 1. In SA, the potentiometric contours within the Renmark Group are also perpendicular to the northern model boundary, so a no-flow boundary condition can be applied in Layer 3. In Victoria, the Renmark Group potentiometric contours are not precisely perpendicular to the model domain, so general head boundary conditions (GHBs) may be more appropriate, to provide an ability to simulate flows across the boundary. The assigned heads should be based on observations and contours both within and outside of the model domain, and GHB conductance varied during calibration.

For the eastern boundary, the boundary conditions applied will depend on the final decisions regarding the extent of the model domain. If the model domain follows the Tertiary model of Brown (2000), then GHBs should be used, based on observed heads to simulate lateral groundwater flow from adjacent regions/aquifers, and conductance should be varied during calibration. This applies to both layers 1 and 3. If the model domain is extended eastwards to the groundwater divides north and south of the Dundas Plateau/pre-Cainozoic outcrop, then no-flow conditions should be applied at the groundwater divides. No-flow boundary conditions should also be applied to the limit of the Renmark Group in layer 3, if this is included in the model.

No-flow boundary conditions should be adopted for all of layer 2 as it represents an aquitard, so there will be minimal lateral flow into the model domain.

9.7.2 THE COASTAL BOUNDARY

Boundary conditions must be applied at or near the coast for aquifer layers 1 and 3. GHB boundary conditions should be used in particular for the confined aquifer, because it allows for the representation of the aquifer continuation off-shore. The boundary condition could be placed at the coast or further out to sea. The potentiometric heads and conductances must be specified, taking into account density effects.

As discussed in Section 3.2.4, coastal boundary conditions can be challenging to define due to the various pathways by which submarine discharge can occur. Springs and seeps exist along the southern coast, but there may also be diffuse coastal discharge and offshore discharge. The hydrogeochemical study presented in Chapter 6 concludes that most of the submarine groundwater discharge between Port MacDonnell and the Victorian border occurs close to the coastline, but other parts of the proposed model domain were not investigated. Also, the lack of evidence for offshore discharge does not mean that it is not significant.

Potentiometric head depends on groundwater density due to salinity. The location of the freshwater/seawater interface may therefore be important in defining coastal boundary conditions (Section 3.2.4). Section 8.9 summarises the evidence to date on the location of the interface, as investigated through well sampling and geophysical methods. The location of the interface may be closer to the coast than the proposed grid spacing of 1000 m, and hence any assessment of the interface will require a higher resolution model.

Few potentiometric head observations are available near the coast. Potentiometric head in the unconfined aquifer may vary with season by 1 m or more. At some locations, the potentiometric head remains below 0 mAHD all year (e.g. WAT012 south of Robe, adjacent to Lake Eliza), presumably due to ET , pumping and/or the influence of near-coastal wetlands. Potentiometric head near the coast in the confined aquifer may be much greater than sea level, e.g. ~18 mAHD at observation well MAC077 near Port MacDonnell.

Given the many unknowns, there are two interrelated questions to be answered. Firstly, how would different conceptual models of coastal discharge impact the potentiometric head and coastal groundwater discharge in the unconfined and confined aquifers? Secondly, how sensitive would the regional model be to changes in the specified coastal boundary conditions?

The simplest option would be to vary the specified potentiometric head and conductances within reasonable bounds as part of a sensitivity and/or uncertainty test of the regional model. However, it is presently unclear what those “reasonable bounds” might be. To address this, an exploratory model is suggested (time permitting). This would be a multi-layer layer cross-sectional model using a code which simulates variable-density groundwater flow and transport, such as SUTRA (Voss and Provost, 2010) or FEFLOW (DHI-WASY GmbH, 2012). Different conceptual models would be simulated, for example, in which the confined aquifer discharges at various offshore distances. Parameters would also be varied. The exploratory model would then determine a likely range of coastal potentiometric head and discharge rates at the coast. The choice of coastal boundary conditions for the regional model would depend on the results of the exploratory model.

9.7.3 RECHARGE AND EVAPOTRANSPIRATION

Net recharge is defined here as the vertical recharge from the land surface to the unconfined aquifer, derived from rainfall and irrigation, minus evapotranspiration from the watertable. This includes the impacts of forestry on both recharge interception and direct groundwater extraction. Net recharge is likely to have varied hugely spatially and over time in the study area, due to climate, soil type, land clearance, the construction of drains, the development of irrigation and forestry, and changes in the depth to the watertable. Extreme events such as bushfires and destruction of crops by locusts or aphids can very quickly change the vegetation type and hence recharge. These have been experienced in the history of the Lower South East (LSE).

Approaches used by earlier models of the South East

Prior numerical models of groundwater flow in the South East have adopted a variety of approaches to simulating vertical recharge to the watertable. Many of the models adopt different approaches in different geographical areas.

The simplest approach is to adopt recharge rates that are constant over time across the entire domain. This is the approach adopted by Harrington et al (1999) for a simulation of conditions prior to European settlement.

More commonly, constant recharge rates vary spatially, depending on factors such as land use and soil type. Spatial distributions of recharge are presented in Bradley et al (1995), Brown (2000) and Stadter and Yan (2000). These distributions are adopted and sometimes modified for use in numerical groundwater models, including Brown (2000), Stadter and Yan (2000), REM (2007), and Aquaterra (2010). Aquaterra (2008) adopts a variant approach where recharge rates depend on the type of irrigation.

Recharge rates may also be simulated so that they vary over time as well as spatially. Modelled recharge may vary by decade due to changes in land use (Wohling et al., 2005), annually with mean rainfall (REM, 2007, Aquaterra 2008), or seasonally (Aquaterra 2010). Modelled recharge may also vary with specific events, such as the growth phase of a forestry plantation (Aquaterra 2010) or extensive bushfires (REM 2007).

Net recharge has been estimated using a one-dimensional unsaturated zone model, BioSym. BioSym provided monthly estimates for net recharge for every grid cell in the groundwater flow models of Catchment Management Authority regions in Victoria, including two with domains which overlap with the proposed SE regional model, those of Hocking et al. (2010) and SKM (2010). This is the most detailed approach yet applied to modelling recharge on a regional scale in the study area.

Suggested approaches for the regional model

Regional groundwater models must either (i) specify recharge over time or (ii) estimate recharge through inverse modelling. Inverse modelling to estimate recharge is unsuitable for the LSE Groundwater Flow Model, as the method requires reliable regional estimates of hydraulic conductivity, which are not available for the model domain.

Two approaches are suggested as possibilities. The first approach is to estimate recharge based on land use maps, soil maps and crop factors (i.e. estimates of net groundwater recharge that depend only on the crop type). Land use maps for different years are under development (Chapter 4); soil maps exist; and crop factors should be based on the recharge review of Chapter 5. Recharge rates should vary over time, depending on changes in land use. They should be varied seasonally, so that the seasonal variations in watertable can be simulated. The recharge rates should be compared with prior modelled values. ET should be applied across the model, based on data from the Bureau of Meterology or, if time permits, remote sensings surveys. This is the simplest way of estimating recharge; its accuracy depends on the uncertainty inherent in the crop factors. It does not take into account depth to water. This method may be sufficient to determine the regional water balance. If need be, rates can be modified to represent the impacts of climate variations, forestry and natural disasters, following the methods used in prior models of the SE.

A second approach is suggested by the review of South East recharge given in Chapter 5. The approach is more sophisticated than most used for regional models but remains conceptually simple. As described in Section 5.3, it is proposed to develop a look-up table for net recharge based upon the variables that contribute to the magnitude (and direction) of the net recharge. These variables are:

- Soil type
- Monthly rainfall
- Month of the year
- Vegetation type
- Depth to water table

The look-up table will be populated using the outputs of numerical recharge modelling conditioned on the recharge estimated in Chapter 5.

Four out of five of the variables will be known *a priori*. A representative soil type will be assigned to each grid cell. The monthly rainfall will be taken from observation data. Vegetation type will depend on location and type, and will be derived from the proposed land use maps.

However, the depth to water is calculated for each stress period by the MODFLOW model and depends on the recharge of the previous time step. The standard MODFLOW packages for recharge and ET (RCH, EVT and ETS) are not designed to assign look-up recharge values depending on the depth to water. It is suggested that one of these modules be modified to permit this. The FORTRAN source code is publicly available for modification.

Note that the look-up table will not include values for wetlands and swamps. These areas will be treated separately, as described in Section 9.7.6. This approach may also be required in other parts of the flats and plains where the groundwater level may be above the ground surface in winter.

9.7.4 DRAINS

The representation of drains within the model is limited by a lack of data. Construction dates are known, sometimes approximately for earlier decades. As described in Section 8.5.2, there are almost no records of flows or how control structures are used.

A simple representation is proposed. Using the MODFLOW drain (DRN) package, the drains should be included, assuming a base 2 m below the ground surface unless there is documentation otherwise. Conductance values can be varied during calibration to match observed heads. This approach assumes that the drains are gaining features only and that any flux from flowing drains back into the groundwater is minimal. One exception to this conceptualisation is the Reflows floodway that goes through the Coles-Short area (Noorduijn et al., in prep-b). Forestry in this area has caused a cone of depression and the water level is below the base of the drain (Aquaterra, 2010a).

