South East Regional Water Balance Project – Phase 2
Development of a Regional Groundwater Flow Model

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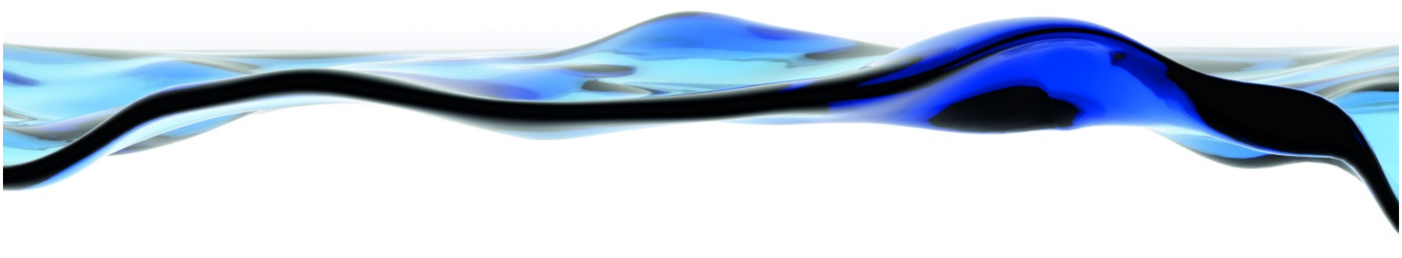

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Preface

South East Regional Water Balance Project Background

The South East Regional Water Balance project is a collaboration between Flinders University, CSIRO and the Department of Environment, Water and Natural Resources (DEWNR), funded by the Goyder Institute for Water Research. The project commenced in September 2012, with the objective of developing a regional water balance model for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). The project was initiated following conclusions from the South East Water Science Review (2011) that, 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 Lower Limestone Coast region as a whole. The review also concluded that, 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.

The South East Regional Water Balance project follows on from the report of Harrington et al. (2011), which recommended that a consistent framework of models is required to support water management in the South East, with the first step being a regional groundwater flow model to:

- bring together all existing knowledge,
- address regional scale water balance questions
- provide boundary conditions for smaller scale models to address local scale questions, including those around "hotspot" areas and significant wetlands.

Harrington et al. (2011) also identified the critical knowledge gaps that limit the outcomes from a regional scale model. These included but were not limited to:

- Spatial and temporal variability in groundwater recharge and evapotranspiration.
- Inter-aquifer leakage and the influence of faults on groundwater flow.
- The nature of wetland-groundwater interactions
- Understanding of processes occurring at the coastal boundary
- Surface water-groundwater interactions around the man-made drainage network
- The absence of information on historical land use and groundwater extraction

The South East Regional Water Balance project has included numerous tasks that have sought to improve the conceptualisation of the regional water balance, address some of the critical knowledge gaps, incorporate this and existing information into a regional groundwater flow model and understand how this improved understanding can be used in the management of wetland water levels.

An overview of the project and its output can be found in Harrington et al. 2015. *South East Regional Water Balance Project – Phase 2. Project Summary Report.* Goyder Institute Report 15:39.

Executive summary

Background

In the South East of South Australia, groundwater is one of the greatest factors influencing the viability of agriculture, industry and ecosystem health. A number of fundamental scientific questions remain, hindering the development of an effective Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). Major questions include: (a) the scientific validity of existing resource condition triggers, (b) how to achieve integrated management of groundwater and surface water resources, and (c) how much water can be extracted sustainably from the LLC PWA as a whole. This broad uncertainty is due to a number of gaps in the conceptual model of the overall water balance for the LLC PWA. The current tools available to inform water management cannot evaluate the longer-term impacts of land-use and climate change, or the impacts of changes in allocation policy on groundwater-dependent ecosystems. A consolidated approach is required to address key data and knowledge gaps and develop the tools required to support water management.

Objectives

This report describes the work carried out under Task 1 of Phase 2 of the South East Regional Water Balance Project, which commenced in 2014. The focus of this task was to develop a regional water balance model for the study area with the following primary objectives:

- 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.

Longer-term objectives of the regional model are to:

- Provide boundary conditions for future local scale models of “hotspot areas” or areas where local groundwater flow processes are important, e.g. wetlands or components of the drainage network.
- Act as a tool to investigate the impacts of climate, land use and water management scenarios on aspects of the regional water balance and on groundwater levels at a regional scale.

Outcomes

REGIONAL WATER BALANCE MODEL

The regional water balance model consists primarily of a three layer transient MODFLOW groundwater flow model, which has been developed for a large area of the South East of South Australia, including the LLC PWA, and extending across the SA-Vic border to cover the entire regional flow system. This is the first model to include details of both the unconfined and confined aquifers in this region. The groundwater model is complemented by an unsaturated zone model that is used to quantify spatially and temporally variable recharge rates, and that has undergone significant validation and testing. New data sets were developed as part of the project and these have been implemented in the groundwater and recharge models, including hydrostratigraphy, man-made drains, groundwater extraction and historical land use. The groundwater and recharge models therefore act as databases of the latest climate, soils, land use, and hydrogeological data for the region.

The regional groundwater flow model includes: (a) a steady-state version that represents average conditions between January 1965 and December 1974, and (b) a transient version, which adopts monthly stress periods and simulates the period between January 1970 and December 2013. Initial conditions for the transient model are taken from the steady-state model. The model is discretised into 1 km x 1 km cells. The three layers represent the Quaternary/ Tertiary Limestone Aquifer (layer 1), Lower Tertiary Aquitard (layer 2) and the Tertiary Confined Sand Aquifer (layer 3).

A particular focus of the project was on the quantification of rainfall recharge. Despite being thought to be a very large component of the regional water balance (e.g., based on previous studies), a suitable spatial and temporal rainfall recharge dataset that had been validated against real measured recharge data did not yet exist for the study area. Spatially and temporally variable rainfall recharge input data was developed using the Richards equation-based LEACHM unsaturated zone model (Hutson, 2003), implemented in a GIS framework, following previous work in the South East by Fleming and Hutson (2014). The recharge and evapotranspiration outputs of the unsaturated zone model were compared against datasets based on the CSIRO MODIS reflectance based (CMRSET) algorithm (Guerschman et al. 2009) that had been evaluated as part of Phase 1 of the Regional Water Balance project (Crosbie and Davies, 2013; Crosbie et al., 2015). This resulted in a series of improvements to the recharge model used by Fleming and Hutson (2014), and an improved confidence in the use of its outputs in the regional groundwater flow model.

A new method for representing groundwater ET with the MODFLOW EVT package was employed within the groundwater model and involved the use of a modified extinction depth approach. This new approach scales groundwater ET in each MODFLOW cell by the relative area of the cell that is inundated. The approach was validated through comparison with CSIRO MODIS datasets described above. Traditional methods for applying the EVT package that involve the use of a spatially uniform extinction depth of 2 m (somewhat arbitrarily selected) and an ET surface (determined using an approximation of the ground surface elevation in the cell e.g., using the mean DEM value in the model cell) precluded convergence of the groundwater model. This convergence failure is thought to be due to large changes in calculated groundwater ET fluxes between time steps that occur in shallow water table environments such as the South East. The modified extinction depth approach overcomes this problem because it smooths out the changes in groundwater ET between time steps.

Aquifer hydraulic parameters within layer 1 of the groundwater model were subdivided into five zones based on the distribution of geology and the approximate location of the Tartwaup Fault. Layer 2 was treated as a single unit of low hydraulic conductivity. Layer 3 was divided into four zones that were developed by amalgamating hydraulic conductivity zones used by Brown (2000) in the Tertiary Confined Sand Aquifer model, as well as by considering measured head contours. Calibration of the steady-state model was carried out using the automated parameter estimation software PEST. Transient model calibration was achieved using a trial and error approach due to the large computational times associated with the transient model (one model run takes about 15 hours). Storage parameters were implemented using a single zone in each layer. There was limited spatial hydraulic property data for the study area and hence only a small number of zones have been employed during calibration.

Despite the relatively simple nature of the groundwater model's parameterisation, the calibration statistics in terms of model-to-measurement fit are considered to be of a reasonable level (steady-state model root-mean-square error (RMSE) = 5.4 m and scaled root-mean-square error (SRMS) = 3.6%; transient model RMSE = 6.5 m and SRMS = 5.0%).

The transient hydrographs show a good match between short-term (i.e., seasonal) head changes in the majority of cases in the unconfined aquifer. This indicates that seasonality of recharge, groundwater evapotranspiration and extraction are being represented with reasonable accuracy in the model. Long-term trends in head also match reasonably well, indicating that long-term climate, extraction, irrigation and land use change impacts are generally well represented including, for example, the rise in water levels following the 1983 Ash Wednesday bushfires, which destroyed extensive areas of plantation forestry and native vegetation, with the resulting increase in recharge being obvious in hydrographs around that area. However, differences in long-term modelled and measured head trends do occur in hydrographs close to the Kimberley Clark pulp and paper mills and South Australian highlands. Also, a number of hydrographs have a steeper decline in modelled heads than measured heads for the period since 1990, especially in forested areas.

The transient model produces reasonable water balance results, when compared to measured estimates of net recharge (gross recharge minus groundwater ET), drainage fluxes, coastal discharge fluxes and inter-aquifer leakage. For the 2001 to 2010 period the model produces a spatially averaged net recharge (i.e., gross recharge minus groundwater ET) of 48 mm/y, which compares well to the estimate by Crosbie (2015) of 40 mm/y for the same period. Also, the model estimates drainage fluxes of around 250 GL/y for the entire simulation period, which compares well to the sum of measured drain flows to the sea and estimates of evaporation from the drains, which is 425 GL/y (and considered an upper limit). Patterns of inter-aquifer leakage are in general agreement with results of isotopic analysis by Love (1992) and Harrington et al. (1999) as well as measured head differences between layer 1 and layer 3.

The model is considered to have the majority of the characteristics of a Class 2 model, as described by the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). In particular, the groundwater head observations and bore logs are available but do not provide adequate coverage throughout the model domain; Drainage flow data estimates only at a few points (i.e., at outlets to the sea); Calibration statistics are generally reasonable but suggest significant errors in parts of the model domain; Long-term trends are not replicated in all parts of the model domain; Seasonal fluctuations are not adequately replicated in all parts of the model domain. As such, it is able to provide: (a) valuable information on intermediate and regional groundwater flow paths, particularly in relation to the influence of these on wetlands (see Taylor et al. (2015)), (b) areas of the model that require improved conceptualisation and the attainment of additional field measurements, (c) semi-quantitative information about the likely impacts of future climate or management scenarios, and (d) improved estimates of the regional water balance and how it varies over time.

LIMITATIONS OF THE REGIONAL GROUNDWATER FLOW MODEL AND RECOMMENDATIONS FOR FURTHER WORK

The large spatial scale of the study area requires the regional-scale model to have relatively coarse levels of spatial discretisation (i.e. large model cells). For this reason, regardless of its level of calibration or the amount of input data included, the regional groundwater model will be able to represent intermediate and regional groundwater flow systems, but not local-scale processes. With this in mind, it is intended that the regional groundwater flow model will provide a basis for future local-scale groundwater models to answer local-scale hydrogeological questions.

It is important to remember that the regional groundwater flow model is a simplified model of a complex natural system. As such, it includes a large number of standard assumptions about the system it represents and its outputs are limited by the degree of initial system understanding and amount of input data available. For example, there is limited field data within the large model domain on hydraulic parameters and fluxes. This restricts the ability to constrain many of the parameters used within the model and hence there is currently a high degree of uncertainty in model outputs. Future work is needed to improve the calibration when additional information becomes available. The model has been developed as a regional-scale water balance model and hence the focus has been on incorporating large scale water balance processes rather than calibration to measured heads. Additional work is needed for the model to be able to simulate localised changes in water levels in response to stresses such as pumping. A detailed uncertainty analysis is required to improve understanding of the models suitability for use as a management tool.

A number of activities are recommended to improve the knowledge pertaining to the water balance of the South East, and to characterise and reduce the uncertainty that is inherent in the recharge and groundwater models that were developed as the central focal points of this project.

- There is a surprisingly small amount of measured hydraulic parameter data available for the South East of South Australia, which has impacted calibration activities within this project. Improving the dataset of measured aquifer hydraulic parameters will enhance future calibration activities. Additional pump test data is available for the Naracoorte Ranges, Tatiara, Upper South East, Bordertown and Padthaway regions (George Mackenzie, DEWNR, pers. comm., April 2015). Obtaining this information will require searching for the relevant reports, which are only available in hard copy in the majority of cases, if available at all. It is recommended that all pump test data for the South East be entered into SAGeodata.
- Additional data is needed for the Victorian portion of the model domain, if available, including measured heads and hydraulic parameters.
- Rainfall recharge is a process that is notoriously difficult to quantify, because of the number of factors that influence it and the fact that it is difficult to measure. However, it is often a large component of a regional water balance. This project has included a large effort to improve the capability to model rainfall recharge in the South East, using a combination of new and different modelling approaches and all available field data including remote sensing data. Even following this, there remains a difference of 20% between the modelled and measured (remote sensing) average areal recharge rate suggesting that further work, to refine these methodologies and draw comparisons between them would be beneficial.
- The recharge model needs further refinement to improve representation of lag times in recharge reaching the water table after clearing of native vegetation in the 1960s, if we wish to represent the effects of this process accurately in the model. One approach to doing this would be to use a spatially variable soil column depth for the model domain.
- Seasonal trends in modelled heads show a reasonably good match to measured heads in the unconfined aquifer. This provides evidence that the ratio of net recharge to storage (in particular in the upper model layer) in the model is reasonable. However, long-term trends in modelled groundwater heads show a steeper decline than measured heads after 1990 in some areas. This requires further investigation to ascertain aquifer parameters and/or LEACHM crop factors that require adjustment in these areas.
- Modelling of the confined aquifer requires further attention to be able to better simulate seasonal and long-term trends, particularly in the areas of highest groundwater use.
- Incorporating flux estimates (i.e., for drain discharge and discharge to wetlands, if these can be obtained) into the calibration process will assist in reducing the non-uniqueness of calibrated parameters. Further, regularisation applied to parameters estimated during calibration will further alleviate non-uniqueness and thereby provide more reliable model parameters.
- A spatially variable extinction depth has been used, following the modified extinction depth function described in Section 4.8. It is recommended that a time-varying extinction depth approach be employed to incorporate changes in the spatial extent of forestry.

- The representation of topography was found to have a significant influence on modelled groundwater evapotranspiration, and hence the water balance. At a regional-scale, topographic variation is downscaled significantly within regional-scale models. For the groundwater model developed as part of this project, each of the 1 km square groundwater model cells has 10,000 DEM cells (of 10 m square) and hence there is a significant loss of information relating to topographic variation and evapotranspiration fluxes. To overcome this, a modified extinction depth approach was applied within the MODFLOW EVT package which better represents which scales evapotranspiration using topographic variation information from the DEM. Preliminary analysis indicated an improved fit between modelled and observed evapotranspiration (i.e., the CMRSET estimates of evapotranspiration) using this approach compared to traditional approaches. A more detailed assessment of the value of this new approach would benefit future modelling activities for the South East, and regional scale modelling of other shallow water table environments.
- Density corrected heads are applied at the coast (which is better than using values of 0 m AHD), but there remains areas where the assigned coastal boundary head differs to measured values. Future work should extend the model domain offshore and use a general head boundary to better represent heads at the coast. More work is needed to account for the impact of the continuation of aquifers offshore on the choice of head values at the coast.
- Additional sensitivity and uncertainty analyses will provide an indication of the uncertainty around flux predictions and more importantly, which parameters are most influential to individual flux predictions.
- Scenario modelling to evaluate possible future hydrogeological conditions in the South East, including under the impacts of climate and land-use change, are recommended.
- Further refinement of extraction rates for the Kimberley Clark extraction wells is needed.
- A significant amount of carbon-14 data exists (Love et al., 1993) and was used to guide model development but could be used as a formal calibration parameter in future to constrain groundwater flow paths and inter-aquifer leakage.
- Further work to include the new MODFLOW net recharge and recharge lookup-table approach in the regional model and an assessment of the results against the results using the LEACHM and modified extinction depth ET approach. As described below, the module has been tested within the steady-state groundwater model but requires further evaluation under transient model conditions, and the results of the new module are yet to be assessed.

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Figures

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1 Introduction

1.1 Background and Objectives

In the South East of South Australia, groundwater is one of the greatest factors influencing the viability of agriculture and industry, and ecosystem health. The majority of wetlands in the South East are thought to be groundwater dependent (Brooks, 2010). The extensive scheme of natural and man-made drainage channels that moves water around the landscape, draining agricultural land and feeding ecologically and culturally significant lakes and wetlands, is intrinsically linked to the groundwater system. Groundwater is the underlying link between land management practices, water users, drains and ecologically valuable wetlands and many wetlands are particularly vulnerable to groundwater exploitation. Hence an ability to simulate the groundwater system and all of its interactions with confidence is key to the effective management of surface water and groundwater availability and quality.

The highly modified nature of the South East landscape and numerous competing stakeholders present immense challenges in water resource management. In addition to this, a number of fundamental scientific questions remain, hindering the development of an effective Water Allocation Plan for the Lower Limestone Coast Prescribed Wells Area (LLC PWA). Major questions include: (a) the scientific validity of existing resource condition triggers, (b) how to achieve integrated management of groundwater and surface water resources, and (c) how much water can be extracted sustainably from the LLC PWA as a whole. This broad uncertainty is due to a number of gaps in the conceptual model of the overall water balance for the LLC PWA. The current tools available to inform water management cannot evaluate the longer-term impacts of land-use and climate change, or the impacts of changes in allocation policy on groundwater-dependent ecosystems.