An alternative approach may be possible. DEWNR is currently funding a small study, where a fully-coupled surface water-groundwater model will be used to simulate the drains and better determine how they function. The work will be based on a fieldwork study of the Fairview Drain, currently being carried out as part of a PhD project (Noorduijn et al., in prep-a). Insights from this study inform the representation of the drains in the regional model.

9.7.5 NATURAL WATERCOURSES

Most of the creeks within the model domain are ephemeral. They depend on winter rainfall or are fed seasonally by springs. Other watercourses, such as Deep Creek and the Glenelg River flow throughout the year.

Permanent watercourses can be simulated using the MODFLOW river package (RIV). The potentiometric head should be based on median observed values, linearly interpolated between gauging stations. Where there are no gauging stations, a height relative to ground surface should be specified, based on local advice. The conductance should be varied during the calibration: it may be difficult to calibrate to local observed heads given that the watercourse will be narrow in comparison to the grid size of 1000 m. Model results should also be compared to estimated flux values, where these are available.

Ephemeral watercourses could be simulated similarly, except that the RIV boundary conditions would be applied only in the winter months when flow is expected. It is doubtful that there is sufficient data or need to simulate ephemeral watercourses using a MODFLOW stream package such as SFR1, which calculates a surface water budget.

9.7.6 WETLANDS, LAKES AND SWAMPS

Permanent creek-fed water bodies can be simulated using the RIV package, using median observed levels. Only large water bodies should be included, due to the large cell size adopted for the regional model.

Swamps and other surface water features which are surface expressions/exposures of groundwater, such as Blue Lake, can be simulated as areas of high ET. ET rates could be estimated from satellite data. The function describing how ET varied with the depth to the watertable should be discussed with the Wetland Connectivity Project team. It can be implemented using either the EVT or ETS packages.

9.7.7 GROUNDWATER EXTRACTION

Most groundwater extraction in the model domain is used for irrigation, for which there are meter record in the South East since 2009/10 only. There is also minor extraction for stock and domestic use.

Extraction for major town water supplies should be simulated based on available records from SA Water. Towns with many seasonal visitors, such as Robe, are likely to have significant seasonal variations in extraction rate.

The simplest approach for irrigation is to estimate extraction based on land use maps, a crop requirement, median monthly/quarterly climate information, and well location. A more complex approach is calculation of irrigation requirements via the recharge modelling (Section 9.7.3). The recharge calculations necessarily estimate the volume of irrigation water required by the crop, so a second look-up table for irrigation requirements could be created. It would be assumed that the required irrigation comes from extracted groundwater and the volume would be assigned to nearby irrigation bores.

The irrigation extraction estimates should be compared to historical Management Area scale estimates, the available monitoring data from 2009 and other, more local, datasets such as historical management area scale estimates.

9.8 Layer properties and faults

9.8.1 LAYER PROPERTIES

The hydraulic conductivities of the both the unconfined and Tertiary confined aquifers are observed to vary by one or two orders of magnitude. This presents a considerable challenge to the model design. Initially, property zones will be based on geological evidence such as the stratigraphic unit(s), texture, and trends in observed properties (e.g. the trends described in Mustafa and Lawson (2002)) and summarised in Section 8.3) . All properties will be varied during calibration. Zones may be redefined to improve calibration where this is consistent with the hydrogeological evidence.

Careful comparisons should be made with parameter values used in other models, which may only be simulating specific stratigraphic units of those grouped together for the regional model. Consideration should be made of the success of the calibration of those other models.

Where no aquifer test data is available, porosity measurements should be considered as upper bound on specific yield.

The Gambier Limestone is karstic. Karst aquifers have flow via pores and flow via dissolution features which act as preferential flow paths. A variety of modelling approaches are possible which vary by sophistication and data requirements (Lindgren et al., 2009). Evidence in the South East suggests that the karst areas are not connected over large distances and so individual karst features have only a local impact. For a regional-scale model, with the aim of estimating the regional water balance, the importance of small-scale karst features is likely to be minimal. Hence it is appropriate to use a relatively simple equivalent porous media, with high hydraulic conductivities in karst regions.

9.8.2 FAULTS

The simulation of faults will require considerable testing in the model design and initial calibration phases. Where a significant displacement of aquifer units hinders regional groundwater flow (Section 8.3.3), the fault may be modelled using Horizontal Flow Barrier package so that cell size can be wider than the fault e.g. the Tartwaup Fault. Laterally extensive fault zones may be simulated using anisotropic hydraulic conductivity.

The Kanawinka Fault and Escarpment zone divides the Gambier Basin from the Murray Basin, so it will be represented in model via layer thickness and parameter zones. Initial model results during calibration may indicate whether an Horizontal Flow Barrier feature is also required.

The Gerang Gerung Fault coincides roughly with the extent of the Murray Group and Renmark Group, so it will be represented in the model via the thickness and elevation of model layers 1 and 3.

Where there is evidence of faults enhancing vertical leakage, higher vertical conductivities will be adopted.

9.9 Model calibration and confirmation

9.9.1 STEADY STATE

The calibration will begin with a consideration of the steady-state conditions. Hydraulic conductivity and model boundary conditions should be varied to obtain a rough match to the estimated steady-state conditions. Depending on the final choice of steady-state period, as discussed in Section 9.5.1, there may be no relevant data with which to compare the model results. As much of the unconfined aquifer has seasonally-varying heads, the steady-state comparison should be to some median, constant, condition. It may be necessary to test more than one conceptual model at this stage, e.g. different assumptions regarding flow across faults.

9.9.2 TRANSIENT CALIBRATION TO HYDRAULIC HEADS

Once the steady-state calibration is satisfactory, the transient calibration will commence. Model outputs should be compared to observed potentiometric heads in the two main aquifers, including level, seasonal amplitude, overall trends and contours. All available observation data should be used for a scaled root mean square (SRMS) error calculation, unless it is self-contradictory (e.g. two bores very close to each other with very different trends) or clearly erroneous (e.g. indicates watertable level above ground surface in an area where this is not observed). Some of the data may be specific to a particular sub-unit of the modelled layer, so care will need to be taken in its interpretation. Head observations that mainly reflect a local phenomenon (e.g. in a karst area or close to a drain) should distinguished from head observations that represent regional flow dynamics. In some cases it may be appropriate to assign reliability weightings to the observed heads prior to the calculation of the SRMS error. The SRMS error should be calculated for both the area of interest (LLC) and the entire model region, for key years.

Hydrograph information for all observation wells in the South Australian portion of the study area has been downloaded from DEWNR's Obswell database (DEWNR, 2013). Some examples of this are shown in Section 8.4. Observation well data for the Victorian portion of the study area has also been obtained from the Victorian Department of Sustainability and Environment (DSE). The locations of all of the observation wells for which data has been obtained are shown on Figure 8.5. Water levels in the South Australian observation well network are measured quarterly (March, June, Sept and Dec); the reading schedule usually extends beyond the starting month as it can take two months to complete a network. There are a number of wells with data loggers (approximately 100 wells) with most of them recording every 4 hours but some every 12 hours.

For historical calibration, before the observation well network became effective, the historical water level record for Blue Lake, which is a surface expression of the water table, provides one observation point with records going back to approximately 1880 (Figure 8.16). This may also provide a calibration point for the steady state model. More recent observations, captured as monthly or quarterly manual readings up to 2012, and hourly water level logger data subsequent to that, is now available on the Obswell database (observation number BLA106).

An additional pre-development qualitative calibration dataset is available as the locations of pre-drainage groundwater springs found in the paper of Williams (1964) and shown in Figure 8.10. This paper on the history of the drainage network also includes some comments on times of flooding, which could be used as a qualitative check of historical model results.

Another qualitative calibration option could be to ensure that the model is able to reproduce the effects on groundwater levels of discrete purturbations to the water balance, i.e.

- the aphid infestations that occurred in 1978, and ruined Lucerne crops, causing widespread flooding in the 1980s and early 1990s.
- the 1983 bushfires, which removed large areas of forest plantations and resulted in water table rises that are clearly identifiable in hydrographs. The map of the bushfire extent has been obtained from DEWNR.

9.9.3 CALIBRATION TO INFORMATION OTHER THAN HYDRAULIC HEADS

A further step is to compare model outputs against other data and information sources, not limited to: previous regional water balance estimates, location of springs and other artesian areas, water quality data (salinity), hydrogeochemical evidence e.g. of flow rates, and estimated fluxes to specific surface water features. DEWNR refers to this process as `confirmation' while the *Australian Groundwater Modelling Guidelines* (Barnett et al., 2012) do not separate this stage from the rest of the calibration.

Particular examples of information available for checking model performance are summarised below from Chapter 8 and include:

Tertiary Limestone Aquifer:

- Brown et al. (2001) inferred average groundwater residence times from CFC-12 values of ~ 30–35 years for shallow groundwater (between 1.5 and 2 m below the watertable) in the Tarpeena and Nangwarry areas.
- Harrington et al. (1999) estimated lateral flow in the TLA to range between 4 and 38 m/year using ^{14}C data in a combined MODFLOW and Compartmental Mixing Cell approach.
- Karstic flow in the Mount Gambier area results in local groundwater flow velocities towards Blue Lake of 0.5 to 1.5 km/yr (Vanderzalm et al., 2009).