The South East Regional Water Balance project is a collaboration between Flinders University, CSIRO and the Department of Environment, Water and Natural Resources (DEWNR), funded by the Goyder Institute for Water Research. The project commenced in September 2012, with a number of tasks that have sought to (a) address key gaps in the conceptual model for the water balance of the Lower Limestone Coast, (b) facilitate the development of a regional groundwater flow model for the LLC PWA and (c) improve the understanding of impacts of changes to the regional water balance on wetland water regimes.

The focus of Task 1 of the project was the development of a regional water balance model for the study area. This report provides the details of the model development and results.

The primary objectives of the 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.

Longer-term objectives of the regional model are to:

- Provide boundary conditions for future local scale models of “hotspot areas” or areas where local groundwater flow processes are important, e.g. wetlands or components of the drainage network.

- Act as a tool to investigate the impacts of climate, land use and water management scenarios on aspects of the regional water balance and on groundwater levels at a regional scale.

1.2 Associated Reports and Research Papers

Technical Reports:

Harrington, N and Lamontagne, S (eds.), 2013*, Framework for a Regional Water Balance Model for the South Australian Limestone Coast Region.* Goyder Institute for Water Research Technical Report 13/14.

Morgan, L, Harrington, N, Werner, A, Hutson, J, Woods, J and Knowling, M, 2015, *South East Regional Water Balance Project – Phase 2. Development of a Regional Groundwater Flow Model.* Goyder Institute for Water Research Technical Report 15/38.

Harrington, N, Lamontagne, S, Crosbie, R, Morgan, L, Doble, R, Werner, A, 2015, South East Regional Water Balance Project – Phase 2. Project Summary Report. Goyder Institute for Water Research Technical Report 15/39

Doble R, Pickett T, Crosbie, R and Morgan L (2015) A new approach for modelling groundwater recharge in the South East of South Australia using MODFLOW, Goyder Institute for Water Research Technical Report 15/26.

Taylor, AR, Lamontagne S, Turnadge, C, Smith, SD and Davies, P, 2015, *Groundwater-surface water interactions at Bool Lagoon, Lake Robe and Deadmans Swamp (Limestone Coast, SA): Data review.* Goyder Institute for Water Research Technical Report 15/14.

Smith, SD, Lamontagne, S, Taylor, AR and Cook, PG, 2015, *Evaluation of groundwater-surface water interactions at Bool Lagoon and Lake Robe using environmental tracers.* Goyder Institute for Water Research Technical Report 15/13.

Turnadge, CJ and Lamontagne, S, 2015, *A MODFLOW-based Wetland-Groundwater interaction simulation model.* Goyder Institute for Water Research Technical Report 15/12.

Barnett, S, Lawson, J, Li, C, Morgan, L, Wright, S, Skewes, M, Harrington, N, Woods, J, Werner, A and Plush, B, 2015, *A Hydrostratigraphic Model for the Shallow Aquifer Systems of the Western Otway Basin and South Western Murray Basin.* Goyder Institute for Water Research Technical Report 15/15.

Harrington, N and Li, C, 2015, *Development of a Groundwater Extraction Dataset for the South East of South Australia: 1970-2013.* Goyder Institute for Water Research Technical Report 15/17.

Harrington, N, Millington, A, Sodahlan, ME and Phillips, D, 2015, *Development of Preliminary 1969 and 1983 Land Use Maps for the South East of SA*. Goyder Institute for Water Research Technical Report 15/16.

Research Papers:

Crosbie RS, Davies P, Harrington N and Lamontagne S (2015) Ground truthing groundwater-recharge estimates derived from remotely sensed evapotranspiration: a case in South Australia. Hydrogeology Journal 23(2), 335-350.

Lamontagne S, Taylor A, Herpich D and Hancock G (2015) Submarine groundwater discharge from the South Australian Limestone Coast region estimated using radium and salinity. Journal of Environmental Radioactivity 140, 30-41.

1.3 Study Area

1.3.1 PHYSICAL CHARACTERISTICS AND CLIMATE

The area of interest for the South East Regional Water Balance project is the Lower Limestone Coast Prescribed Wells Area (LLC PWA). However, the study area is broader than this to encompass the whole groundwater flow system, being roughly bounded by the structural highs of the Padthaway Ridge and the Dundas Plateau, extending northward toward Keith and also including parts of western Victoria (Figure 1.1). Hydrogeologically, it includes the Gambier Basin of the Otway Basin and the south-western margins of the Murray Basin.

The study area comprises an undulating coastal plain which generally slopes to the west and south-west toward the Southern Ocean (Figure 1.1). 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 1.1). Other, but less significant topographic highs in the study area include the Mount Burr and Naracoorte Ranges.

The climate in the South East region is Mediterranean to Temperate, 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 mean annual rainfall ranging from 450 mm/y in Bordertown to 835 mm/y in the elevated Mount Burr Ranges (north-east of Millicent). Approximately 75% of annual rainfall falls between April and October, which coincides with periods of highest recharge (i.e. when precipitation exceeds evapotranspiration). An approximate north-south evapotranspiration gradient also exists, with potential evapotranspiration ranging from approximately 1400 mm/y in Mount Gambier to approximately 1,700 mm/y in Keith, which is just north of the study area.

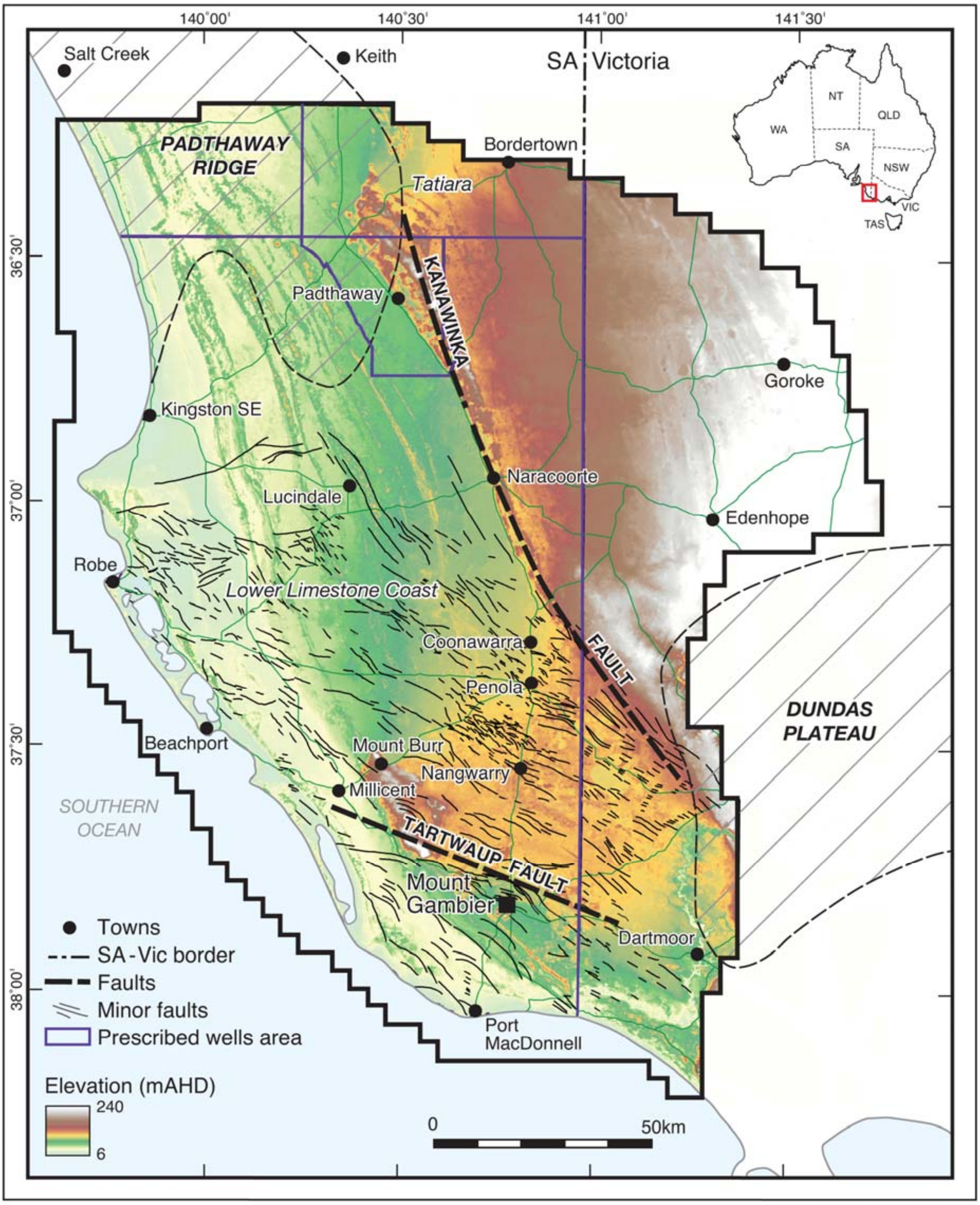

Figure 1.1 Study area.

1.3.2 GEOLOGICAL SETTING

The study area consists of the Gambier Basin, which is a Tertiary groundwater basin of the Otway Basin, in the south, and part of the south-western Murray Basin in the north. Recent mapping of fault locations in Tertiary sequences 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).

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 1.2)(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 water table lies within the pre-Cainozoic bedrock (Mann et al., 1994). 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 to the Continental Shelf (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 1.1). 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). Although indicated as linear features in Figure 1.1, the Tartwaup Fault, in particular, is believed to be more of a “fault zone” of smaller parallel faults. An important structural high, the Gambier Axis occurs to the north of the Tartwaup Fault (Kenley, 1971).

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.

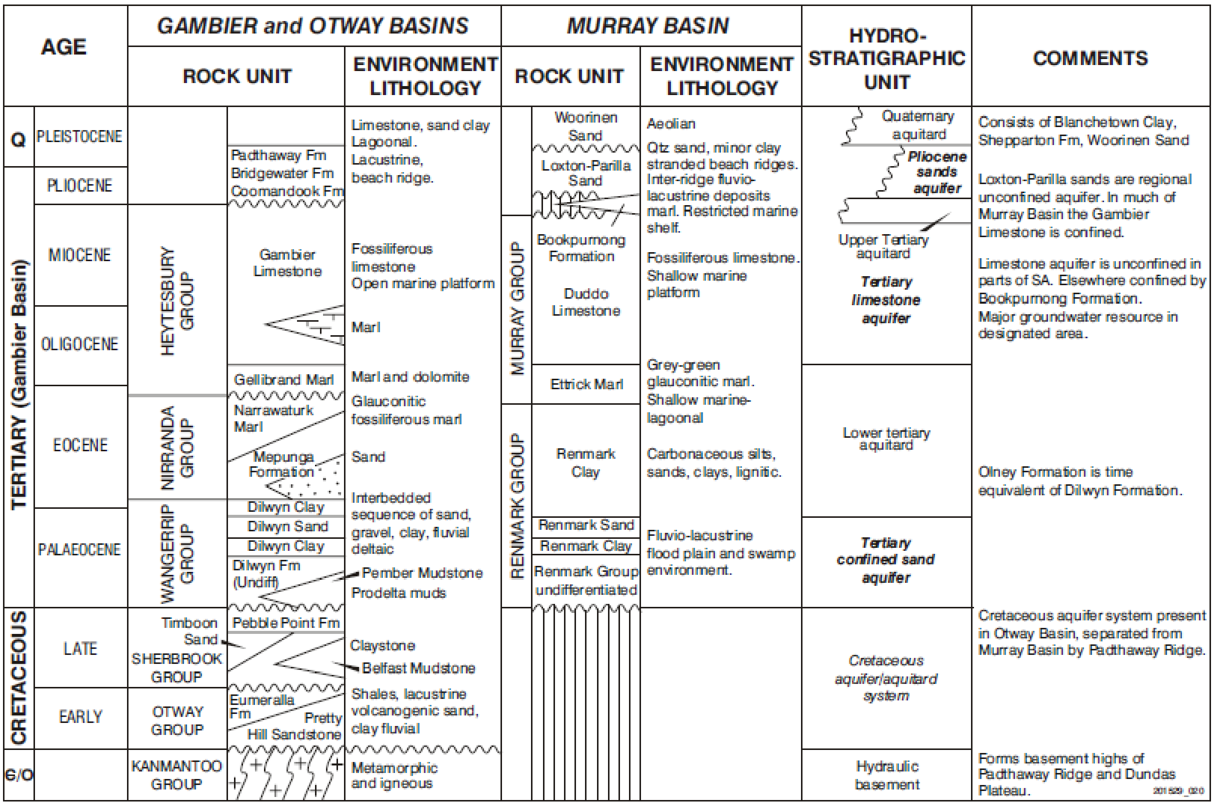

Figure 1.2 Stratigraphic and hydrostratigraphic units of the Otway and Murray Basins (Rammers and Stadter, 2002).

The Murray Basin is a large, Cainozoic, intercratonic sedimentary basin located in south-eastern Australia (Brown, 1989). 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 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). As described above, 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 1.2. 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 Hydrogeological Conceptualisation

2.1 Introduction

Most elements of the conceptual model were described in the Phase 1 report (Harrington et al., 2013) and the current chapter should be read in conjunction with that report, although all details relevant to the regional model development are presented here. The conceptual model is summarised in Figure 2.1. Further diagrams representing individual aquifers are provided within Section 2.3.

A number of areas of the conceptual model were identified by Harrington et al. (2011) as providing significant challenges for the development of a regional groundwater model. These were:

- Historical land use
- Historical groundwater extraction
- Evapotranspiration
- Spatial and temporal variability in groundwater recharge
- Processes occurring at the coastal boundary
- Surface water / groundwater interactions around the artificial drainage network
- The nature of wetland-groundwater interactions.
- The influence of geological faults on groundwater flow
- Inter-aquifer leakage
- Incorporating groundwater use by plantation forestry

A large body of work towards addressing these challenges in various ways has been carried out in Phases 1 and 2 of this project, and is described in the various reports listed in Section 1.2. However, despite these advancements, these are considered to be ongoing challenges for developing groundwater models for the South East.

All datasets that were collected, processed or modified for the purposes of constructing the regional groundwater model are available with the groundwater model through the DEWNR Model Warehouse[1]. Metadata for the model and related datasets can be found through the Goyder Institute for Water Research and Australian National Data Service websites.

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[1] Access to items in the DEWNR Model Warehouse is currently via request to DEWNR.

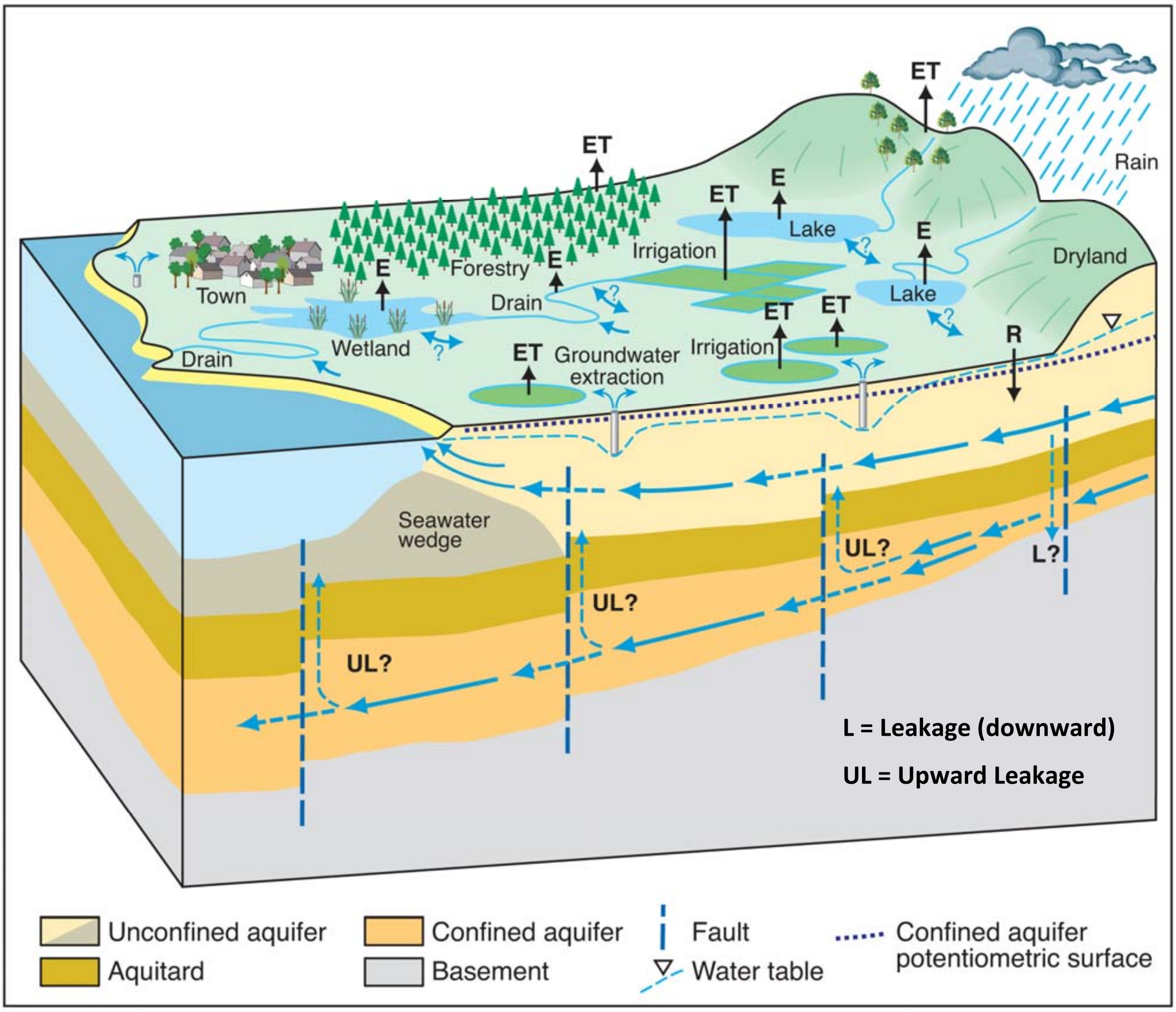


Figure 2.1 Summary of the conceptual model of the study area.