Lower Tertiary Confined Sand Aquifer:

- Harrington et al. (1999) estimated lateral flow velocities in the TCSA to range between 0.4 and 5.5 m/year using ^{14}C data in a combined MODFLOW and Compartmental Mixing Cell approach.
- Love et al. (1994) estimated groundwater travel times in the TCSA between the ZHD line and the coast of 12 800 yrs (±20%) from ^{14}C data. The ^{14}C data integrates the impacts of groundwater flow conditions over the timescales of groundwater flow and hence, reproducing the travel time would require running the model for at least 13 000 yrs and reproducing past hydraulic gradients through changes to the coastal boundary.
- In doing this, the regional model should then be able to reproduce the ^{14}C distributions measured by Love et al. (1993; 1994).

Interaquifer Leakage

- There should be no significant downward leakage of water from the unconfined aquifer to the confined aquifer between the eastern margin of transect AA’ and Naracoorte (Figure 8.5).
- Downward leakage through the aquitard should occur between Naracoorte and the ZHD line along transect AA’ (Figure 8.5). This is the dominant method of recharge to the confined aquifer in this area rather than localised recharge along the Kanawinka Fault. The average recharge rate to the TCSA along this line is 2.1 mm/yr to 8.5 mm/yr (Harrington et al., 1999).
- There should be no recharge to the confined aquifer (either from below or above) between the ZHD line and the coast along transect AA’, although it is noted that there is some evidence for upward leakage from underlying aquifers right at the coast (Love et al., 1993).
- Downward leakage from the unconfined aquifer to the confined aquifer should occur along transect BB’ (Figure 8.5) between the northern edge of the transect and the ZHD line.
- There should be no recharge to the confined aquifer between the ZHD line and the coast along transect BB’.
- Drawdowns in the unconfined aquifer in Province 1 of the Border Designated Area as a result of groundwater pumping should result in drawdowns in the underlying confined aquifer as shown by hydrographs for that region.

Due to the simplifications required for a regional model, there may be some areas that the model is unable to simulate accurately. These will be highlighted in the report and recommendations made regarding further field work or smaller-scale modelling studies that may resolve the difficulty.

9.10 Sensitivity Analysis

A sensitivity analysis should be performed for parameters for which there is a wide range of possible values. This is likely to include the horizontal hydraulic conductivity of the aquifer layers, the vertical hydraulic conductivity of the aquitard layer, specific yield, storativity, and some boundary condition parameters. For each parameter, a reasonable regional minimum and maximum should be selected. A copy of the calibrated historical model (including both steady-state and transient periods) should have one parameter altered and the model run. Key outputs should be compared: calibration statistics (SRMS), and water balance fluxes.

9.11 Uncertainty Analysis

Uncertainty is inherent in all regional groundwater models. The accuracy of model results depends on:

- The type, quantity, location and accuracy of available data
- The conceptual model
- How the conceptual model is represented numerically, including the:

    a. Governing equations used to describe physical processes
    b. Numerical methods used to solve the governing equations
    c. Boundary conditions
    d. Parameters.

Some aspects of the conceptual model of the South East remain uncertain, e.g. the impact of faults on horizontal flow within an aquifer and the vertical flow between aquifers. Conceptual uncertainties should be tested by building multiple versions of the numerical model, each employing different assumptions, and comparing the model outputs. This will be necessary during the iterative process of numerical model development and calibration, and it is possible that the numerical model will demonstrate that some conceptualisations are not consistent with observations and so can cautiously be ruled out. The impact of conceptual uncertainties should also be explored for predictive scenarios.

MODFLOW employs well-tested governing equations and numerical methods. The approach to net recharge described in Section 9.7.3 is new to MODFLOW but is likewise based on well-established governing equations. Some uncertainty may be introduced by the use of a look-up table, and this could be investigated by e.g. varying whether net recharge is calculated for depths to water with increments of 0.2, 0.5 or 1 m.

Uncertainties in hydrogeological parameters, including those used in boundary conditions, depend on the reliability, location and frequency of field observations. Barnett *et al.,* 2012 describe three main approaches to parameter uncertainty: linear, non-linear and ‘other’. Linear approaches are the simplest to use. The calibrated historical model and a key scenario should be run multiple times, each case using a different altered parameter kept within a reasonable range. Also, `best case’ and `worst case’ combinations of parameters should be simulated for a given key output. Non-linear and ‘other’ methods are suggested only if there is sufficient expertise, time and budget.

10 Conclusions

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This report provides the details of the data review, hydrogeological/hydrological system conceptualisation and specific technical projects carried out under Phase 1 of the Goyder Institute funded South East Regional Water Balance Project. Phase 1 of the project was designed to provide the foundations for the development of a regional water balance model for the Lower Limestone Coast Prescribed Wells Area, to be carried out in Phase 2.

In Phase 1, we have collated and assessed all available data and knowledge required to construct a regional water balance model of the designated study area, which is shown in Figure 2.1, and includes the area of interest, being the Lower Limestone Coast Prescribed Wells Area. In addition to this, a series of other tasks were carried out, which add new understanding to the conceptual model of the study area and begin to address identified knowledge gaps. These were:

- Creation of the first preliminary historical land use/land cover maps for the study area, dating back to 1890, with an assessment of the techniques that can be used to further refine these (Chapter 4).
- A review of all available data on groundwater recharge to the study area, re-estimation of recharge across the whole study area using a series of complimentary techniques and analysis of the key factors influencing recharge. This has been done with a view to developing better tools for implementing recharge in the regional water balance model (Chapter 5).
- A preliminary investigation into the use of environmental tracers to identify and quantify groundwater discharge to the marine environment (Chapter 6).
- A preliminary investigation into the influence of geological faults on lateral and vertical groundwater flow in the study area (Chapter 7).
- Re-development of the hydrostratigraphic model of whole the study area, where separate models previously existed for the South Australian and Victorian portions. This included alignment of the South Australian and Victorian stratigraphic datasets (Section 8.2).
- Collation and graphical comparison of recent and historical groundwater extraction data, including that estimated under the old irrigation equivalent system and more recently collected metered data (Section 8.8).
- A review of the information on the processes occurring at the coastal boundary in the region to the south of Mount Gambier, and assimilation of this information into cross-sectional conceptual models for future modelling of the seawater interface in this region (Section 8.9).

The following conclusions and recommendations can be made about the conceptual model for the water balance in the Lower Limestone Coast PWA, the science available to support development of a regional water balance model, and priority activities for Phase 2 of the project.

10.1 The study area

The area of interest for the proposed regional water balance model is the Lower Limestone Coast Prescribed Wells area. However, a preliminary model domain was selected based upon the need to minimise model boundary effects on model predictions in the area of interest, and hydrogeological boundaries and flow lines. The study area for Phase 1 of the project corresponds to the model domain of the previous Tertiary Confined Sand Aquifer model (Brown, 2000), which was based on interpreted hydrogeological boundaries. This study area extends into Victoria, including Zones 1A/1B to Zone 6A/6B and part of Zones 7A/7B of the Border Designated Area. Hydrogeologically, the study area includes the unconfined Tertiary Limestone Aquifer (TLA), the Tertiary Confined Sand Aquifer (TCSA) and the intervening aquitard.

10.2 Collation and review of existing data

Existing datasets collated and reviewed for the purposes of developing the regional water balance model of the study area have included:

- information on groundwater flow and aquifer properties for both the unconfined and confined aquifer systems and the intervening aquitard, including information from previous studies using environmental tracers.
- groundwater level trends in both aquifer systems.
- all available information on the natural and man-made surface water systems in the study area, including historical data on natural (pre-development) surface flows, and the history of the implementation of the man-made drainage scheme.
- Currently available (GIS-based) land use maps.
- Collation of all data available for model calibration, including hydrographs, as well as information on groundwater ages and flow rates from environmental tracer data.