2.2 Hydrostratigraphic Layers

The hydrogeology of the study area is described in Harrington and Lamontagne (2013). The main hydrogeological units of interest in the Gambier and Murray Basins are shown in Table 2.1. The Cretaceous aquifers are generally saline and generally too deep for economic utilisation (Love et al., 1993). The two major low salinity groundwater systems occur within the Cainozoic sequence:

a) the Tertiary Confined Sand Aquifer system (TCSA), comprising primarily of Dilwyn sand and clay units in the Gambier Basin and the Renmark Group Sands in the Murray Basin, and
b) the multi-lithological unconfined Tertiary Limestone Aquifer (TLA) system, consisting primarily of the Gambier Limestone in the Gambier Basin and the Murray Group Limestone in the Murray Basin.

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. The latter includes the Narrawaturk Marl, the Mepunga Formation (which can occur in areas as a discontinuous aquifer) and a clayey unit of the

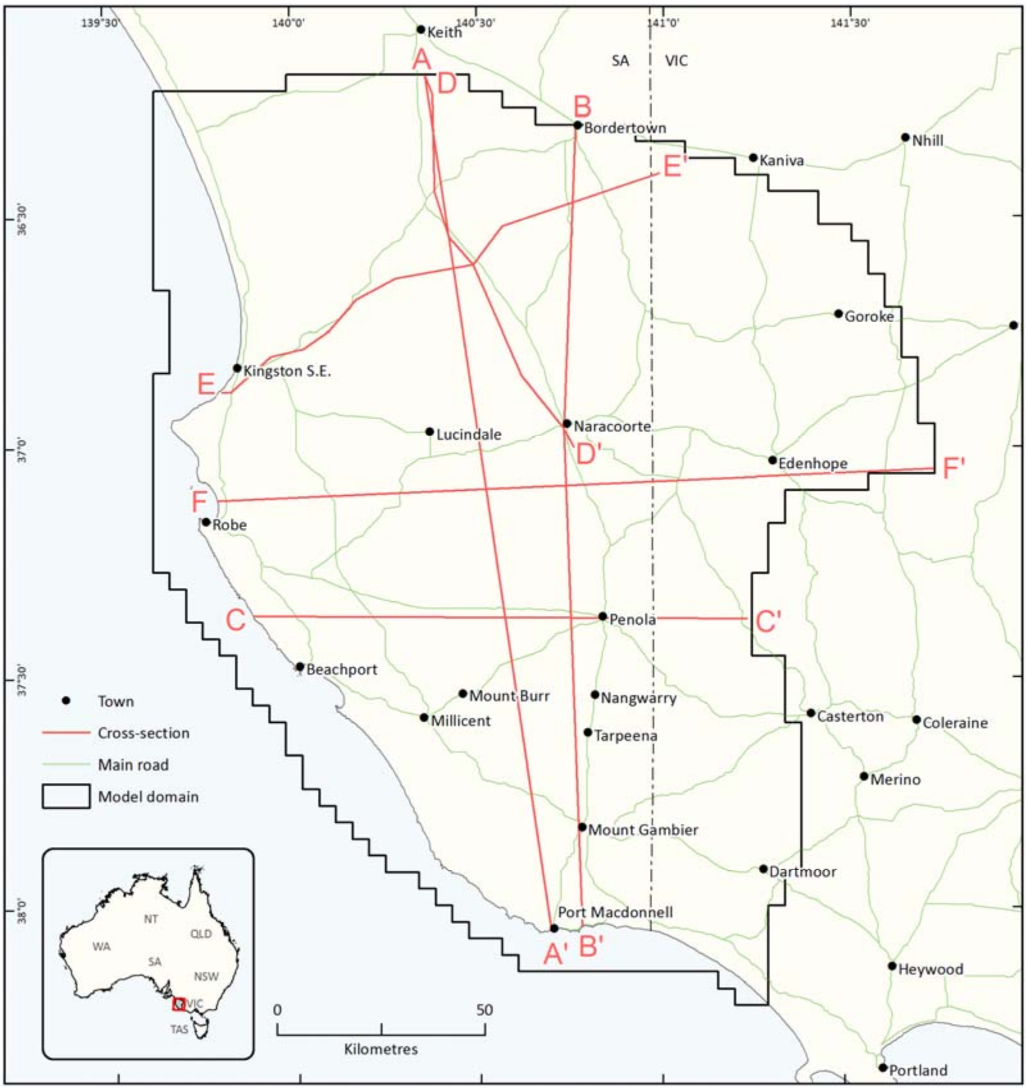
Dilwyn Formation itself, known as the Dilwyn Clay in the Gambier Basin, and the Ettrick Formation-Geera Clay aquitard in the Murray Basin (Figure 1.2).

The Quaternary age Padthaway and Bridgewater Formations (Gambier Basin) and the Pliocene Loxton-Parilla Sand (Murray Basin) are generally grouped together with the TLA to define the unconfined aquifer in the study area as they are in direct hydraulic connection. 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 within the study area 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.

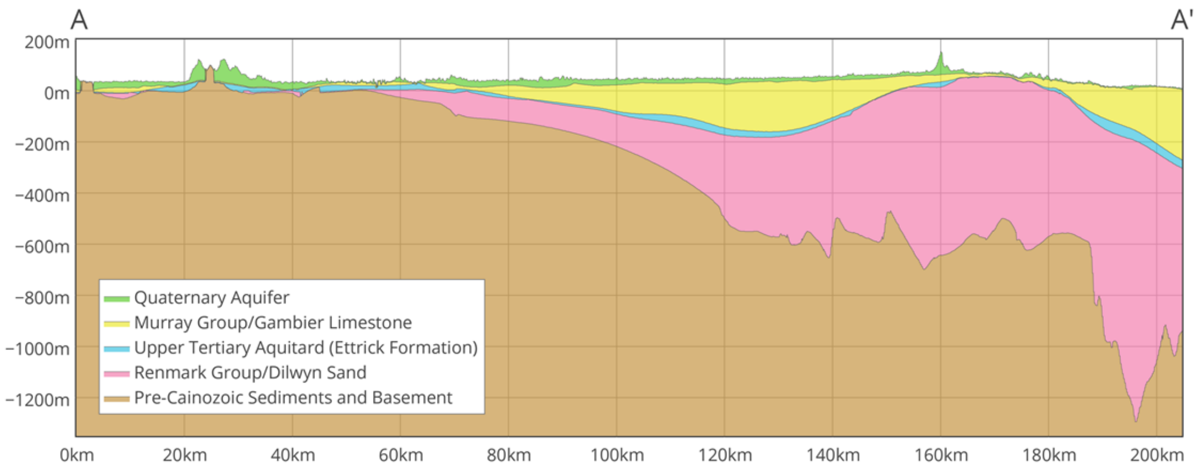
A revised cross-border hydrostratigraphic model was developed by DEWNR in collaboration with this project. Full details are provided in a separate report (Barnett et al., 2015). The hydrostratigraphic model includes five layers, as described in Table 2.1 and shown in Figure 2.2.

Table 2.1 Otway Basin and Murray Basin geological and hydrostratigraphic units and their representative layers in the 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 Confined 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

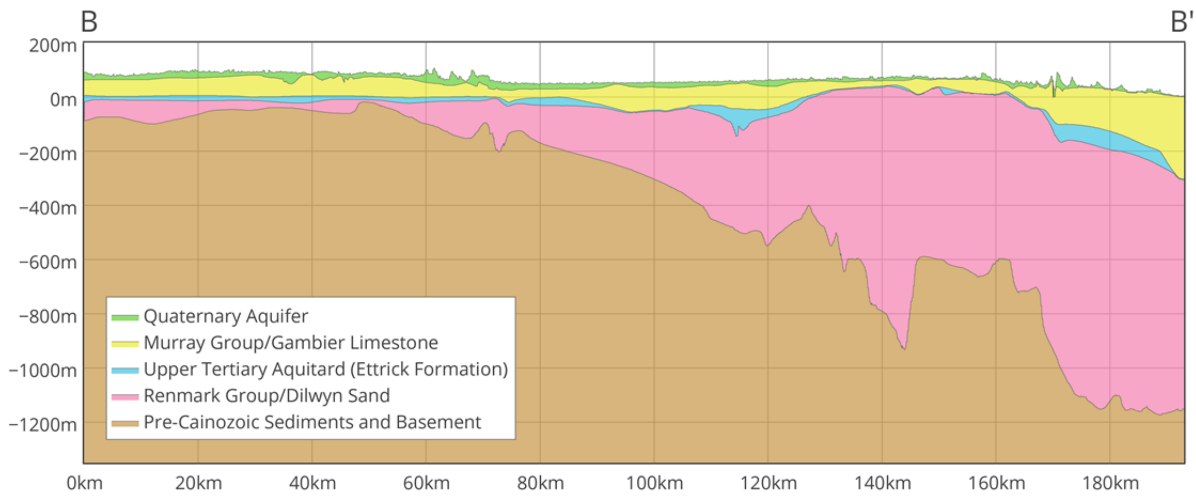


(a)



(b)

Figure 2.2 Hydrostratigraphic model (a) cross section locations, (b-g) cross sections AA' – FF'.



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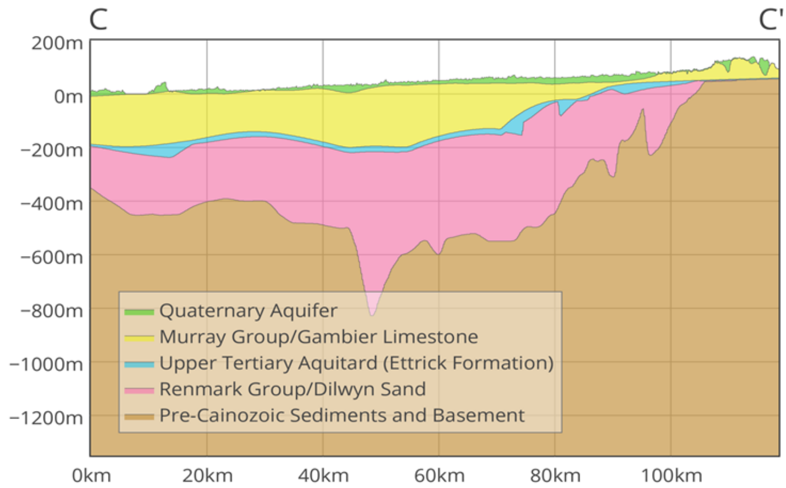

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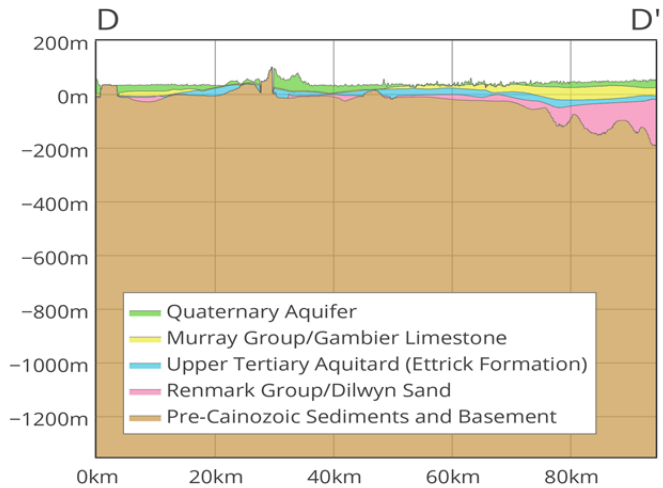
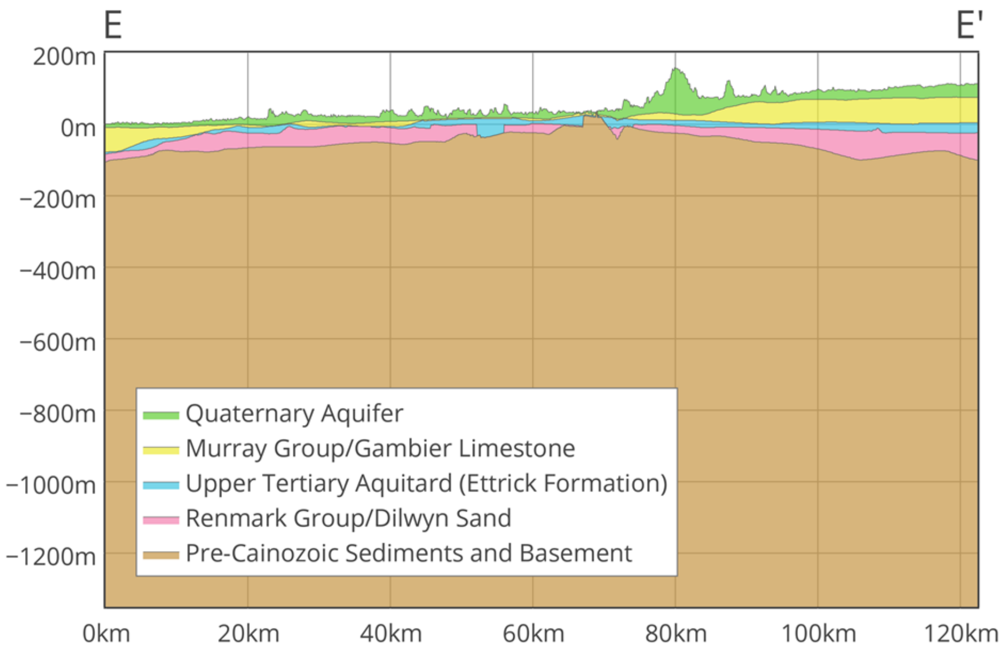
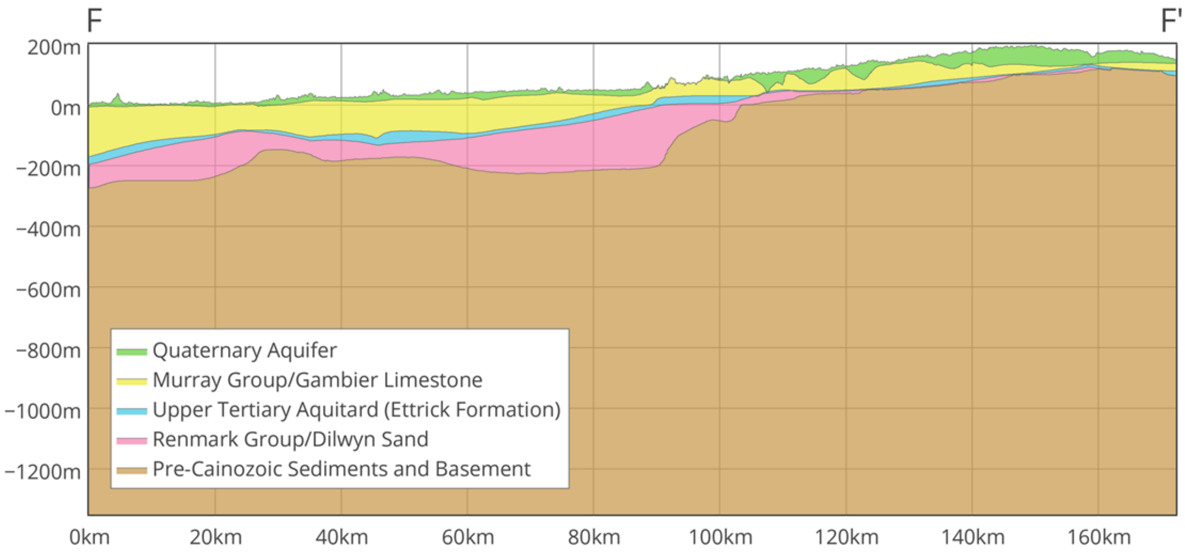


(e)

Figure 2.2 (cont'd). Hydrostratigraphic model (a) cross section locations, (b-g) cross sections AA' – FF'.



(f)



(g)

Figure 2.2 (cont'd). Hydrostratigraphic model (a) cross section locations, (b-g) cross sections AA' – FF'.

2.3 Conceptualisation of Groundwater Flow

2.3.1 UNCONFINED AQUIFER

Figure 2.3 summarises the conceptual understanding of the unconfined aquifer, including potentiometric contours (September 2010), measured and modelled aquifer properties, groundwater flow rates and residence times, and other information on aquifer characteristics. Figure 2.3 should be viewed in conjunction with Figure 2.4 and 2.5, which show information on the confined aquifer and inter-aquifer leakage respectively.