Relative to many other regions in Australia, there are large quantities of data available for the study area and there have been numerous technical investigations into various components of the water balance. However the complexities of the water balance dictate that large amounts of data are required for accurate representation of this in numerical models. A number of knowledge gaps in aspects of the conceptual model have already been identified (Harrington et al., 2011), and some of these are being addressed as part of this project. However, during the process of collating existing data, specific deficiencies in the spatial and temporal coverage of certain basic datasets have also been noted. These are:

- Aquifer property data. The most comprehensive aquifer property dataset exists for the unconfined aquifer, and this is often of low quality, as assessed by Mustafa and Lawson (2002), and patchy in its spatial coverage (Appendix B). There is little or no data for the Murray Basin portion of the study area. There are few aquifer property measurements for the confined aquifer and the Upper Mid-Tertiary Aquitard. Whilst aquifer properties are the most commonly unknown parameters in regional groundwater flow models and tend to be adjusted as part of the model calibration process, the complexity and range of unknowns in the study area mean that having as good a constraint as possible on aquifer property data would be extremely beneficial to model outcomes.
- The level of information available on surface water fluxes and surface water-groundwater interactions in the study area is extremely poor. The understanding of surface water – groundwater interactions has been previously noted as a knowledge gap. Although the study area is a groundwater dominated environment, surface drains move large quantities of water around the landscape. Drains will be implemented in the regional water balance model initially in a simplified way, as boundary conditions with gauging station data being used as a check on the quantities of water that are moved through these boundaries. However, for such an extensive drainage network, only a handful of gauging station data exists and the records for these stations are often temporally short, limiting the ability to constrain these fluxes in the regional model (Appendix C). This may not be a significant problem for the regional model and will be assessed during model construction and calibration. However, any future modelling exercises required to address specific questions about the interaction of the drains and natural watercourses with the groundwater system, including those necessary to facilitate a decision support system designed to manage risks around ecosystem health and flood mitigation will require prioritisation of the collection of surface water monitoring data as well as shallow groundwater data adjacent the drains.
- Offshore extents of aquifers. Groundwater discharge to the marine environment is likely to be a large component of the regional water balance and modelling of this requires an understanding of how far aquifers extend offshore. This information is difficult and expensive to obtain and commonly unavailable for regional groundwater modelling.

10.3 Historical land use mapping

As part of the data collation, review and conceptual model development carried out under Task 1 of this project, it was recognised that having historical land use/land cover information would be of great benefit to the outcomes of the project. This is because of the dynamic nature of the hydrological system in the South East and the large influence of land use over this. Two methods for creating historical land use datasets were explored with "demonstration products" produced. These were: (1) interpretation of Landsat image data for the period 1975 to 1995, and (2) collation and mapping of hundred-scale agricultural census data for the period 1857 to 1974. Key results included:

- Method 1 has the potential to develop a high resolution product for 1975 to 1995. As a demonstration, the method was used to create a 1995 land use map that could be compared with an existing 1998 land use map. The key challenges in this method were identified through analysis of areas where the two maps did not agree. Although there are significant challenges in achieving an acceptable accuracy for this product, a number of options have been identified that will improve this in future studies.
- Method 2 has proven to offer a wealth of useful information to support the understanding of the impacts of hydrological changes relating to land use/land cover change in the South East of SA. For example, maps of native vegetation cover produced for 1890, 1925, 1935, 1955 and 1964 show patterns of vegetation clearance over time for the region. Although at a fairly coarse scale, this is the first spatial and temporal picture produced of historical land use change in the South East.
- There is a very high potential for creating a 'seamless' record of land use in the South East from the later 1850s through to the present day at the hundred and, later, at finer spatial resolutions if required for a regional water balance model. This 'seamless' record would be based on the agricultural census data up to the 1970s, and satellite imagery from the 1970s onwards.

10.4 Recharge estimation

The Recharge Estimation component of this project estimated recharge for the entire study area from observational data using (1) the water table fluctuation method (WTF), (2) the chloride mass balance method (CMB), (3) a water balance using satellite derived estimates of actual evapotranspiration (Satellite ET). These methods vary in the type of recharge they estimate, i.e. gross recharge, net recharge (positive only, with net discharge resulting in a recharge value of zero) and an alternate definition of net recharge (positive or negative). The results of these methods are therefore complimentary but not comparable. It should also be noted that application of the WTF method included the assumption of a uniform specific yield value of 0.1 across the whole study area. Hence the results of this method are useful as a comparison, but should not be considered as absolute values. Key findings for this component of the study included:

- The average recharge estimates for the study area from the three methods were:
    a. WTF method (gross recharge): 84 mm/year (ranging from 2 to 259 mm/year).
    b. CMB method (net recharge, non-negative): 21 mm/year (plausible range of 13 to 34 mm/year).
    c. Satellite ET method (net recharge or net discharge; time frame 2001 to 2010): -5 mm/yr (-0.9% of rainfall)
- A negative trend in the gross recharge of almost 1 mm/year was observed over the period 1970 to 2012 from the WTF method. The cause of this trend (whether climatic or development related) was not determined during this study but further investigation is recommended as part of Phase 2 to ensure that all factors influencing recharge are adequately represented in the regional water balance model.
- Considerable inter-annual variability was observed in the average net recharge rates derived from the Satellite ET method for between 2001 and 2010. The extremes were 2006 with -163 mm and 2010 with +126 mm.
- When broken up by vegetation type, although there is considerable variability within each vegetation type, the average net recharge from the Satellite ET method, as a percent of rainfall, was as follows:

a. Crops: +2.8%
b. Pastures: +1.4%
c. Native vegetation: -3.6%
d. Softwoods: -9.7%
e. Irrigation areas: -13.4%
f. Hardwoods: -16.4%

- The Satellite ET method produced some interesting results in relation to the relationship between net recharge and depth to water table (DTWT):

a. As expected, recharge under pastures was independent of water table depth due to the shallow rooting depth of the associated plants.
b. Softwood plantations over sandy soils showed results that were consistent with the results of Benyon et al. (2006), with the greatest discharge occurring with DTWT at a few metres, and discharge becoming negligible beyond 6 m DTWT.
c. For heavier textured soils (clay content 5 to 25%), maximum groundwater discharge occurred with the water table between 3 to 7 m depth, with discharge below this decreasing towards zero. The maximum depth to which vegetation could extract groundwater was 9, 13 and 16 m for soils with clay contents of 5 to 10, 10 to 15 and 15 to 25% respectively (These depths may be a result of capillary rise of groundwater into the unsaturated zone rather than the maximum rooting depth of the trees but this cannot be confirmed within the current project).
d. For soils with even greater clay contents, the watertable depth at which trees could access groundwater was estimated to be greater than 20 m.

Due to the fact that the three methods used estimate different types of recharge, the recharge quantities for the model domain estimated varied considerably. However, this gives us more insight into the processes driving the water balance. For the LLC PWA, these estimates were 1 241 GL/year for the WTF method (average gross recharge for the period 1970 to 2012), 411 GL/year for the CMB method (net recharge but applicable only to net recharge zones and may not be representative of the current land use), and 37 GL/year for the Satellite ET method (net recharge applicable to both net recharge and net discharge zones over the period 2001 to 2010).

Each of these three recharge estimates has its limitations. The water table fluctuation method is reliant on point data that does not represent all combinations of soil / land use / depth to water table and so the gross recharge estimates derived from this method are biased toward those combinations where we do have data. The chloride mass balance is estimating recharge over the residence time of the water in the aquifer and is influenced by up-gradient areas and so may not be providing current estimates of recharge at the location indicated, it is also not appropriate to use in groundwater discharge areas. The water balance estimates of recharge from the remotely sensed ET gives the best spatial and temporal resolution; however, the magnitude of the results and associated uncertainty has not been evaluated.

10.5 Submarine groundwater discharge (SGD)

A range of environmental tracers were sampled in seawater and potential source waters to evaluate which tracers are most useful to locate and potentially quantify SGD in the study area.

Salinity, temperature and radon-222 appeared to be the best tracers to map SGD along the coastline (that is, in intertidal groundwater, the surf zone and probably slightly further offshore). However, sampling in seawater should be made at a high spatial resolution (<100 m) because the footprint for some of the largest freshwater springs found along the coastline was relatively small (100 – 200 m). It would be possible to estimate the groundwater flux using radon-222 near the coastline using the approach used here with radium, with the advantage that, unlike for radium, fresh regional groundwater is relatively enriched in radon-222.

Whether offshore submarine groundwater occurs in the study area could not be determined from the results of this study. However, the hydrodynamically active environment of the Southern Ocean would tend to favour mixing of groundwater and seawater within the seabed rather than in the water column. Thus, offshore SGD may be better assessed by looking for evidence of freshwater within the seabed rather than in the water column.

10.6 The influence of geological faults on groundwater flow

Twelve groundwater wells located adjacent to the Tartwaup and Kanawinka faults were sampled for hydrochemistry and environmental tracers. Key aims of this study were to evaluate the influence of the faults on lateral groundwater flow and identify and potentially quantify any interaquifer exchange, currently major uncertainties in the conceptual model of the South East region. Key findings included that:

- Hydrochemical and environmental tracer analyses of groundwater sampled from the wells did not identify significant, consistent trends associated with well location or sampling depth, which is probably attributed to the broad extent of many well screens.
- However, the results achieved were promising that, if these wells were completed with discrete screen intervals, differences in hydrochemistry and age may be identified between hydrostratigraphic units, and trends evaluated in relation to groundwater flow paths and flow rates.
- For example, environmental tracer results suggest that the groundwater sampled was a mixture of both young (< 60 years old) and old (>5000 years old) water.
- Groundwater flow and groundwater age transport modelling was used to demonstrate the possible effects of the regional geologic faults on flow paths and the spatial distribution of age. Future re-sampling of wells after adequate completion could identify differences in ages between hydrostratigraphic units, which could subsequently be used to constrain boundary conditions and hydraulic parameters used in numerical models of groundwater age.