The unconfined limestone aquifer ranges in thickness from absent to 300 m. Groundwater flow is generally from the highlands in the north east of the study area towards the coast, in a southerly and westerly direction (Figure 2.3). The water table 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. The unconfined aquifer contains numerous local flow systems due to the proximity of the water table to the ground surface and undulating landscape (Love et al., 1993). It features a secondary porosity in the form of karst features, meaning that hydraulic properties are highly variable (Table 2.2). Point measurements of transmissivities between 35 and 560 m^2/d are considered to be reliable for the Lower South East, based upon an assessment of all available data and the methodologies by which this was derived (Mustafa and Lawson, 2002). Measured and previously modelled aquifer property values are shown in Table 2.2. Despite the karstic nature of the aquifer, it is believed that the karst features do not form a substantial interconnected system and that groundwater flow is predominantly inter-granular, with groundwater flow rates of between 4 and 38 m/y being estimated along transect AA' (Harrington et al., 1999). An exception to this is in the Mount Gambier area where measured rates of karstic groundwater flow towards the Blue Lake range between 500 and 1,500 m/y (Vanderzalm et al., 2009). In some areas, dissolution of the limestone along karstic features has caused brecciation and collapse, forming numerous "runaway holes" or "sinkholes" (Figure 2.3). These sinkholes may enhance recharge to the unconfined aquifer, but this is only thought to have a localised effect on groundwater levels and salinities (< 150 m radius), and to represent less than 10% of total recharge (Herczeg et al., 1997).

A steep hydraulic gradient zone to the north of Mount Gambier coincides with the location of the Tartwaup Fault (Figure 1.1). The exact influence of the fault on groundwater flow is believed to be complex and is not yet fully understood, however, there is some evidence for significant stratigraphic displacement across it (Lawson et al., 2009). Just to the north of this, rapid thinning of the entire unconfined aquifer sequence occurs due to up-warping along the Gambier Axis and a sealevel transgression during the Pleistocene, which truncated and re-worked the top part of the sequence. A groundwater divide occurs here (Figure 2.3). Another 'steep gradient' zone is observed in the water table along the base of the Naracoorte Ranges and is associated with the Kanawinka Fault line, probably due to thinning of the aquifer sediments on the eastern side of the fault (Lawson et al., 2009) (Figure 2.3).

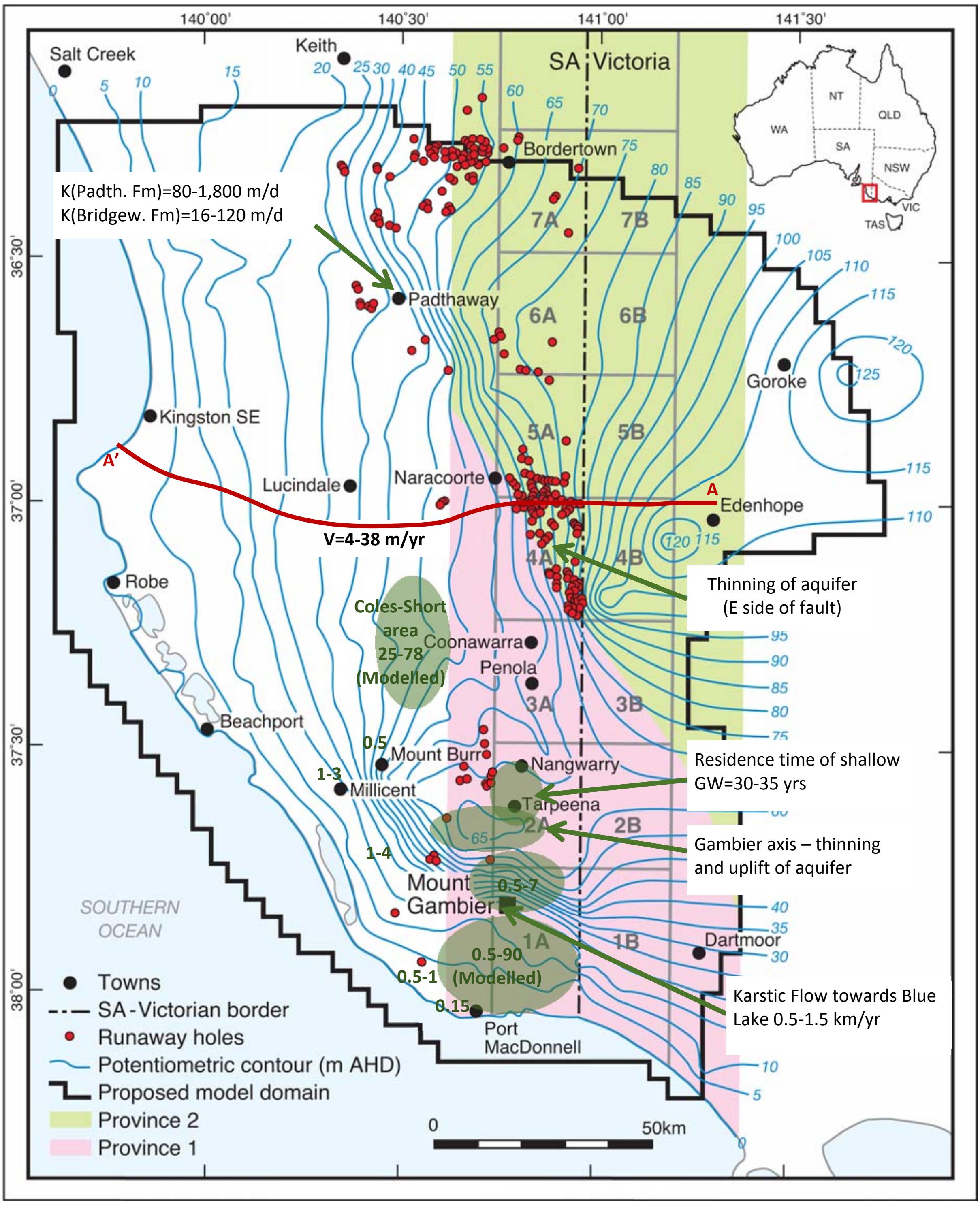


Figure 2.3 Conceptual diagram of groundwater flow in the unconfined aquifer. Values in green are hydraulic conductivities, in m/d, measured unless otherwise specified.

2.3.2 CONFINED AQUIFER

Figure 2.4 summarises the conceptual information for the Tertiary Confined Sand Aquifer, including potentiometric contours (June 2010), measured and modelled aquifer properties, groundwater flow rates and residence times, and locations of observed or potential recharge areas. This figure should be viewed in conjunction with Figures 2.3 and 2.5, which show information on the unconfined aquifer and inter-aquifer leakage respectively.

The Lower Tertiary Confined Sand Aquifer (TCSA), which comprises mainly the Dilwyn Sand aquifer in the Gambier Basin and the Renmark Sand in the Murray Basin, generally increases in thickness towards the south, being up to 800 m thick offshore to the south of Mount Gambier. 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 is 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 clay layers increases.

The Dilwyn Formation is underlain by an aquitard (the Pember Mudstone), across much of the Gambier Basin. Further Tertiary sequences (e.g. Pebble Point Formation) underly the Pember Mudstone, however little is known about them due to the lack of exploratory drilling and availaibility of good quality groundwater in the unconfined aquifer and TCSA.

Major recharge zones for the TCSA, inferred from the presence of groundwater mounds in the confined aquifer potentiometric surface, have been identified in the Nangwarry – Tarpeena area on the South Australian side of the border (Brown et al., 2001), and south of Strathdownie, which is approximately 33 km north-east of Mount Gambier, on the Victorian side (SKM, 2010) (Figure 2.4). The mound in the Nangwarry-Tarpeena area coincides with a slight depression in the watertable of the unconfined aquifer, which is inferred to suggest leakage from the unconfined to the confined aquifer. This is also likely because it is a region where the TCSA is close to the surface and the overlying aquitard is relatively thin (Brown et al., 2001). The Lake Mundi area, approximately 21 km east of Nangwarry, on the other side of 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). Love et al. (1993) and Blake (1980) describe the potential for upward leakage to the TCSA from underlying Cretaceous aquifers and leakage to the overlying unconfined aquifer respectively, although no direct evidence for these forms of TCSA recharge exists.

Groundwater within the TCSA has a residence time (i.e. time since recharge) of at least 30,000 years and lateral flow velocities ranging between 0.4 m/y and 5.5 m/y, with velocities likely to be decreasing towards the coast (Harrington et al., 1999; Love et al., 1993; Love et al., 1994). 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 and this fits with the understanding of the geology (Table 2.2).

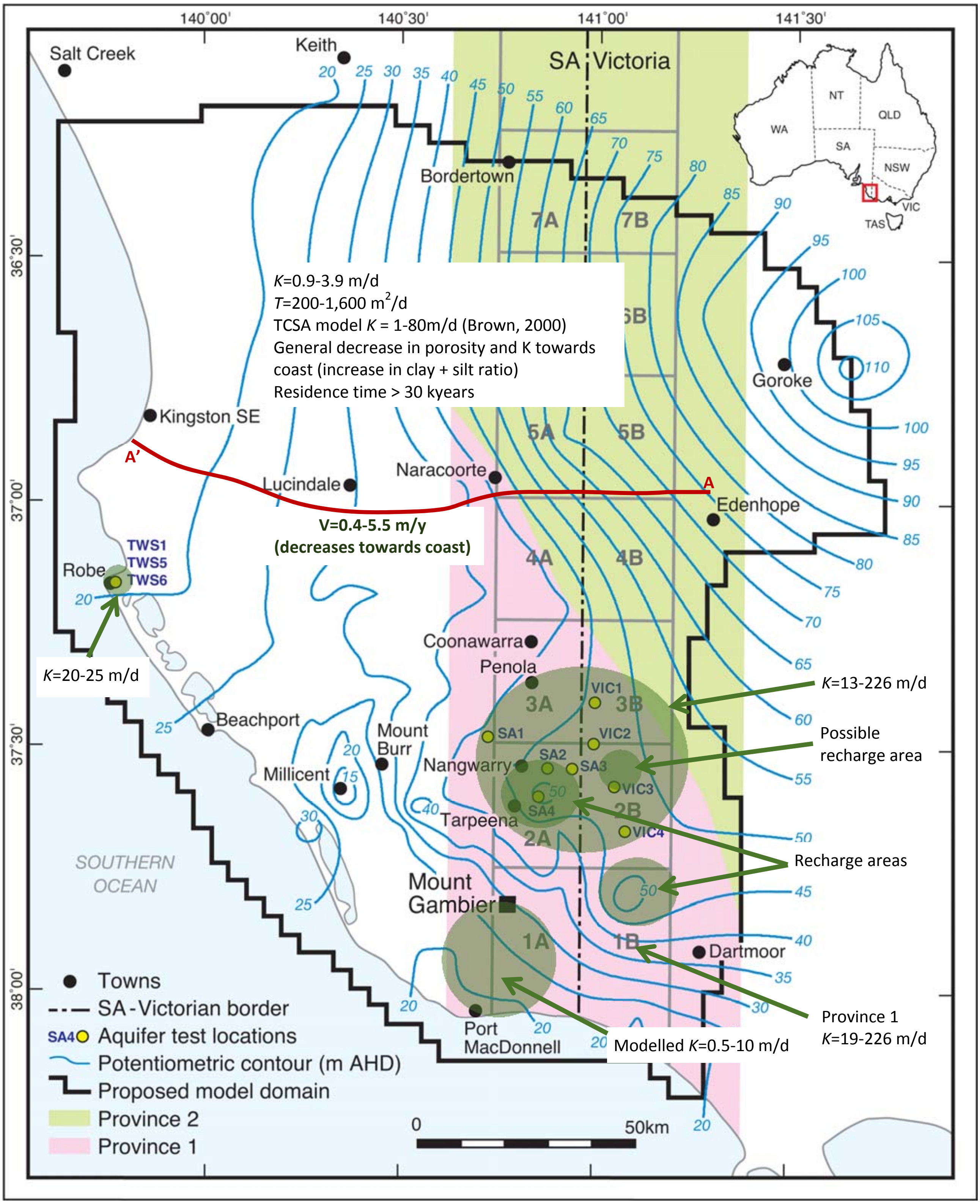


Figure 2.4 Conceptual diagram of groundwater flow in the confined aquifer.

2.3.3 UPPER TERTIARY AQUITARD AND INTER-AQUIFER LEAKAGE

Identified occurrences of inter-aquifer leakage have been discussed in detail in the Phase 1 report and are summarised below and on Figure 2.5.

Major areas of leakage from the unconfined to the confined aquifer have been identified:

- In the Nangwarry / Tarpeena area (Brown et al, 2001)
- South of Strathdownie (approx. 33 km NE of Mt Gambier)
- In the Lake Mundi area (approx. 21 km east of Nangwarry) – no aquitard exists here (J. Lawson, pers. comm., 2013).

Stable isotope and carbon-14 signatures suggest that (Love et al, 1993):

- Along Transect AA' (Figure 2.5):
  - Significant downward leakage from the unconfined to the confined aquifer is not occurring in the area between the 0 km point and Naracoorte (approximately).
  - Significant downward leakage from the unconfined to the confined aquifer is occurring between Naracoorte and the Zero Head Difference (ZHD) line (see Figure 2.5).
  - The magnitude of this leakage is estimated to be between 2.1 mm/y and 8.5 mm/y (Harrington et al., 1999).
  - There is negligible leakage (either from above or below) into the confined aquifer to the west of the ZHD line.
  - Upward leakage of water from the underlying aquifers to the confined aquifer occurs at the western end of Transect AA'.
- Along Transect BB' (Figure 2.5):
  - There is active vertical recharge to both the unconfined and confined aquifers between the northern end of the transect and the ZHD line.
  - Significant downward leakage occurs from the unconfined to the confined aquifer between the northern end of the transect and the ZHD line.
  - There is no vertical leakage to the confined aquifer (from above or below) between the ZHD line and the coast.

Consistent hydrograph trends between the confined and unconfined aquifers suggest that these aquifers are connected in the area to the north of the Tartwaup Fault in Province 1 of the Border Designated Area.

In theory, downward leakage between the unconfined and confined aquifers could be occurring throughout the whole area between the north-eastern ends of the green leakage zones identified in Figure 2.5 and the ZHD line. This area, estimated approximately using GIS, could be up to 9,360 km^2. If the leakage rates estimated along Transect AA' of 2.1 mm/y – 8.5 mm/y were applied across this entire area, this results in a downward flux of the order of 20 – 80 GL/y. There is a large amount of uncertainty in both the leakage rates applied to this calculation and the area over which this should be applied, so this estimate should be considered for the purposes of a preliminary water balance only.

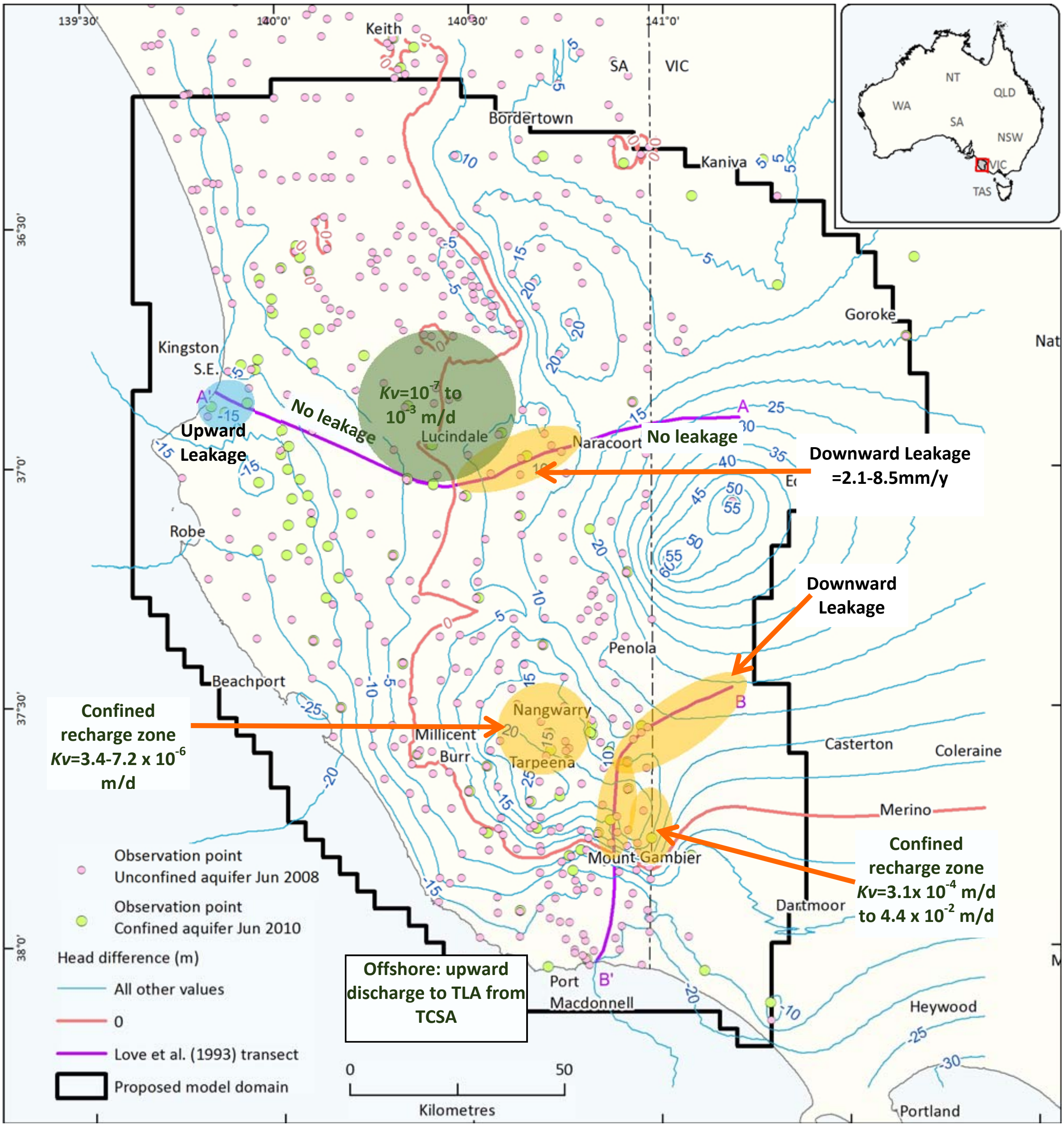


Figure 2.5 Map showing the hydraulic head difference between the unconfined and confined aquifers (unconfined – confined), with the locations of areas where evidence for inter-aquifer leakage has been found.

Table 2.2 Measured and previously modelled aquifer property values.

Source	Location	Measured / Modelled?	T (m^2/d)	K (m/day)	Porosity (%)	Sy (-) or Ss (/m)	*v* (m/y)	Residence Time (years)
				<u>Unconfined Aquifer</u>				
Brown et al. (2001)	Tarpeena-Nangwarry area	Measured						30-35 yrs (1.5 m to 2 m below water table)
Harrington et al. (1999)	Cross-section AA’ of Love et al. (1993).	Modelled (chemistry data)					4-38	
Various (see Phase 1 report)	Regional	Measured			30-61% (incl. Padthaway & Bridgewater Fms)			
Lawson et al. (2009)	Regional	Measured			Gambier Lst: 6-18 Bridgewater Fm: 5-20 Fractured rock (Padthaway?): 20-30			
Mustafa and Lawson (2002)	Lower SE (map in Phase 1 report shows distribution)	Measured	35-560 (most between 200-500) These are probably mostly Gambier Limestone values in this area.					

Various	Padthaway area	Measured	1,100-11,000 (Padthaway Fm) 320-2,400 (Bridgewater Fm)	80-1,800 (Padthaway Fm) 16-120 (Bridgewater Fm		
Stadter and Yan (2000)	South of Mt Gambier	Modelled		0.5-90		0.1 (S_y)
Aquaterra (2010)	Coles-Short area	Modelled		25-78		
BGARC (2008)	Border Zone Province 2	Modelled	2,000			0.1 (S_y)
				<u>Upper Tertiary Aquitard</u>		
Love and Stadter (1990)	Northern portion of Gambier Basin, near Lucindale	Measured		10^{-7} to 10^{-3} (K_v)		
Brown et al (2001)	Nangwarry / Tarpeena	Measured		3.4 to 7.2 x 10^{-6} (K_v)		
Lawson et al (2009)					7.1 to 7.2 (Mepunga) 9.5 (Narrawaturk Marl)	
Mustafa and Lawson (2011)	Border zone	Measured		3.1 x 10^{-4} to 4.4 x 10^{-2}*		

				<u>Confined Aquifer</u>				
Love et al. (1993); Love et al. (1994)	Regional	Estimated / Measured		0.9 to 3.9				> 30,000
Harrington et al. (1999)	Regional	Modelled (chemistry data)					0.4 to 5.5	
Various (see Phase 1 report)	Regional		200 to 1,600		20-30			
Osei-Bonsu and Dennis (2004)	Robe	Measured	64 to 82	20 to 25		1×10^{-5} to 5×10^{-5} (S_s)		
Mustafa and Lawson (2011); SKM (2012)	Border Zone Province 1		267 to 2,260	19 to 226		1.2×10^{-5} to 6.5×10^{-4} (S_s)		
Stadter and Yan (2000)	South of Mt Gambier	Modelled		0.5 to 10		10^{-6} (S_s)		
Brown (2000)	regional	Modelled		1 to 80		8×10^{-5} to 10^{-9} (S_s)		

*Authors acknowledged considerable uncertainty – use these values with caution.

2.4 Groundwater Recharge

2.4.1 RAINFALL RECHARGE

Rainfall and evapotranspiration are by far the largest components of the regional water balance for the South East. Recharge is one of the dominant elements of the aquifer water budget (Wood, 2010). Rainfall recharge is thought to be the primary driving factor for groundwater flow and storage changes in the study area, and is particularly challenging to quantify given the large spatial extent and complicated surface-subsurface interactions that occur across the region. For this reason, a series of major activities aimed at better quantifying recharge for the South East have been undertaken as part of the South East Regional Water Balance Project.

Crosbie et al. (2015) and Crosbie and Davies (2014) reviewed the various field estimates of recharge for the study area. They also presented a method for obtaining spatially and temporally varying estimates of recharge over the study area. They adopted a simple water balance approach using estimates of evapotranspiration from CSIRO's MODIS reflectance-based scaling evapotranspiration (CMRSET) algorithm (Guerschman et al., 2009) to estimate recharge from rainfall data. The method provides estimates of net recharge on a 250 m spatial grid every 8 days from the year 2001, when the first data are available. Figure 2.6 shows the ten-year (2001–2010) average recharge over the study area, equal to a total volumetric rate of inflow of 1,040 GL/y, or a spatially averaged recharge rate of 40 mm/y.

A series of recharge modelling activities have been carried out as part of the South East Regional Water Balance Project in order to (a) improve our ability to predict future rainfall recharge to the area under varying climate and land use scenarios, (b) to better understand the influence of the modelling approach selected on modelled recharge rates, (c) to better understand the various components of the land surface-unsaturated zone water balance (leading to aquifer recharge), (d) provide a basis for providing long-term, time-varying recharge during periods when remote sensing data (i.e. CMRSET) are unavailable to support the development of the regional groundwater flow model, and (e) to provide a means of estimating crop irrigation requirements as a function of agricultural practices and climate variations. These activities are described in detail in Doble et al. (2015) and Morgan et al. (2015).

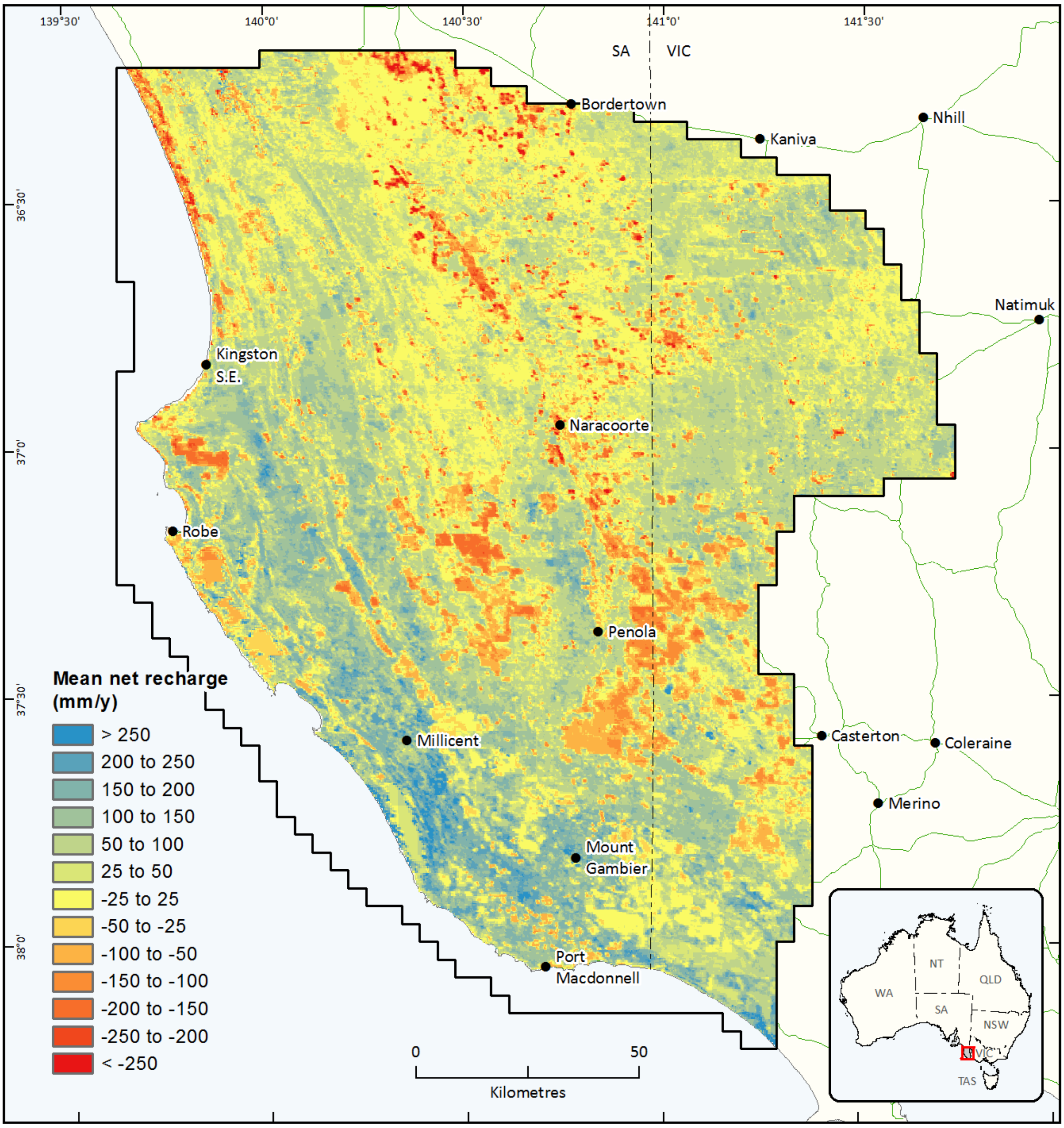


Figure 2.6 Ten year average (2001-2010) annual recharge for the study area using the water balance approach of Crosbie et al. (2015) and the MODIS satellite data analysed using CMRSET algorithms.

2.4.2 RECHARGE VIA RUNAWAY HOLES AND DRAINAGE BORES

In some areas of the South East, dissolution of the limestone has led to the development of karstic features that in places have undergone brecciation and collapse near the ground surface, forming numerous sinkholes. Figure 2.3 shows the mapped locations of some of the major sinkholes (also known as 'runaway holes') observed by DEWNR; however this map identifies only a selection of the preferential recharge pathways of the region. 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.

Additionally, there is a large number of drainage bores in the South East, and these serve to alleviate flooding by draining excess stormwater into the unconfined aquifer. The dataset of locations of these bores is available from DEWNR, however the volumes of water that recharge the unconfined aquifer via these bores is unknown.

2.5 Groundwater Extraction

2.5.1 LICENCED GROUNDWATER EXTRACTION – SOUTH AUSTRALIA

A historical groundwater extraction dataset for the South Australian portion of the model domain was developed based on recent metered groundwater extraction data for 2009-2013, provided by DEWNR. The full details of the development of the dataset and its limitations are provided in a separate report (Harrington and Li, 2015) and only a summary is provided here.

The dataset includes metered groundwater extraction volumes from both the confined and unconfined aquifers for irrigation, municipal and industrial uses in the South Australian portion of the study area. The metered dataset contained 3,812 metered groundwater extraction records, for each year between 2009/10 and 2012/13 inclusive. The dataset was quality checked, removing obvious errors and issues with inconsistent reading dates, and consolidated to make it ready for use in a groundwater flow model (see Harrington and Li, 2015). Geographical coordinates were assigned to the meter records based on meter position data provided by DEWNR. Where these data were not available (for 1,032 wells) the extraction volumes for these wells were distributed evenly across wells in corresponding groundwater management areas that did have geographical coordinates. This ensured that water balances were correct at least at the management area scale.

Historical groundwater extraction data dating back to 1970 were produced by first assigning extraction “commencement dates” to the meter records using a variety of methods with varying uncertainty associated with them (Harrington and Li, 2015). These methods included (a) assigning the drilling dates of the associated wells provided in a dataset by DEWNR (approximately 3,000 meters were matched to bores using this database but only 2,811 of these had drilling dates), (b) assigning the drilling dates of the nearest extraction well, within 500 m of the meter using a GIS matchup process, and (c) assigning the licence activation date for the associated licence where available. Average groundwater extraction rates for individual meters for the metered period (2009/10 – 2012/13) were applied historically back to the meter “commencement dates”.

The dataset produced is available from DEWNR, and the associated report can be found through the Australian National Data Service (ANDS) and Goyder Institute for Water Research websites. Figure 2.7 shows the estimated decadal groundwater extraction (GL/y) from the unconfined and confined aquifers for both the whole study area and the Lower Limestone Coast PWA. Figure 2.8 and Figure 2.9 show the spatial distribution of groundwater extraction for the unconfined and the confined aquifer respectively.

A number of limitations are associated with the constructed historical groundwater extraction dataset, due to the broad assumptions used to match meter records with extraction wells, assign pumping “commencement dates” and determine the historical extraction rates to be applied. These are listed in Harrington and Li (2015).

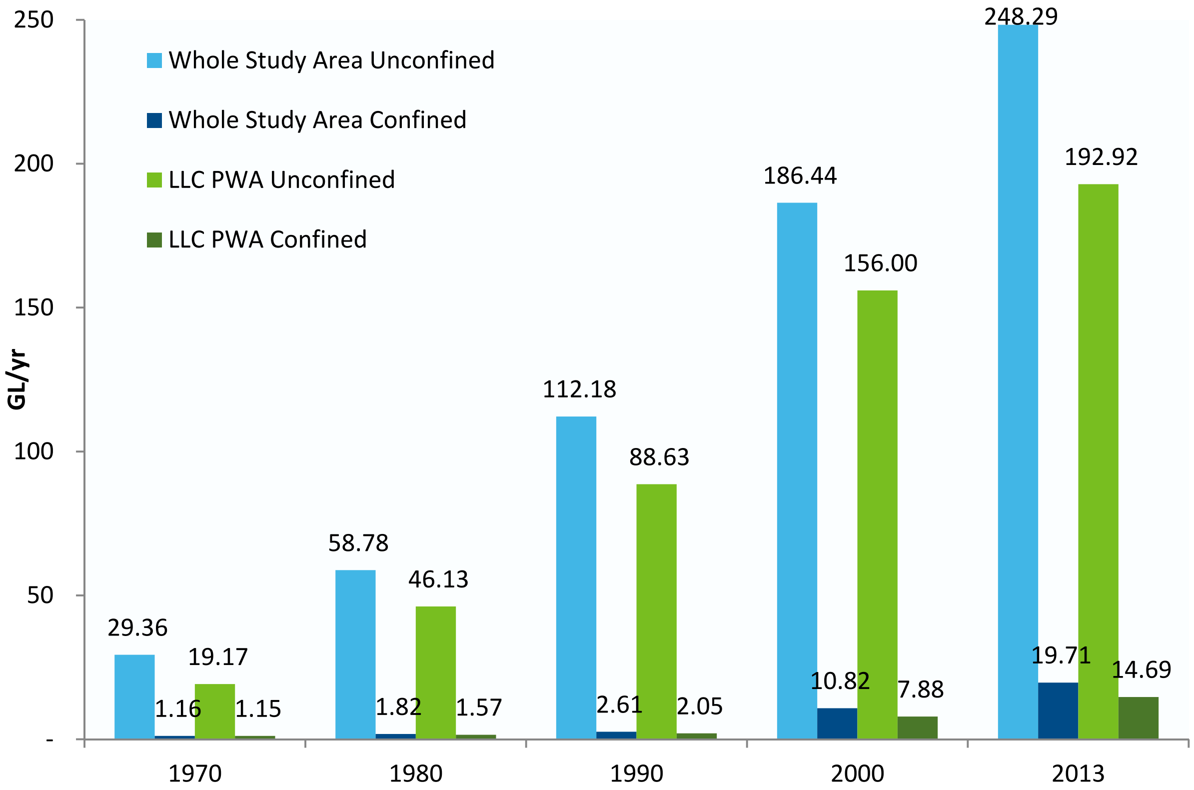


Figure 2.7 Estimated decadal groundwater extraction (GL/y) from the unconfined and confined aquifers for both the whole study area and the Lower Limestone Coast PWA (Harrington and Li, in prep).

2.5.2 PUBLIC WATER SUPPLY WELLS

Most public water supply wells associated with towns in the study area extract water from the confined aquifer. Extraction data for public water supply wells between 1991 and 2005 shows that extraction has been relatively constant over that time period (Harrington and Brown, 2007 (unpublished)). The exception was Robe, for which annual extraction increased from 196 ML to 312 ML. Harrington and Brown (2007 (unpublished)) calculated that approximately 35% of the total annual extraction occurs over the winter half of the year, with 65% occurring over the summer half. It has been noted that a number of the pumping commencement dates provided in the Licenced Groundwater Extraction dataset described above, for the wells with Public Water Supply use types, are not likely to represent the actual commencement of pumping for that public water supply. The commencement dates are generally based upon the drill dates of the associated bore, and many of these have been replaced over the history of the water supply, with commencement dates in the 1990s or 2000s. In this case, the start date listed would represent the drilled date for the replacement well and the actual commencement of pumping would be much earlier than this. For the purpose of the conceptual model of the groundwater system, it is assumed that these wells extract groundwater from at least 1970, which is the beginning of the time period of interest in this study. The city of Mount Gambier obtains its water supply from both the Blue Lake (described in Section 2.5.3 below), as well as confined aquifer production bores.