10.7 Re-development of the hydrostratigraphic model

A major outcome of Phase 1 of this project was the re-development of the hydrostratigraphic model of whole the study area, where separate models previously existed for the South Australian and Victorian portions. This included alignment of the South Australian and Victorian stratigraphic datasets. This was done in collaboration with DEWNR as the hydrostratigraphic model for the whole South East region (including the Otway Basin and the south-western portion of the Murray Basin) was being revised by DEWNR for the Bureau of Meteorology National Aquifer Framework project (S. Barnett, pers. comm). In collaboration with the current project, it was decided to extend the study area for the hydrostratigraphic model across the border to the Dundas Plateau, considered to be a natural hydraulic boundary for groundwater flow. The previously existing hydrostratigraphic model included only 5 data points from the Victorian side of the Border. Additional hydrostratigraphic data from Victoria was obtained from the Victorian Department of Sustainability and Environment and interpreted to extend the South Australian hydrostratigraphic model.

A preliminary hydrostratigraphic model of the study area has been developed and checked against existing cross-sections from DEWNR reports, hydrogeological maps, and knowledge of a local hydrogeologist with expertise in the South East (J. Lawson, pers. comm., 2013). Some areas along the SA/Victorian border, where the preliminary hydrostratigraphic model shows the Tertiary Limestone Aquifer and the Upper Mid-Tertiary Aquitard to be absent are believed to be incorrect (J. Lawson, pers. comm.). Datasets to be used to rectify this are being compiled and this will be carried out and the hydrostratigraphic model finalised as part of Phase 2 of the project.

10.8 Historical groundwater extraction data

All available recent and historical groundwater extraction data has been collated as part of this project. For the South Australian portion of the study area, most management area scale irrigation equivalent (IE) data is available from the 1997/98 irrigation season onwards, with data from the Padthaway Prescribed Wells Area extending back as far as 1985/86. The first full set of metered data is available for the 2009/10 financial year, with 2007/08 and 2008/09 data considered to be 'transitional' and of low quality. Although quality checked metered extraction data is now available for 2009/10, 2010/11 and 2011/12, only the dataset for the latter year has been obtained from DEWNR to date. This dataset includes groundwater extraction data by well, with details of well co-ordinates and the groundwater Management Area in which it is located.

Simple corrections have been applied to the early IE data to account for factors such as irrigation system losses and drainage to the water table so that the data can be graphed alongside the metered data for individual management areas, producing a quasi-time series of data. Temporal trends in the historical groundwater extraction data for individual management areas can then be used with historical land use information and bore drilling records to produce logical temporal groundwater extraction datasets for input into the numerical model. This would be a significant activity in Phase 2, being undertaken in parallel with model construction.

Spreadsheets of metered groundwater extraction data for the Victorian portion of the study area, collated by the SAFE program are available, but have not yet been received. These will represent point-scale metered groundwater use for the most recent measurement period, considered to be the most accurate. Rasters of groundwater use density created from these data sets have been provided by DSE. Historical datasets have not been obtained for the Victorian portion of the study area and it is considered that major patterns of land use change (i.e. conversions to irrigated land uses) could be used to create some simple temporal variation in groundwater extraction for this portion of the study area, which is outside the main area of interest for the current project. Future applications of the regional water balance model could incorporate more detailed temporal datasets if required.

10.9 Processes occurring at the coastal boundary

Most of the knowledge of processes occurring at the coastal boundary of the study area is focused around the seawater-freshwater interface in the region to the south of Mount Gambier. The results and interpretation of the resistivity profiles, observation well groundwater salinity data and salinity versus depth profiles of King and Dodds (2002) and Mustafa et al. (2012) are summarised on the original resistivity profiles of King and Dodds (2002) in Figure 8.22(a-e). These figures show a seawater wedge, which can extend more than 2 km inland in some places but in others appears to be constrained by hydrogeological features. In general, where seawater or a mixture of seawater or freshwater is interpreted from the resistivity data, observation well groundwater salinity or salinity vs depth profile data, where available, is in agreement with this. The information presented on Figure 8.22(a-e) could be used as a basis for "exploratory" cross-sectional models of the coastal boundary as described in Section 9.7.2. Unfortunately, such information does not exist for the majority of the coastline in the study area and, due to differences in physical characteristics along the coastline, for example the presence of coastal lakes, this information cannot be readily up-scaled. Thus, defining coastal boundary conditions will remain a significant challenge in the development of the regional groundwater model.

10.10 Recommendations

Development of Regional Water Balance Model

Detailed recommendations for the design of the Regional Water Balance Model have been provided in Chapter 9. Key recommendations are that the model should:

- Cover a larger area than the LLC PWA to ensure a minimal impact from boundary condition assumptions.
- Use a three layer hydrostratigraphical model comprising the unconfined Tertiary Limestone Aquifer, the Mid-Tertiary Aquitard and the Tertiary Confined Sand Aquifer.
- Be developed using the MODFLOW code in the Groundwater Vistas platform to be consistent with industry standards and DEWNR protocols.
- Incorporate all current and historical data available for the region.
- Where necessary and possible, be informed by the development of small scale, simple "exploratory models" of key processes, such as groundwater flow at the coastal boundary or around drains.
- Be developed in close consultation with the Wetlands Connectivity project proposed for Phase 2 to ensure that the necessary feedbacks between the two models are able to occur.

Recharge Modelling

Two approaches to simulating rainfall recharge in the Regional Water Balance Model are suggested:

- Estimation of recharge based on land use maps, soil maps and crop factors (i.e. estimates of net groundwater recharge that depend only on the crop type). Development of land use maps for different years may continue as a Phase 2 activity (Chapter 4); soil maps exist; and crop factors would be based on the recharge review of Chapter 5. Recharge rates should vary over time, depending on changes in land use. They should be varied seasonally, so that the seasonal variations in watertable can be simulated. The recharge rates should be compared with prior modelled values. ET should be applied across the model, based on data from the Bureau of Meterology or, if time permits, remote sensings surveys. This is the simplest way of estimating recharge; its accuracy depends on the uncertainty inherent in the crop factors. It does not take into account depth to water. This method may be sufficient to determine the regional water balance. If needed, rates can be modified to represent the impacts of climate variations, forestry and natural disasters, following the methods used in prior models of the SE.
- An approach suggested by the review of South East recharge given in Chapter 5. This approach is more sophisticated than most used for regional models but remains conceptually simple. As described in Section 5.3, it is proposed to develop a look-up table for net recharge based upon the variables that contribute to the magnitude (and direction) of the net recharge. These variables are:

  a. Soil type
  b. Monthly rainfall
  c. Month of the year
  d. Vegetation type
  e. Depth to water table

  The look-up table will be populated using the outputs of numerical recharge modelling conditioned on the recharge estimated in Chapter 5 with a representative soil type assigned to each grid cell, monthly rainfall taken from observation data and vegetation type derived from land use maps. In this approach, the depth to water is calculated for each stress period by the MODFLOW model and depends on the recharge of the previous time step. The standard MODFLOW packages for recharge and ET (RCH, EVT and ETS) are not designed to assign look-up recharge values depending on the depth to water. It is suggested that one of these modules be modified to permit this. The FORTRAN source code is publicly available for modification. Note that the look-up table would not include values for wetlands and swamps. These areas should be treated separately, as described in Section 9.7.6. This approach may also be required in other parts of the flats and plains where the groundwater level may be above the ground surface in winter.

Historical land use maps

- Options should be explored for further refinement of historical land use maps developed as part of Phase 1, using ancillary information (e.g. Woods and Forest Department annual reports, aerial photographs and anecdotal information) for the hundred-scale maps prior to 1970 and using high temporal image stacks of Landsat image data for the Landsat-based maps from 1970 to 1995.

Submarine groundwater discharge

- High spatial resolution sampling for salinity, temperature and radon-222 in intertidal groundwater and inshore coastal waters could be used to map SGD locations along the coastline.
- Two dimensional modelling using conceptualised cross-sections could be used to further evaluate the significance of SGD along the coastline, including for evaluating the potential role of the large coastal lakes along the western section of the coastline in influencing regional groundwater flow processes.
- Land-based or aerial geophysical soundings could be used to further characterise the depth to the saline interface along the coastline.
- Similar geophysical techniques could be used to evaluate the presence of freshwater in the seabed in offshore areas.

The influence of faults on groundwater flow

- The primary recommendation for future investigations of groundwater flow across the Tartwaup and Kanawinka faults is to complete the recently-drilled (c.2009) wells as multi-level piezometer nests. This would enable sampling to be undertaken at discrete depths below ground surface. Vertical profiles of chemical and isotopic concentrations could then be obtained, which would likely provide greater insights into the dynamics of flow between hydrostratigraphic units.
- A second recommendation is that the deep (>100 m depth) wells be extended in order to intersect the Tertiary Confined Sand Aquifer. It is possible that displacement at or around the faults is sufficient to facilitate upward flow of older water from the Dilwyn aquifer into the Tertiary Limestone Aquifer. Deeper well completions (followed by installation of multi-layer piezometer nests) could provide significant insight into connections between the confined and unconfined aquifers.
- A third recommendation is to undertake additional drilling along the Kanawinka fault transect. Similarities in the stratigraphic logs of wells drilled to-date suggest that the location of fault displacement has not been identified. It has been hypothesised that the fault offset may occur upgradient of well 7023-7259; future drilling activities may wish to target this section of the transect.