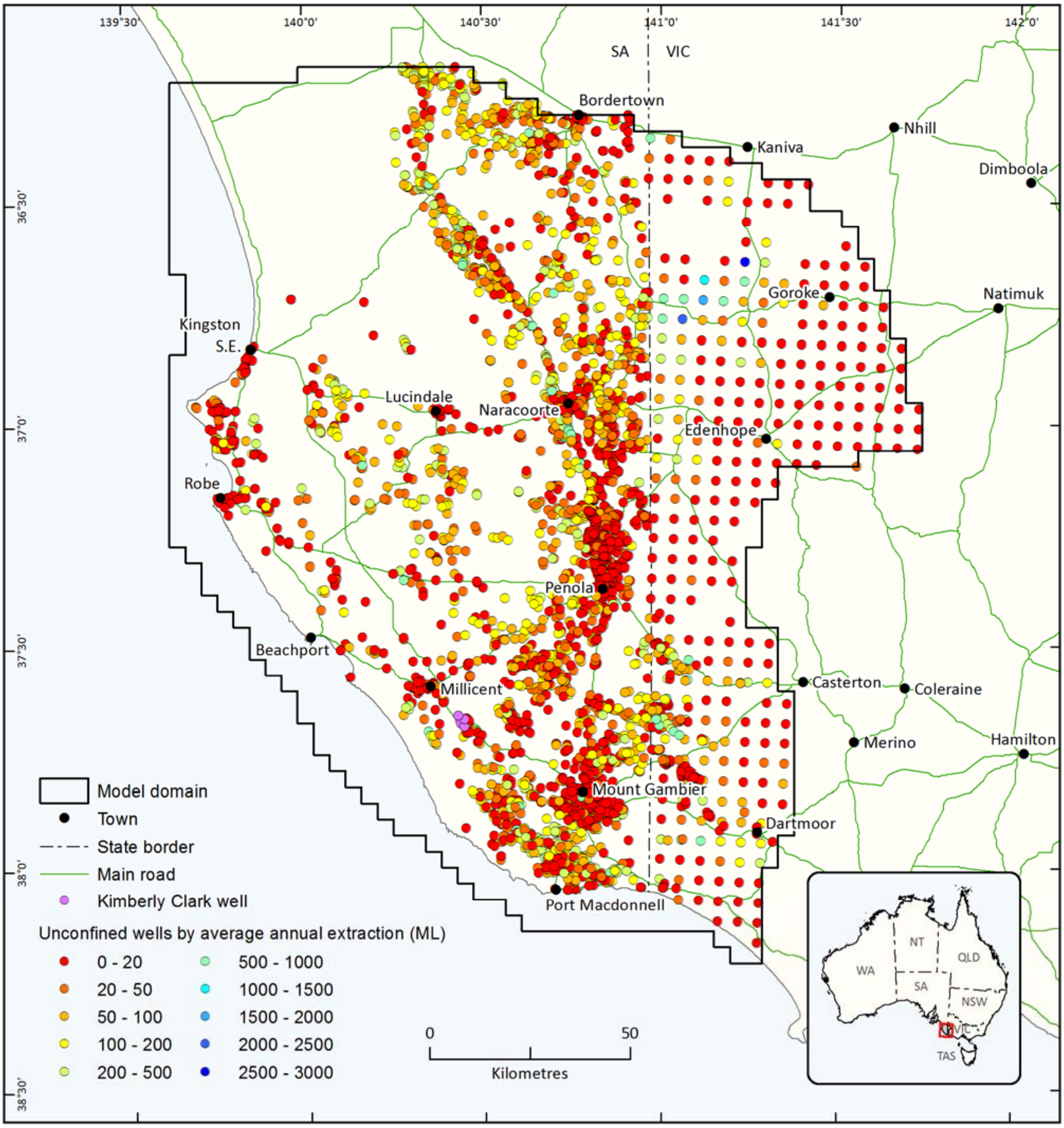


Figure 2.8 Current groundwater extraction density for the unconfined aquifer.

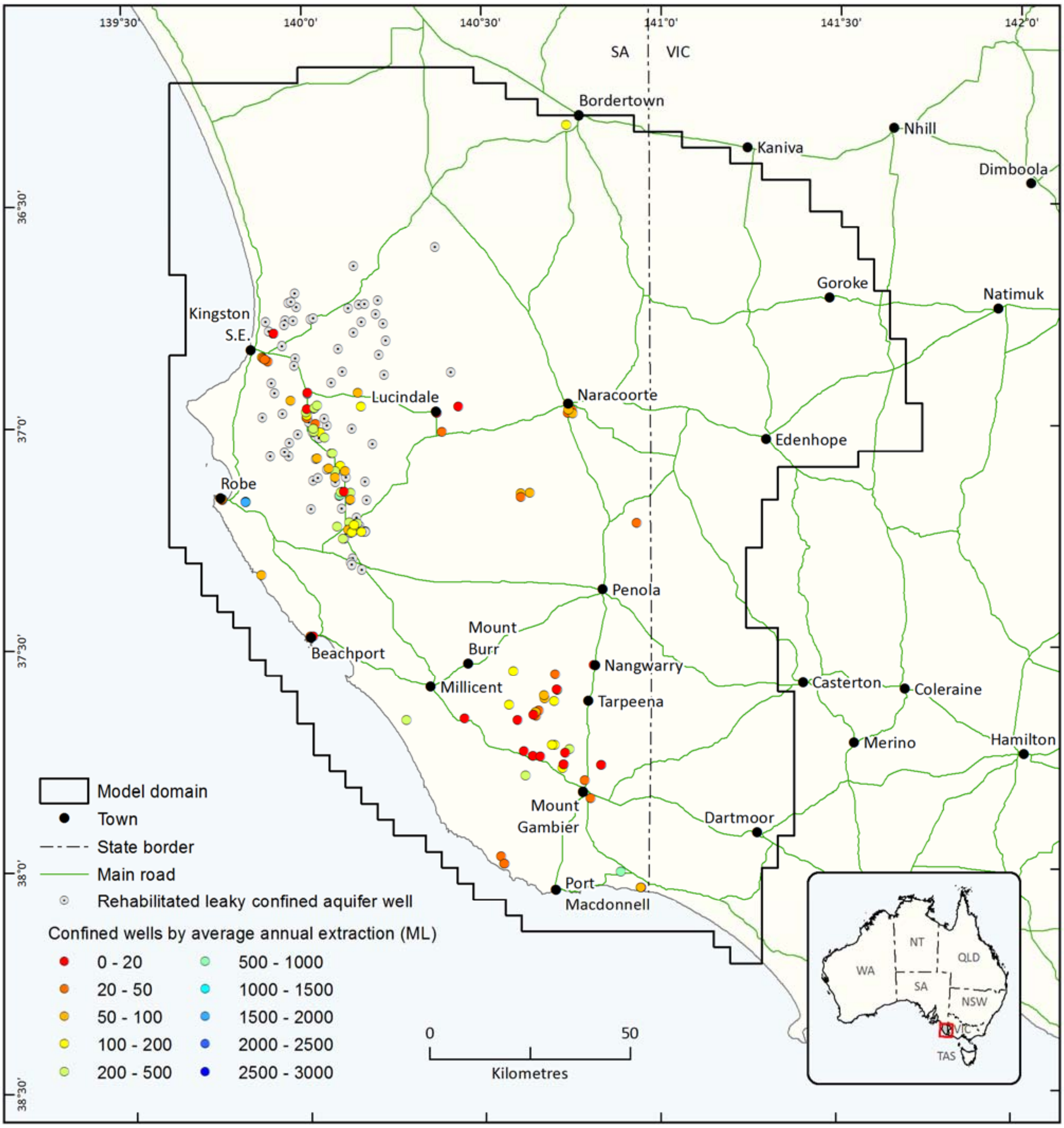


Figure 2.9 Current groundwater extraction density for the confined aquifer.

2.5.3 HISTORICAL EXTRACTION FROM BLUE LAKE

Extraction of surface water from Blue Lake for Mt Gambier's town water supply increased steadily from 1900 to 1965 and has remained between 3,000 ML/y and 4,000 ML/y since 1965 (Figure 2.10). As Blue Lake contains predominantly water from the surrounding unconfined aquifer and is considered a "window" into the groundwater system, this extraction can be considered to be synonymous with groundwater extraction from a production bore. In accordance with this, the Blue Lake pumping wells are administered through an unconfined aquifer licence (licence number 11230). Extraction of surface water from Blue Lake is included in the metered groundwater extraction dataset described above under this licence number, in the same format as for the other metered extractions. However annual extraction data for Blue Lake is also available for the period 1891 to present (S. Mustafa, DEWNR, pers. comm., 2013).

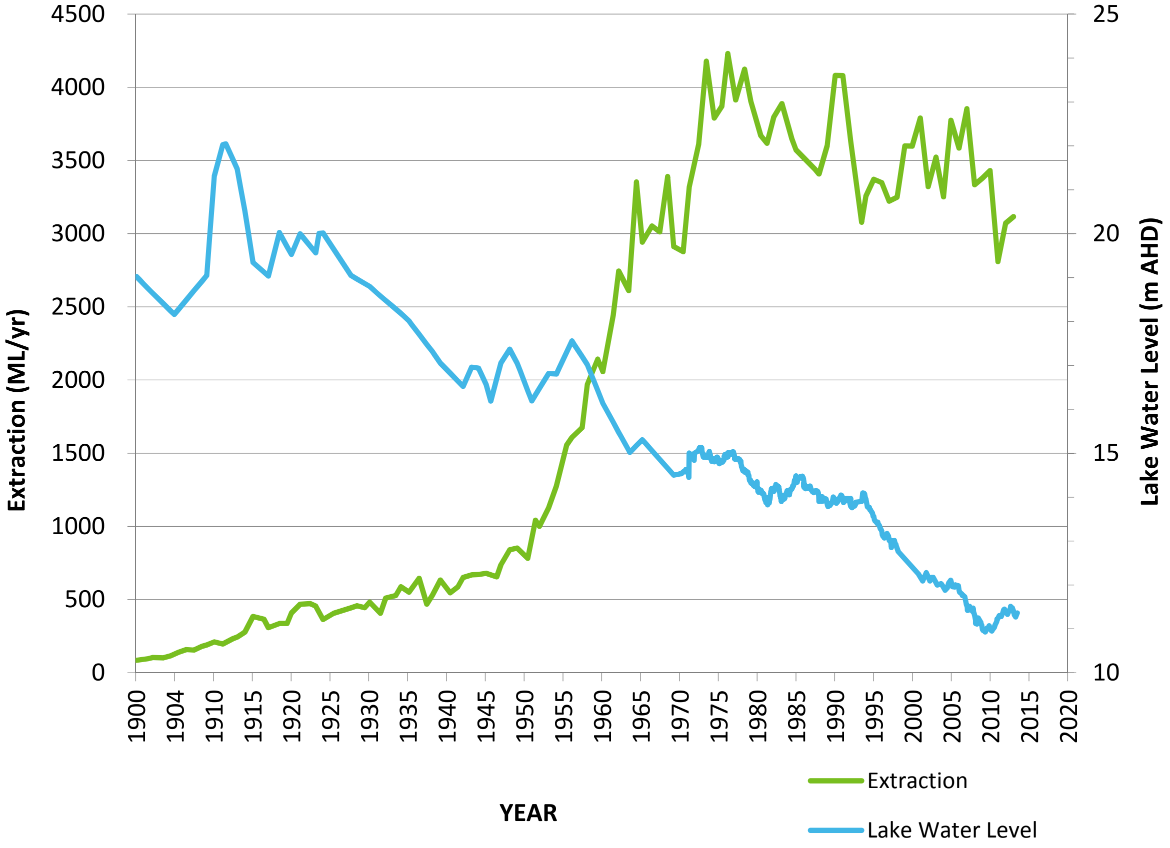


Figure 2.10 Annual extraction (ML) from and lake water levels in the Blue Lake since 1900 (S. Mustafa, DEWNR, pers. comm., 2013).

2.5.4 KIMBERLEY CLARK PULP AND PAPER MILLS

The Kimberley-Clark Tantanoola and Millicent pulp and paper mills opened in the 1960s and groundwater extraction from the unconfined aquifer peaked at 60 ML/d in the 1990s (Kimberley-Clark Australia and New Zealand, 2012; J. Lawson, DEWNR, pers. comm. 2014). Since then, water use has been gradually reduced and reached 30 ML/d just before the closure of the Tantanoola Mill in 2011 (Kimberley-Clark Australia and New Zealand, 2012) (J. Lawson, pers. comm. 2014). The current rate of extraction is between 8 ML/d and 10 ML/d, with annual data available since 2003.

Annual extractions for the eight Kimberley-Clark production bores from 2003/04 to 2013/14 were provided by DEWNR. Prior to this, total groundwater extraction is assumed to be 60 ML/y, spread evenly across all eight production bores. This rate is assumed to occur until annual data are available from 2003 onwards (Table 2.3). Monthly data provided for the 2012/13 and 2013/14 water years showed that extractions are constant on a monthly basis and hence average daily extraction values provided can be extrapolated evenly across the year.

Table 2.3 Total groundwater extractions (ML/d) from the Kimberley Clark Pulp and Paper Mills at Millicent and Tantanoola.

	1960-1990	1990-2003	2003/04	2004/05	2005/06	2006-2008	2008/09	2009/10	2010-2012	2012/13	2013/14
ML/d	20	60	27.4	29	32.5	32.2	30.4	31.1	17.2	10.3	10.2

2.5.5 VICTORIAN GROUNDWATER EXTRACTION

Groundwater extraction data for the Victorian portion of the model domain was available in two formats:

- A raster of groundwater use density from the SAFE (Secure Allocations, Future Entitlements) database (Victorian Department of Sustainability and Environment, 2012). This raster is a 1 km grid-scale density raster that includes the volume of licensed entitlement groundwater use (metered and estimated unmetered use) and stock and domestic use (estimated unmetered use) in ML/y, as per the metadata provided with the dataset. The dataset is based on metered groundwater use information from Southern Rural Water, Goulburn Murray Water and Grampian Wimmera Mallee Water. The dataset includes a combination of data from the years 2008/2009 and 2009/2010. These data cover the entire Victorian portion of the model domain.
- Point data from Glenelg-Hopkins Catchment Management Authority (CMA) groundwater model (Sinclair Knight Merz, 2010). This covers the southern portion of the Victorian part of the model domain only and includes start dates and entitlements as well as estimated annual extractions from 1985-2000.

The two datasets were consolidated into a single Victorian groundwater extraction dataset for use in the regional groundwater model in the following way. As point data are required for input into a groundwater flow model, the groundwater use density data were aggregated to a 5 km x 5 km grid to reduce the number of data points, and then each raster grid cell was converted to a point located at its centre. The effect of the aggregation on the total groundwater extraction from the model domain was checked and it was found that there was a negligible difference between the totals for the 1 km and 5 km grids.

For the Glenelg-Hopkins CMA area, when the point data from the Glenelg Hopkins model (1985-2000) were compared with the data created from the groundwater use density raster (2008/09 to 2009/10), it was found that total extraction from the point data (12,697 ML/y) was 16% higher than that from the groundwater use density raster (10,653 ML/y). This excluded any extractions for wells in the point dataset with start dates listed from 2001 onwards. Such wells had zero extractions in the Glenelg-Hopkins model. Including wells with start dates later than 2001, assuming groundwater use at entitlement values, led to the total groundwater use from point data equal to almost double the value from the groundwater use density raster. It was therefore decided to adopt the point data up to the 2001/02 irrigation season, using the reported groundwater extraction values applied from the reported well commencement dates. End dates for these wells would then be 28 June 2001. Wells with commencement dates from 2001 onwards were not included. The groundwater use density data (interpreted to a 5 km grid spacing) was then used to represent extractions from 1 July 2001 to present.

For the Wimmera CMA, where only recent groundwater use density data are available, it is currently assumed that there was no groundwater extraction prior to 1985. The GW use density data (in point format) is then assumed to represent groundwater extractions from 1985 to present. All extractions listed in this dataset are assumed to occur from the unconfined aquifer as there was no information to suggest otherwise. The method of assigning groundwater extraction values to the Victorian portion of the model domain causes the unusual uniform grid of data shown in Figure 2.8.

2.5.6 LEAKAGE FROM CONFINED AQUIFER BORES

A number of early irrigation and stock bores completed in the confined aquifer were poorly constructed, and leakage between the confined and unconfined aquifers was identified to be occurring in the region from Kingston to Millicent. Here, the upward hydraulic gradient between the two aquifers is large. The time when this leakage could be considered to have started is uncertain, because observed declines in confined aquifer hydrographs can also be attributed to an increase in extraction during that time. The South East Confined Aquifer Well Rehabilitation Scheme rehabilitated (replaced or backfilled) these bores between 2000 and 2010 and a recovery in the confined aquifer potentiometric surface has been attributed to this rehabilitation of leaky wells. The locations of the rehabilitated wells are shown in Figure 2.9 and their details are provided in Appendix A .

2.6 Wetlands

The Phase 1 report contains a broad description of wetlands in the South East of South Australia (Harrington et al., 2013). Wetlands are numerous across the study area (Figure 2.11), and because they are often very shallow, their spatial extents are highly variable over time. Many are seasonal, and their groundwater dependence is also variable (Figure 2.11), although there are little data to provide an understanding of this. It is likely that many wetlands can be conceptualised as surface expressions of the unconfined groundwater system, although many also receive surface water inputs at times. There is anecdotal evidence of low permeability layers occurring in the bases of some wetlands, which may serve to perch surface water after the water table has dropped below the base of the wetland. However, there are only scant data on this also. Two studies of surface water-groundwater interactions around wetlands in the South East are described in the Phase 1 report. A simple reconnaissance study showed that groundwater input is generally low in terms of the overall water balance of the wetlands (Fass and Cook, 2005). However, a more detailed study of Honan's Wetland, approximately 16 km to the west-north-west of Mount Gambier, suggested that groundwater input to wetlands can be highly variable over space and time (Cook et al., 2008).

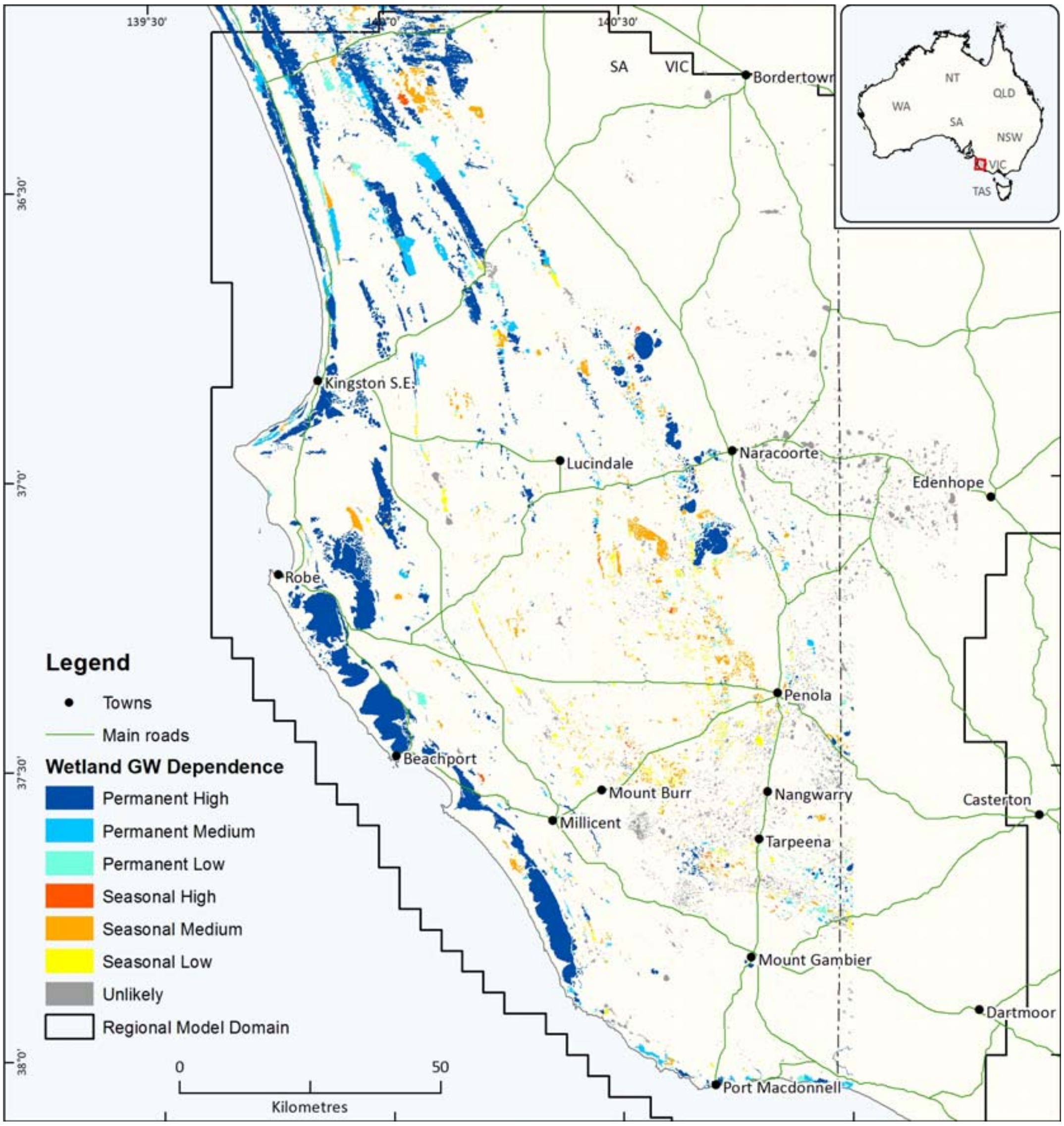


Figure 2.11 Map of wetlands in the South East of SA, showing their degree of groundwater dependence (Data obtained from the South Australian Wetland Inventory Database).

Figure 2.11 shows that a large portion of the wetland area in the study area is currently considered to be permanent, with a high degree of groundwater dependence. However, this regional-scale analysis of groundwater dependence is currently based upon the elevation of a particular wetland relative to the watertable inferred from the regional groundwater observation well network. A more detailed analysis of wetland-groundwater interactions is required to confirm this, especially for wetlands of particular interest. This was an objective of a separate task in the South East Regional Water Balance project (Taylor et al., 2015; Smith et al., 2015; Turnadge and Lamontagne, 2015). That study, which took a generic approach to South East wetlands, but focused on three different case studies, showed that the water regime of individual wetlands may be strongly related to the position of that wetland relative to regional and intermediate flow paths, as well as local factors, such as the presence or absence of a clogging layer at the base of the wetland. Simple two dimensional MODFLOW models were developed to further investigate this.

Several wetlands in the South East are associated with karst springs, of which Piccaninnie Ponds and Ewens Ponds are the most notable examples. These wetlands, which are located near the coast on the South Australian side of the Victoria–South Australia border, are described in some detail in the Phase 1 report. They are conceptualised as windows into the groundwater system, being up to 100 m deep and receiving water from the unconfined aquifer. The volcanic crater lakes, which include Blue Lake at Mount Gambier, can be conceptualised in a similar way.

2.7 Constructed Drains

Constructed drains are a prominent feature of the South East (Figure 2.12). Construction of the drains began in 1864, around Millicent, with the objective of improving agricultural productivity by draining land that became inundated during winter. The drainage network has gradually expanded. The larger cross-country drains, taking water through the remnant dunal ridges to the sea, were constructed in the early 1900s and most of the drains in the Lower South East were constructed prior to 1970 (Figure 2.12). The Upper South East drains were installed between 1998 and 2010 to remove saline water from the root zones of crops and the Reflows Western Floodway commenced operation in 2010 to restore some of the natural surface water flows to wetlands in the Upper South East (SEWCDB, 2012).

2.7.1 DRAIN LOCATIONS AND CONSTRUCTION DETAILS

Drain locations were available as line shapefiles from DEWNR (D Tonkin, DEWNR, pers. comm.). The available information on drain construction can be divided into two groups. i.e. data for:

- The Upper South East drains, which were installed as part of the Upper South East program between 1998 and 2010.
- The Lower South East drains, which were installed prior to 1970.

Upper South East Drains

Construction details for many of the Upper South East drains were available in the following formats:

1. Point shapefiles for individual drain centrelines with details of: design elevation, constructed elevation, cut/fill depth and landowner. These shapefiles had data for points every 50 m along the drain.
2. Electronic (MS Excel) “As built” construction records, with details of: the centreline data described above, plus cross section data for every 500 m along the drain, including drain width, drain cross-sectional area and drain depth.

The data described above were summarised for every 500 m along the drain (as per the cross-sectional data, noting that base elevation data are available at the finer scale of every 50 m along the drains). Data are not available for a number of the Upper South East drains. The South East Water Conservation and Drainage Board (SEWCDB) was consulted on these data gaps and anecdotal data on drain depths and widths were provided where necessary to fill in gaps in the spreadsheet (M. DeJong, SEWCDB, pers. comm., 2014). Construction date data for the Upper South East drains was provided by the SECWMB. A point shapefile was constructed using the summary of this data.

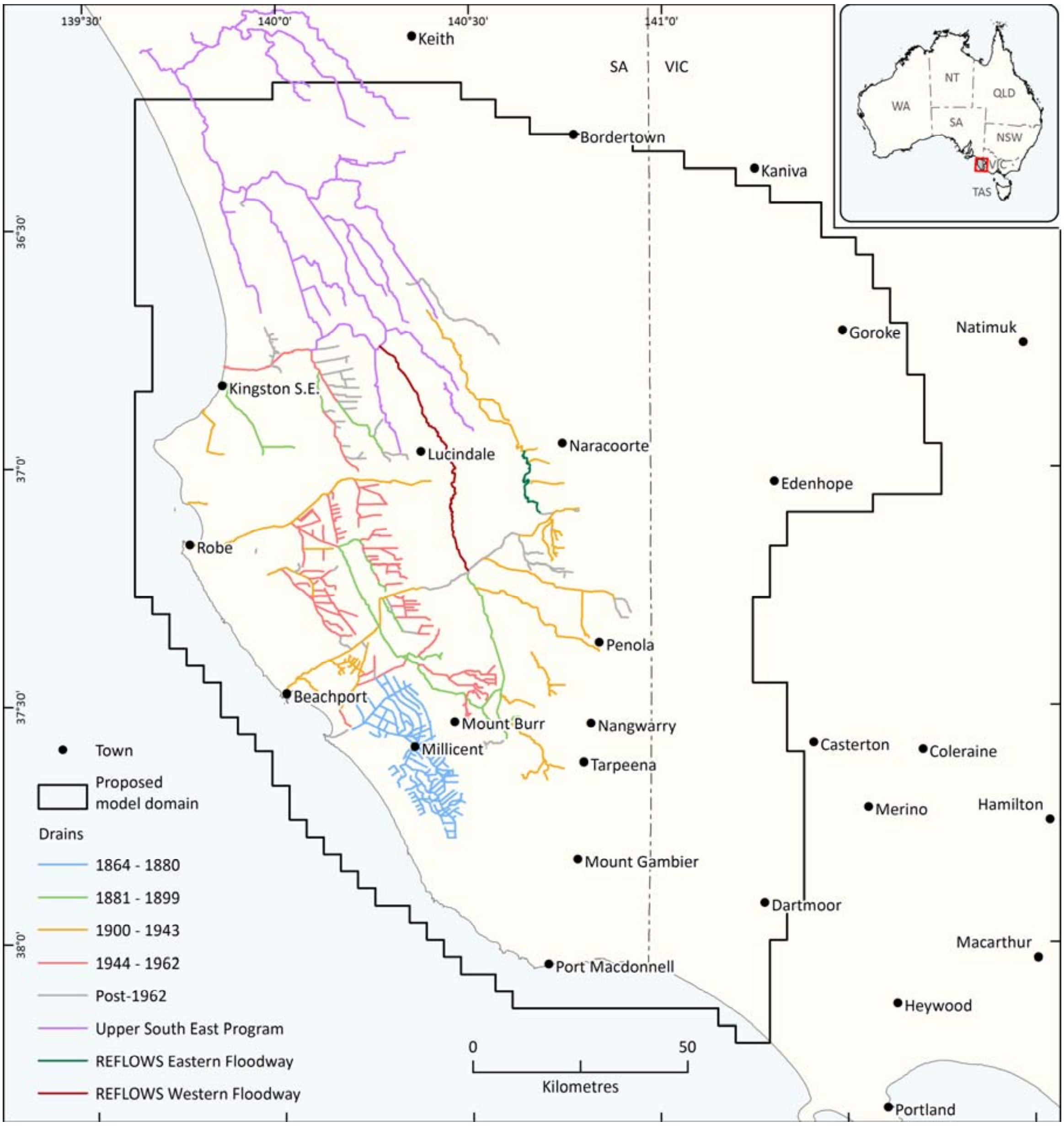


Figure 2.12 Map of the man-made drains in the South East of South Australia, showing the period in which they were constructed.

Lower South East Drains

The Lower South East Drains, which consist of major drains owned by the SECWDB and smaller privately owned drains, are much older than the Upper South East drains, being constructed between 1860 and 1970. Construction details of these drains exist only as pdfs of the original plans, catalogued in an Excel spreadsheet. These plans contain detailed construction drawings of sections of the drains, with details every 200 feet along the drain of: natural surface elevation, invert (planned), depth of cut, average invert as constructed, base width, side slope and planned discharge. Position of a measurement on the drain is given as a “chainage” (the distance along the drain from the discharge point), with no spatial co-ordinates available. Because the plans are of sections of the drains, there may be numerous pdf plans for each drain.

Compilation of all of the construction data for the Lower South East drains into either an Excel spreadsheet or ArcGIS format would provide a useful resource but would require a large amount of time. Because of the regional scale of the groundwater model being developed, such detail on the drains is not necessary for the current project. However, broad summaries of the drain construction details were compiled from the pdf plans as a compromise, to provide some relative accuracy in the implementation of the drains in the numerical groundwater flow model. The details collected for each section of drain included: minimum and maximum base width, and minimum and maximum invert.

The minimum and maximum widths were used to calculate an average width for that section of the drain and then an average width for the entire drain. The minimum and maximum width data could be used in future to provide a more detailed analysis of flows in drains. The minimum and maximum invert data have not been used to date but would be useful in future to provide drain elevations if the beginning and end of each drain section could be spatially referenced using the chainage information. For the purpose of implementing the drains in the regional groundwater model in a reasonable but efficient way, anecdotal information on drain depths was sought from the SECWMB (Mark Dejong, SECWMB, pers. comm., 2014).

2.7.2 DRAIN FLUXES

The drains move large amounts of water around the landscape, but their importance in the regional water balance is unknown. Recent studies have suggested that they are predominantly gaining surface water features (Harrington et al., 2012). The exception may be in the Management Areas of Coles and Short (see Figure 2.3), where a cone of depression around blue gum forestry plantations has resulted in groundwater levels dropping below the base of the drains in that area.

The drainage system is highly regulated, meaning that flows in particular drains can be controlled via gates and weirs to prevent inundation of agricultural land or to divert high salinity water away from wetlands towards the sea, or low salinity water to ecologically significant wetlands. These actions are currently not recorded and occur on an “as needed” basis, and therefore it is presently not possible to provide accurate water balance modelling of the drainage system.

Drain Discharges to the Sea

The man-made drainage network of the study area has several outlets to the sea (or to coastal lakes) (Figure 2.12). The largest of these each have gauges near their outlets that record daily discharge. They are:

- Blackford Drain, just north of Kingston SE
- Drain L at Robe
- Bray Drain
- Drain M which has two branches, each gauged separately (Drain M and Reedy Creek-Mt Hope Drain).

Figure 2.13 shows the large annual variability in the volume of annual outflows from the above drainage system outlets, ranging from 12 GL in 2006 to 367 GL in 2000, with a mean outflow rate of 129 GL/y.

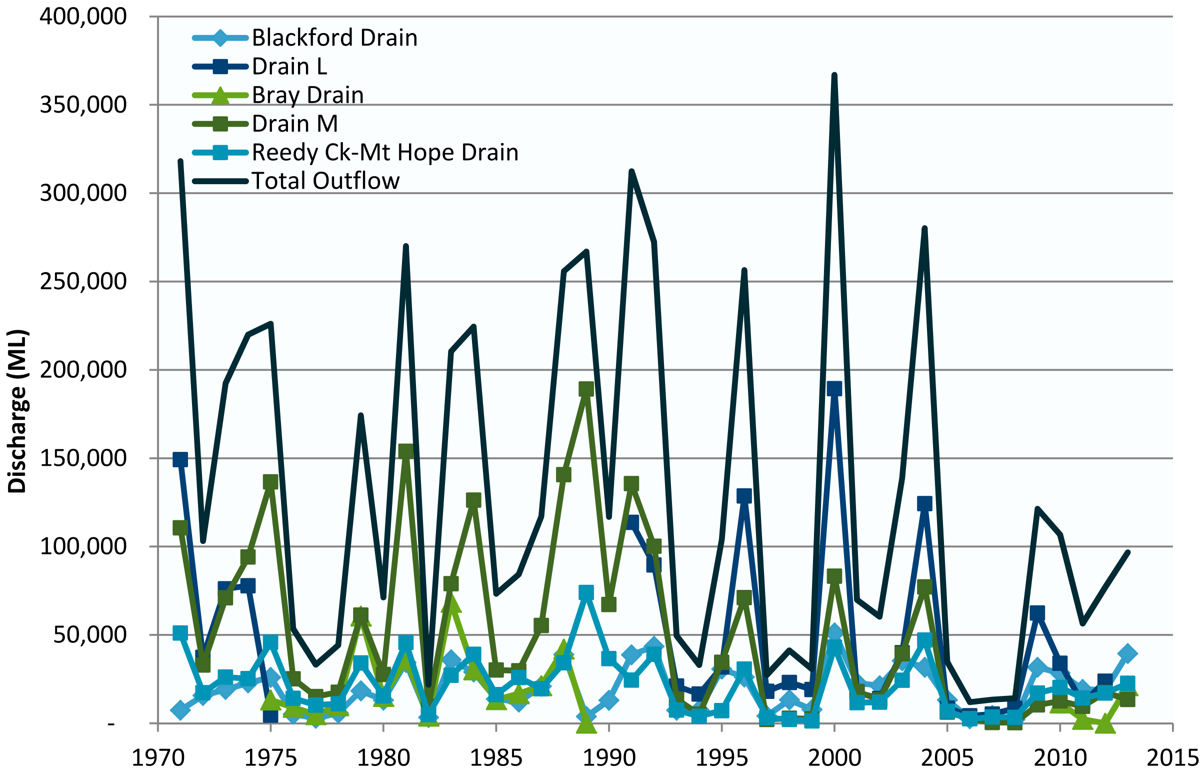


Figure 2.13 Annual discharge measurements from the major outlets of the man-made drainage system.