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Appendix A Counties and Hundreds in the South East Division (after Leadbeater (n.d.))

COUNTY (YEAR PROCLAIMED)	HUNDRED	YEAR DECLARED	AREA (HA)
Grey (1846)	Benara	1862	29392
	Blanche	1858	23024
	Caroline	1862	24466
	Gambier	1858	21840
	Grey	1858	25098
	Hindmarsh	1858	25497
	Kennion	1883	25497
	Kongorong	1862	23739
	Lake George	1871	21654
	MacDonnell	1861	26345
	Mayurra	1869	24934
	Mingbool	1867	23452
	Monbulla	1861	25436
	Mount Muirhead	1869	24994
	Nangwarry	1867	24613
	Penola	1861	23867
	Riddoch	1883	26061
	Rivoli Bay	1871	19063
	Short	1883	26057
	Symon	1855	25323
	Young	1858	24686
			Total 513956
MacDonnell (1857)	Beeamma	1921	34714
	Binnum	1869	37859
	Duffield	1864	27050
	Geegeela (formerly Pfluam)	1907	34970
	Glen Roy	1871	27488
	Hynam	1869	37469
	Lacepede	1861	26106
	Landseer	1888	29997
	Lochaber	1869	25418

	Marcollat	1888	39822
	Minecrow	1878	33923
	Murrabinna	1871	21997
	Parsons	1884	24679
	Peacock	1888	37016
	Woolumbool	1888	36307
			Total 474815
Robe (1846)	Bowaka	1871	24909
	Bray	1877	26002
	Coles	1885	26994
	Comaun	1861	23932
	Fox	1885	38519
	Jessie	1867	26050
	Joanna	1862	21877
	Joyce	1876	24253
	Killanoola	1861	38850
	Mount Benson	1871	25875
	Naracoorte	1867	25792
	Robertson	1867	24156
	Ross	1877	25353
	Smith	1885	25666
	Spence	1886	22981
	Townsend	1878	37785
	Waterhouse	1861	31137
			Total 504446
Cardwell (1864)	Colebatch	1938	34387
	Coombe	1906	44460
	Field	1938	25666
	Glyde	1864	40133
	Laffer	1921	44584
	McNamara	1938	39558
	Messent	1938	32550
	Neville	1864	29051
	Petherick	1938	43672
	Richards	1938	38879
	Santo	1864	27392
	Wells	1938	38514

			Total 437886
Buckingham (1869)	Archibald	1906	39599
	Cannawigara (formerly Paech)	1909	38634
	Makin	1939	34879
	McCallum	1939	35864
	Pendleton	1909	38272
	Senior	1906	38306
	Shaugh	1939	48157
	Stirling	1886	34879
	Tatiara	1871	35864
	Willalooka	1921	38272
	Wirrega	1882	56588
			Total 442338
		South East	Total 5,864,894

Appendix B Summary of unconfined aquifer property data reviewed by Mustafa and Lawson 2002)

Note: The reader is referred to the original reference for details of the data assessment and calculations used to create these figures.

Beachport
Southend
Millicent
Mount Burr
Kalangadoo
Nangwarry
Tarpeena
Tantanloola
MOUNT GAMBIER
Yahl
Carpenter Rocks
Nene Valley
Port Macdonnell
RIVOLI BAY
MOUNT MUIRHEAD
RIDDOCH
GREY
NANGWARRY
YOUNG
MINGBOOL
HINDMARSH
MAYURRA
BENARA
BLANCHE
GAMBIER
KONGORONG
MACDONNELL
CAROLINE
SOUTH AUSTRALIA
VICTORIA
See plan 201431_004 (Fig 4b)
Hundred boundary
Lake
Subject to inundation
Watercourse/channels
Forest
Conservation Park
Game Reserve
National Park
Builtup area
Well with transmissivity value (m²/d) and its reliability rating
170-330 High
60 Medium
130 Low
0 5 10 15 Kilometers
Datum GDA94 - Projection UTM MGA Zone 54
The Department of Water, Land and Biodiversity Conservation
Government of South Australia
South East – Tertiary Limestone Aquifer properties study
Distribution of transmissivity
PIRSA Publishing Services AV:201431_003

Figure 4a

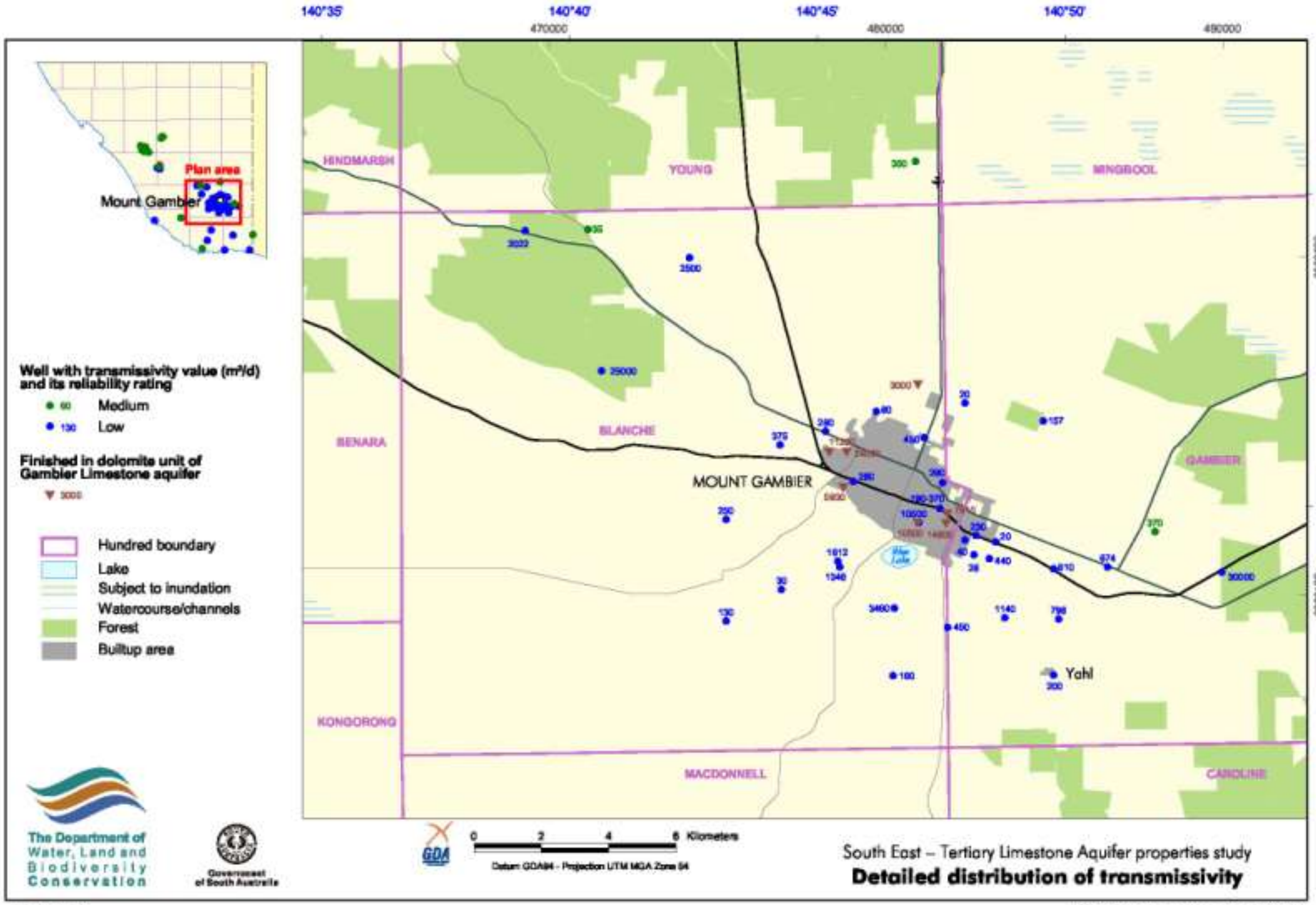


Figure 4b

PIRSA Publishing Services AV:201431_004

Figure 5

PIRSA Publishing Services AV:201431_005

Figure 8

PIRSA Publishing Services AV:201431_008

Figure 9

PIRSA Publishing Services AV:201431_009

Appendix C Summary of available surface water gauging data collated and archived for this project.

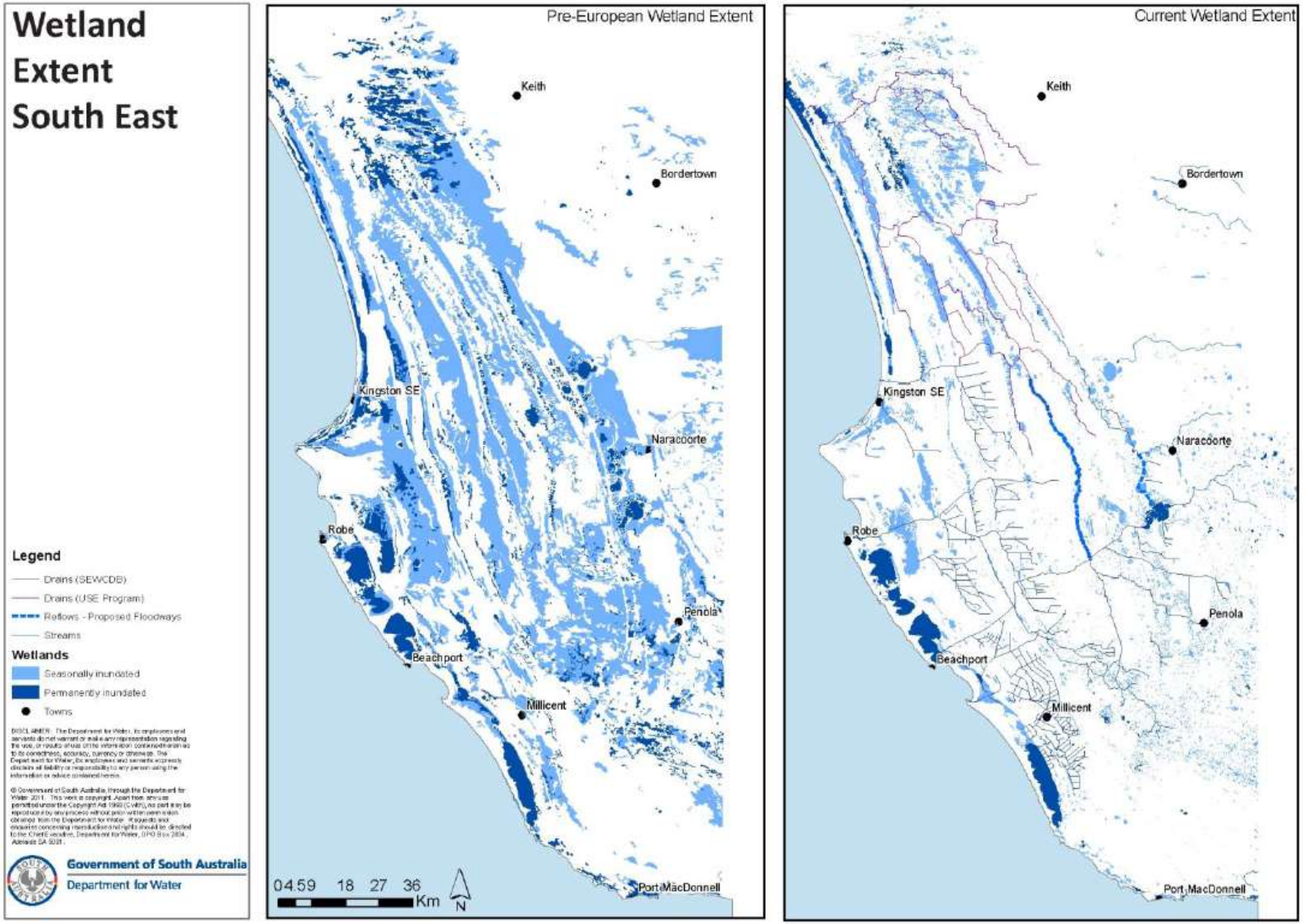
STATION NAME	ID (A239XXXX)	EASTING	NORTHING	WATER LEVEL	EC	FLOW	RAIN	START	END	USED TO CALIBRATE WOOD AND WAY (2010) MODEL?
Drains										
Bakers Range South Drain U/S Callendale Regulator	1125	454858	5878851	y		y		2010		
Bakers Range South Drain @ Phillips Rd	1001	456382	5876637	y		y		2003	2009	Y
Bakers Range South Drain @ Robe-Penola Rd	515	460339	5865550	y	y	y		1971		Y
Bald Hill Drain @ McBride Laneway	1151	406732	5966120	y	y	y		2011		
Bald hill Drain @ Ratcliffe Boundary	1150	416544	5943791	y	y	y		2011		
Bald Hill Junction	1144	402907	5966827	y	y			2010		
Blackford Drain @ Amtd 4.0 km	506	401871	5927128	y	y	y	y	1971		Y
Bray Drain @ Site B	504	410571	5880328	y	y	y		1969		Y
Butchers Gap Drain @ Butchers Gap	1154	393388	5917456	y	y			2011		
Didicoolum Drain Peacock Range	1104	419364	5966957	y	y	y		2009		
Drain 44 @ Milne Gap	521	439721	5831978	y		y		1973	1979	
Drain 48 U/S Lake Bonney Rd Bridge	533	441921	5829428	y	y	y		1976		
Drain C @ Balma Carra	516	465469	5880235	y		y		1971	1979	
Drain E @ Jaffray Swamp	1073	440501	5946700	y	y	y		2006		
Drain L @ U/S Princess Hwy	510	418671	5895678	y		y		1972		Y
Drain L @ Boomaroo Pk	505	397828	5885867	y		y		1971		Y
Drain M @ D/S Bool Lagoon Outlet	541	467769	5888378	y	y	y		1985		Y

Drain M @ D/S Callandale Regulator	514	452907	5878899	y	y	y	1971		
Drain M @ Woakwine	512	417881	5856472	y	y	y	1971		Y
Fairview Drain @ Pitts	565	441302	5935484	y	y	y	1998		
Fairview Drain D/S Keilira Rd	569	424779	5937597	y	y	y	2000		Y
Kercoonda Drain @ Petherick Rd	1092	412042	5971100	y	y	y	2008		
Kercoonda Drain D/S Stopbank H	1142	408293	5971949	y	y		2010		
Northern Outlet Drain @ 4.8 km D/S Bakers Range	1072	391041	5999539	y	y	y	2006		Y
Petherick Rd	1140	411741	5970966	y	y	y	2010		
Reedy Ck – Mt Hope Drain @ 7.2 km NE South End	513	425379	5848325	y	y		1971		Y
Taratap Drain @ England's Crossing	1141	401744	5951997	y	y	y	2010		
Taratap Drain @ Henry Ck Rd	1148	397808	5963722	y	y		2011		
Taratap Drain @ Taratap Rd	1147	403554	5946476	y	y		2011		
Wilmot Drain 9.2 km from Drain L Princess Hwy	527	421321	5886828	y	y	y	1973		Y
Wimpinmerit Drain @ Bald Hill	1145	415830	5953276	y	y	y	2011		
Lakes									
Lake George Big lake	1077	410260	5860278	y	y		2006		
Lake George Little Lake	1078	410681	5857173	y	y		2006		
Mt Gambier Pumping Station (Blue Lake)	538	480306	5811503	y			1882	1993	
Sinkhole @ Woods and Forest Dept	549	483228	5811889	y		y	1989	1992	
Natural Watercourses									

Bakers Range Watercourse @ Callendale	1146	454874	5879940	y		y	2011		
Bakers Range Watercourse @ G Cutting Floodway	556	429570	5944150	y	y	y	1992		
Bakers Range Watercourse @ Mandina Marshes	1152	403971	5982806	y	y		2011		
Bakers Range Watercourse @ Petherick Rd	1005						1988		Y
Bakers Range Watercourse @ Schofield Swamp	1085	433724	5933935	y	y		2007		
Bakers Range Watercourse @ Tatiara Swamp	1153	438676	5927498	y	y	y	2011		
Chris England's Swamp Riparian Zone	1105	400887	5951319				2008		
Henry Ck D/S Litigation Lane	1084	400770	5963830	y	y		2007		
Henry Ck U/S Litigation Lane	1083	400770	5963830	y	y		2007		
Lake Bonney Sea Outlet	526	445280	5806519	y			1973	1989	
Marcollat Watercourse @ Ballater Rd Jip Jip	1023	425514	5964494	y	y	y	1990	2012	Y
Marcollat Watercourse @ Kyeema Swamp	1095	435194	5957062	y	y		2008		
Marcollat Watercourse @ Little Reedy Swamp	1086	437879	5951459	y	y		2007		
Marcollat Watercourse @ Rowney Rd	563	437109	5955102	y	y	y	1997		
Marcollat Watercourse @ South Reedy Swamp	1026	438402	5950877	y			1994	2000	
Morambro Ck @ Bordertown-Naracoorte Rd Bridge	531	469559	5970300	y	y	y	1976		Y
Mosquito Ck @ Struan	519	480092	5894660	y	y	y	1971		Y

Nalang Ck @ Allendale	562	476170	5975469	y	y	y	1995		
Nalang Ck @ Olive Bank	535	481745	5973110	y		y			
Naracoorte Ck @ Naracoorte	542	476872	5911088	y	y	y	1985		Y
Rocky Swamp Riparian Zone	1108	411036	5952073				2009		
Taratap Watercourse @ England's Wetland	1101	400887	5951319	y			2008		
Taratap Watercourse @ Marwoods Wetlands	1082	399889	5954887	y			2007	2008	
Tatiara Ck @ Bordertown	534	479713	5981167	y	y	y	1977		
West Ave Watercourse @ Robertson Rd	1149	412616	5950551	y	y	y	2011		
West Ave Watercourse @ Rocky Swamp	1081	411036	5952073	y			2007		
Woakwine Range-Benara Ck	524	448522	5810878	y	y	y	1973	1976	
Woakwine Range-Stony Ck	523	443778	5826883	y	y	y	1973		

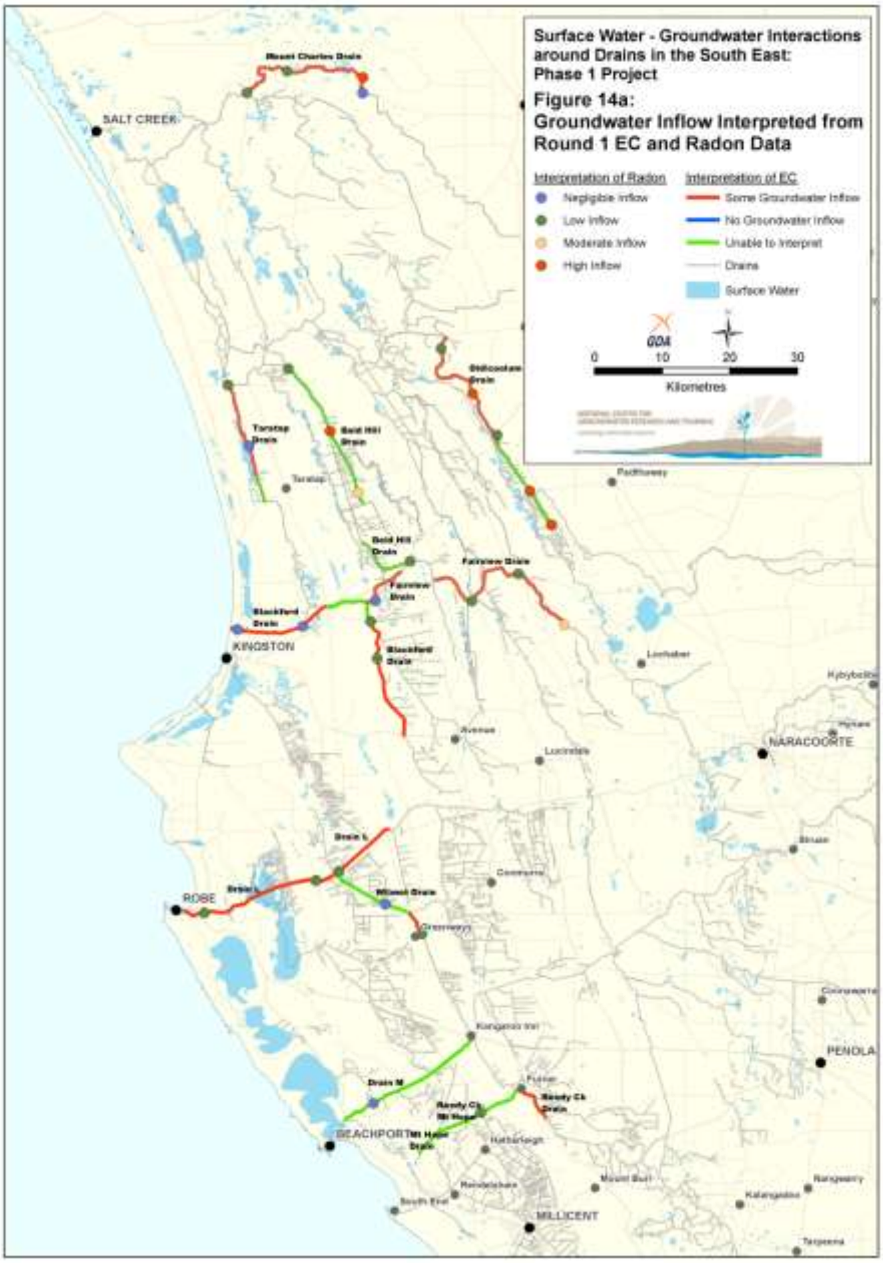
Appendix D Wetland extent in the South East region of SA – Pre-European and current extents (Harding, 2012).



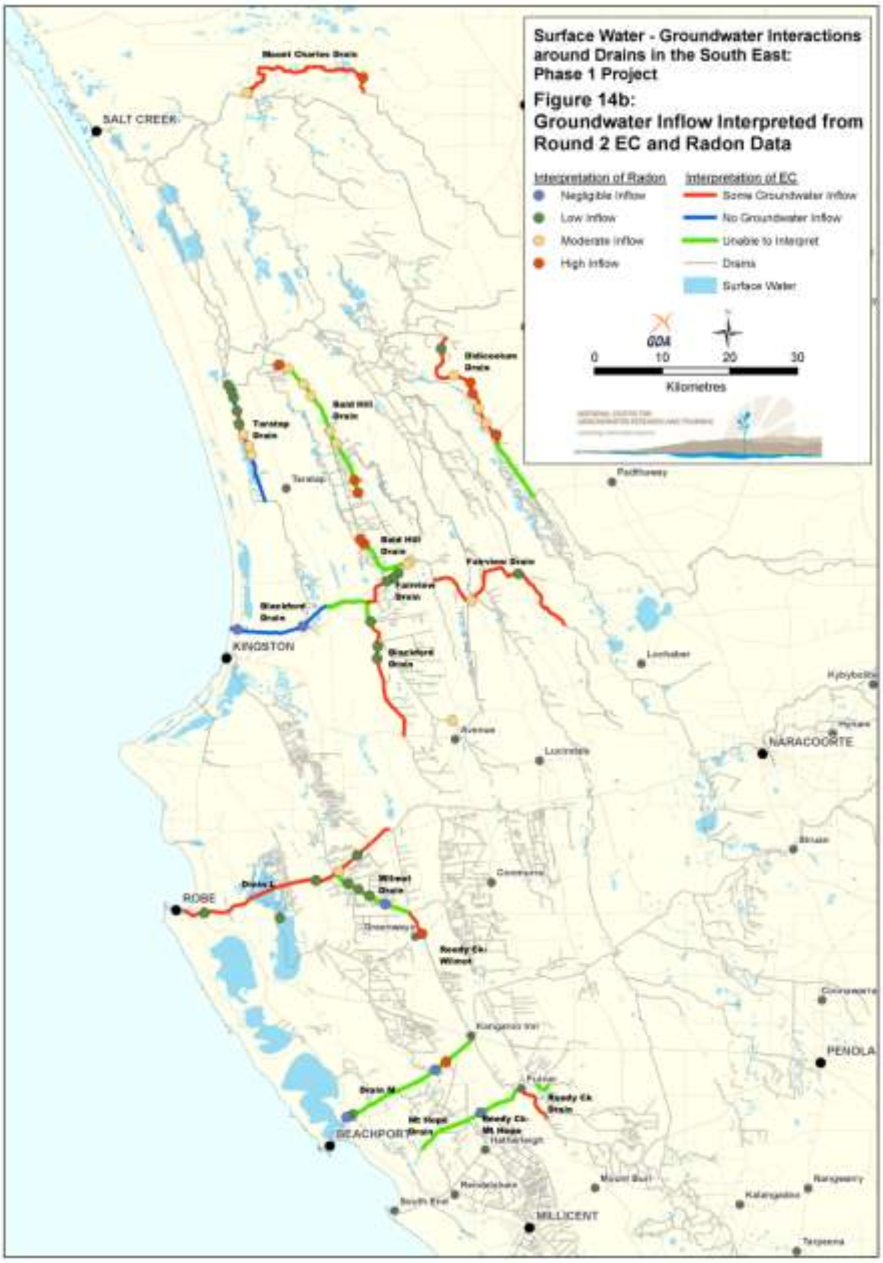
Wetland Extent South East
Pre-European Wetland Extent
Current Wetland Extent
Keith
Bordertown
Kingston SE
Naracoorte
Robe
Penola
Beachport
Millicent
Port MacDonnell
0 4.5 9 18 27 36
Km
N
Legend
Drains (SEWCDB)
Drains (USE Program)
Reflows - Proposed Floodways
Streams
Wetlands
Seasonally inundated
Permanently inundated
Towns
Government of South Australia
Department for Water

Appendix E Semi-quantitative assessment of groundwater inflows to drains using EC and ^{222}Rn surveys of surface water (Harrington et al., 2012).

E.1


Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 14a:
Groundwater Inflow Interpreted from Round 1 EC and Radon Data
Interpretation of Radon
Negligible inflow
Low inflow
Moderate inflow
High inflow
Interpretation of EC
Some Groundwater Inflow
No Groundwater Inflow
Unable to Interpret
Drains
Surface Water
GDA
0
10
20
30
Kilometres
SALT CREEK
KINGSTON
NARACOORTE
ROBE
BEACHPORT
PENOLA
MILLICENT

E.2



Surface Water - Groundwater Interactions around Drains in the South East: Phase 1 Project
Figure 14b:
Groundwater Inflow Interpreted from Round 2 EC and Radon Data
Interpretation of Radon
Negligible Inflow
Low Inflow
Moderate Inflow
High Inflow
Interpretation of EC
Some Groundwater Inflow
No Groundwater Inflow
Unable to Interpret
Drains
Surface Water
GDA
0
10
20
30
Kilometres
SALT CREEK
KINGSTON
NARACOORTE
ROBE
PENOLA
BEACHPORT
MILLICENT

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