The network of smaller drains in the Millicent-Tantanoola area does not have gauging stations at all of its outlets. However, average annual discharges for the larger outlets from this drainage system were estimated from both gauging data and runoff calculations for the decade between 1972 and 1982 by Cramer (1982) to be:

Drain 44	8,500 ML/y
Benara Creek	5,400 ML/y
Stoney Creek	7,000 ML/y
Hatherleigh Drain	13,100 ML/y
Total	**34,000 ML/y**

This total is considered to represent an average annual discharge from that part of the drainage system, albeit this period included a range of high and low flow events.

Figure 2.12 shows that a portion of the Upper South East drainage section flows across the northern boundary of the model domain. There is no gauging station located near the point where that part of the drain system crosses the model domain boundary. However, a gauging station located on the northern outlet drain to the north of the model boundary (gauge number A2391072) records a flux of the order of 390 ML/y, the gauge on Didicoolum Drain at Peacock Range (gauge number A2391104); inside the model domain) records an average of 5,000 ML/y and the gauge on Taratap Drain at England's Crossing (gauge number A2391141); inside the model domain) records an average of 400 ML/y. These three drains have only four years of data recorded (2007-2011). This data suggests that flows in the drains across the northern boundary of the model domain may be of the order of 5-6 GL/y.

Estimation of Evaporation from the Drains

In order to compare modelled fluxes of water to the drains with the measured discharges from the drainage system at the coast, an estimate of the total amount of water leaving the model domain via the drains is required. This requires an estimate of the volume of water that evaporates from the drains.

The area of drain in each model cell was used with the annual potential evaporation from the corresponding weather zone (see Section 3 below) to calculate the potential annual evaporation from each drain cell. This represents an upper estimate of evaporation as we assume in this calculation that all drains have water in them for the whole year.

Total Groundwater Flux to the Drains

A net groundwater discharge to the drainage system (i.e. the difference between groundwater flows into and out of the drains) of 425 GL/y was obtained for the period 2000–2013 by subtracting evaporation losses (Table 2.4) from the total drain discharge to the sea. All of the drains (i.e. both the Upper and Lower South East) were present during this time. An estimate of the breakdown between discharge and recharge to/from drains is presently not possible given that the connectivity between drains and underlying aquifers, and the direction of head gradients (i.e. that dictate the direction of drain-groundwater flow) cannot be characterised at the scale of the study area.

Table 2.4. Estimated potential annual evaporation from the man-made drainage system (GL/y)

	1966-1975	2000-2013
Upper South East Drains	NA	2.88
Lower South East Drains	16.60	16.42

2.8 Other Watercourses

The number of natural surface watercourses in the study area is small compared with the man-made drainage system (Figure 2.14). Of course, the latter often exists where natural surface water flow previously occurred. The main components of the natural surface water system are (Figure 2.14):

- The ephemeral cross-border creeks, Morambro, Naracoorte and Mosquito Creek. The surface water catchments for all of these creeks are in Victoria, and flows are highly dependent on winter rainfall. There is little information about their interaction with the groundwater system. Daily flows are measured via gauging stations. Mosquito Creek, which discharges into the RAMSAR listed Bool Lagoon, has the highest flows and flows most years, whilst the other two creeks are more intermittent (Figure 2.15).
- The Glenelg River, which flows along the eastern boundary of the model domain. The river is likely to be connected with the upper units of the Tertiary Limestone Aquifer with groundwater discharging into the river (Border Groundwaters Agreement Review Committee, 2008), albeit there is little information on the hydrological characteristics of the river. There are gauging stations located at Dartmoor and Sandford, just south-east of Casterton for which there is up to 58 years of flow data available.
- The ephemeral spring-fed creeks at the coast to the south of Mount Gambier: Deep Creek, Cress Creek and Jerusalem Creek.
- The outlets of Piccaninnie Ponds and Ewens Ponds. The former is technically a constructed outlet drain and the latter occurs via Eight Mile Creek. Piccaninnie Ponds and Ewens Ponds are karst spring complexes, so the water discharging from these predominantly originates from the unconfined aquifer. Flows from these coastal spring-fed creeks and outlets have been periodically gauged since the 1970s, with an average flow rate of approximately 97 GL/y (Figure 2.16) (Wood, 2011).

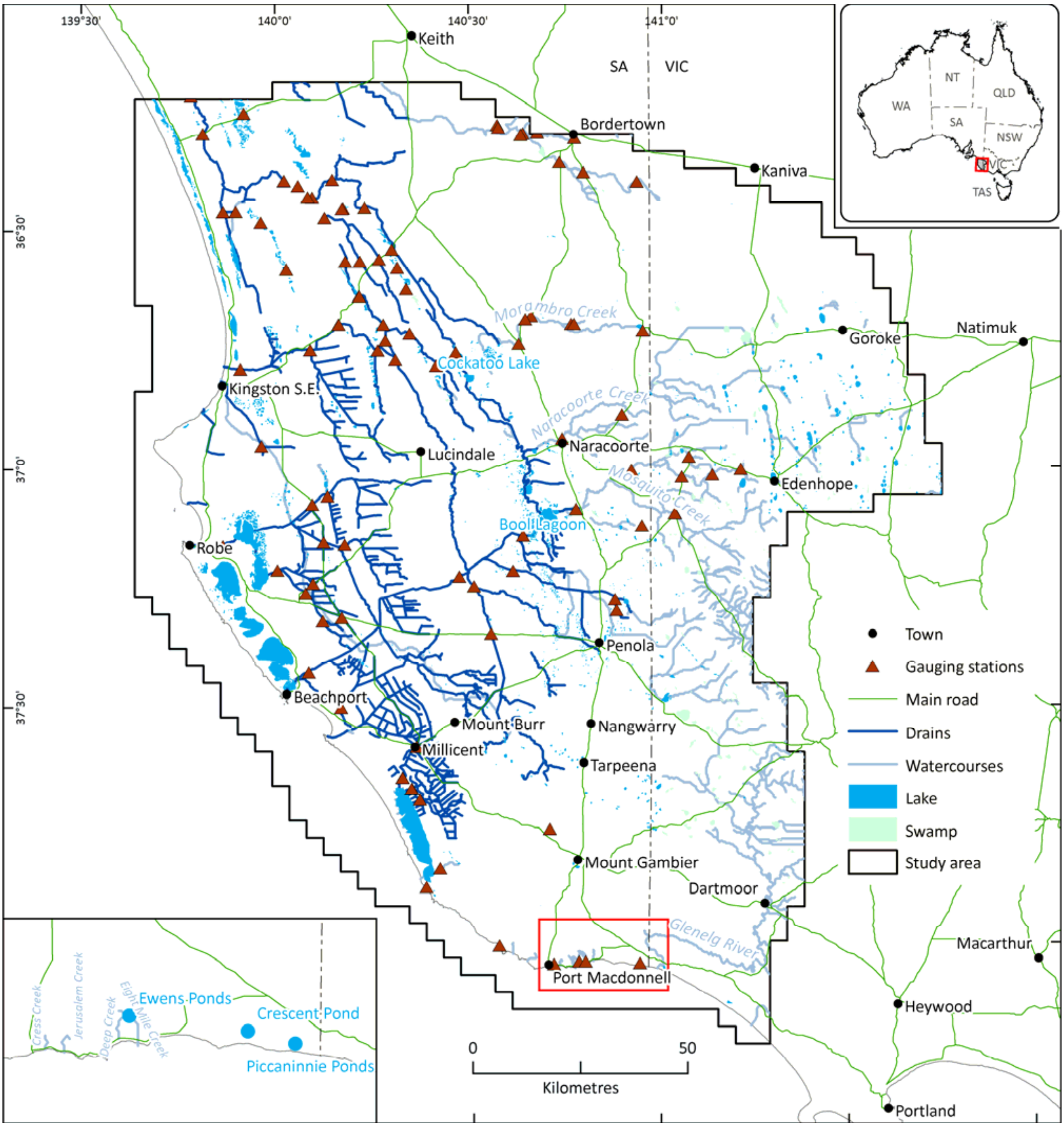


Figure 2.14 All surface water features of the South East.

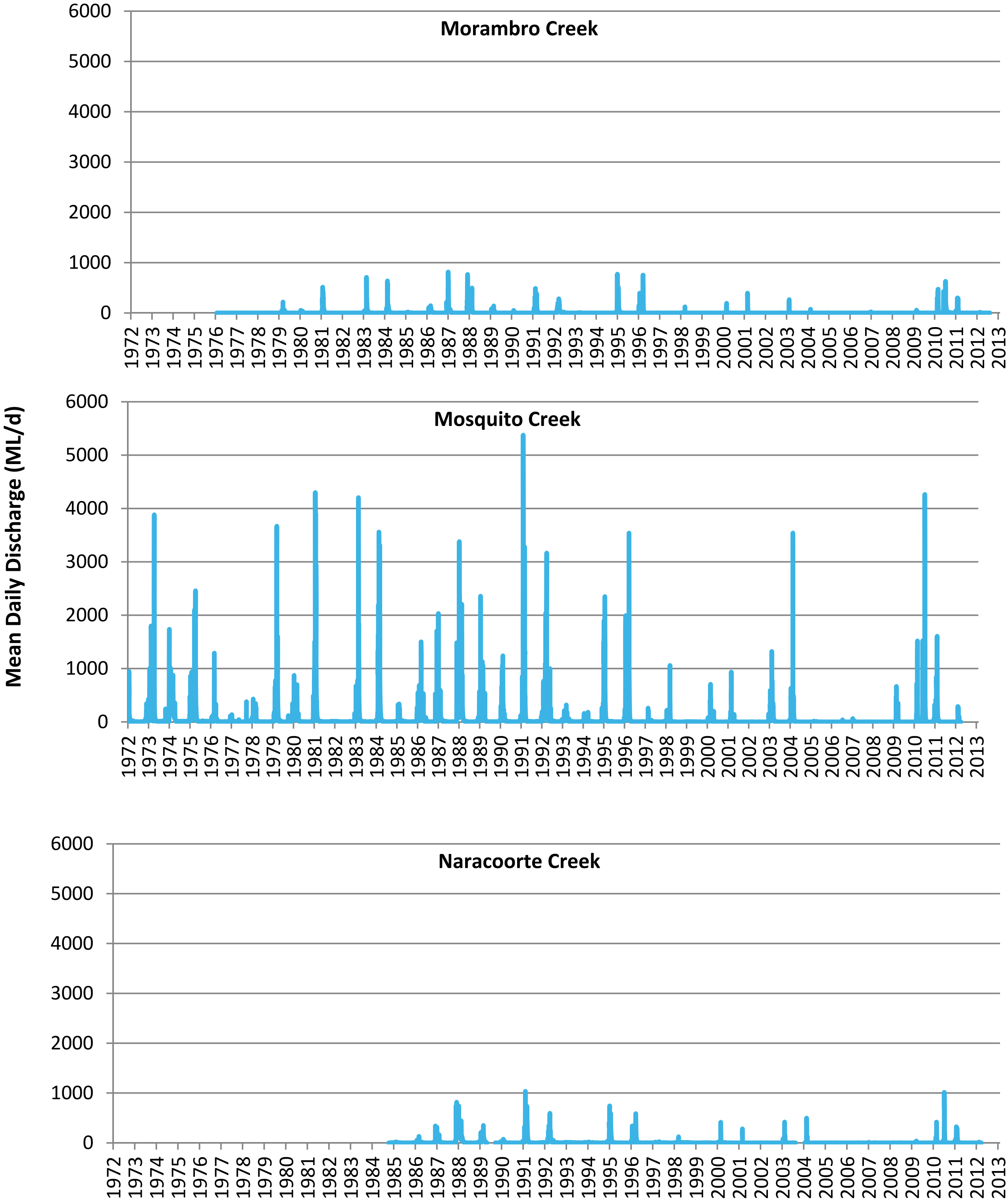


Figure 2.15 Daily flows at the gauging stations on the cross-border creeks.

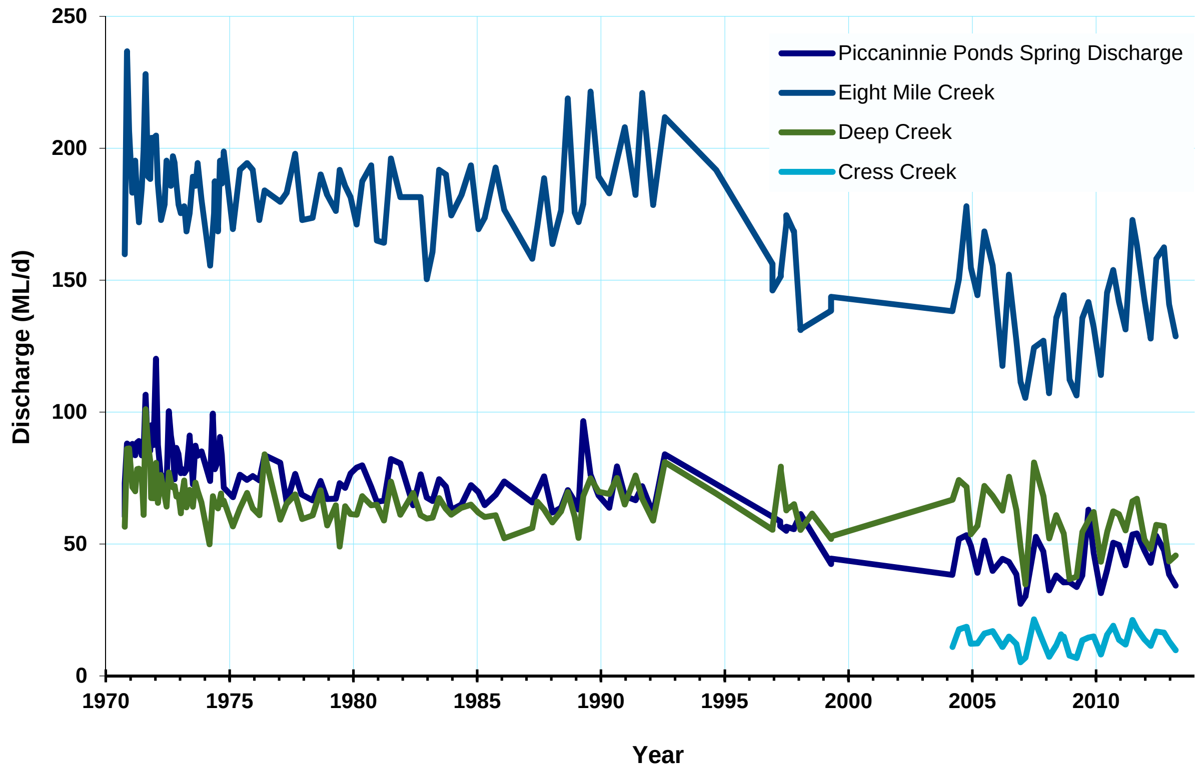


Figure 2.16 Measured daily discharge rates of the coastal spring-fed creeks to the south of Mount Gambier.

2.9 Coastal Boundary

Approximately half the length of the boundary of the model domain is coastline, adjoining the Southern Ocean. Most of the knowledge of processes associated with this boundary is restricted to the area to the south of Mount Gambier, where a network of observation wells dedicated to monitoring the seawater-freshwater interface has been installed, and a series of resistivity transects were collected to identify this interface (King and Dodds, 2002; Mustafa et al., 2012). Further details of these studies are provided in the Phase 1 report (Harrington et al., 2013). In general, the information from the resistivity transects and observation wells in that region was in agreement that the seawater wedge can extend up to 2 km inland, but is often constrained by hydrogeological features, such as zones of low permeability.

It is generally accepted that the TLA and TCSA continue offshore (Smith et al. 1995). It is also known that there is an upward hydraulic gradient between the TCSA and the TLA at the coast, providing a mechanism for upward leakage of water from the confined aquifer in this region. However, how far the aquifers extend offshore and where fresh groundwater may discharge, particularly from the TCSA, is a question that remains unanswered. Groundwater discharges via spring-fed creeks at the coastline to the south of Mount Gambier (Wood, 2011). A series of beach springs, also discharging fresh water, occur in this area. It is unknown whether the groundwater discharging from these features is regional or locally recharged groundwater.

Offshore extension of the onshore hydrostratigraphy using petroleum well data was attempted as part of a Masters study in collaboration with this project (Barandao, 2014). The study area and locations of petroleum wells are shown in Figure 2.17. A series of cross sections was developed and contours of layer elevations were compared with bathymetry data to identify the approximate likely outcrop location of the TCSA, should the aquifer outcrop. The stratigraphy and bathymetry data suggest that such outcrop locations would be beyond the edge of the Continental Shelf (Figure 2.18). It should be noted that this analysis is carried out based on petroleum well log data only, which are sparse (Figure 2.17). A study of geophysical data is proposed as future work to refine this interpretation. Any offshore outcrop location is where the majority of TCSA groundwater may discharge. The exception to this is the locations of numerous faults that may have the potential to facilitate preferential upward flow from the TCSA (J. Lawson, DEWNR, pers. comm., 2012).

A study carried out during Phase 1 of this project investigated the applicability of environmental tracers (temperature, salinity and radium) to identify and quantify the discharge of fresh groundwater at the coast (Lamontagne et al., 2013; Lamontagne et al., 2015). The study estimated that groundwater discharge along a 25 km length of the coast between Port Macdonnell and the SA/Victorian border, at a location 45 km offshore, is approximately 1.2 – 4.6 m^3/s (approx. 50 – 150 GL/y), which is similar in magnitude to the discharge from the spring-fed creeks in the area. This estimate is limited in accuracy, particularly for the offshore discharge component, by the effects of the high energy marine environment, which causes strong and rapid mixing of discharging groundwater with seawater and a large component of measured groundwater discharge to be the result of “recirculated seawater”.

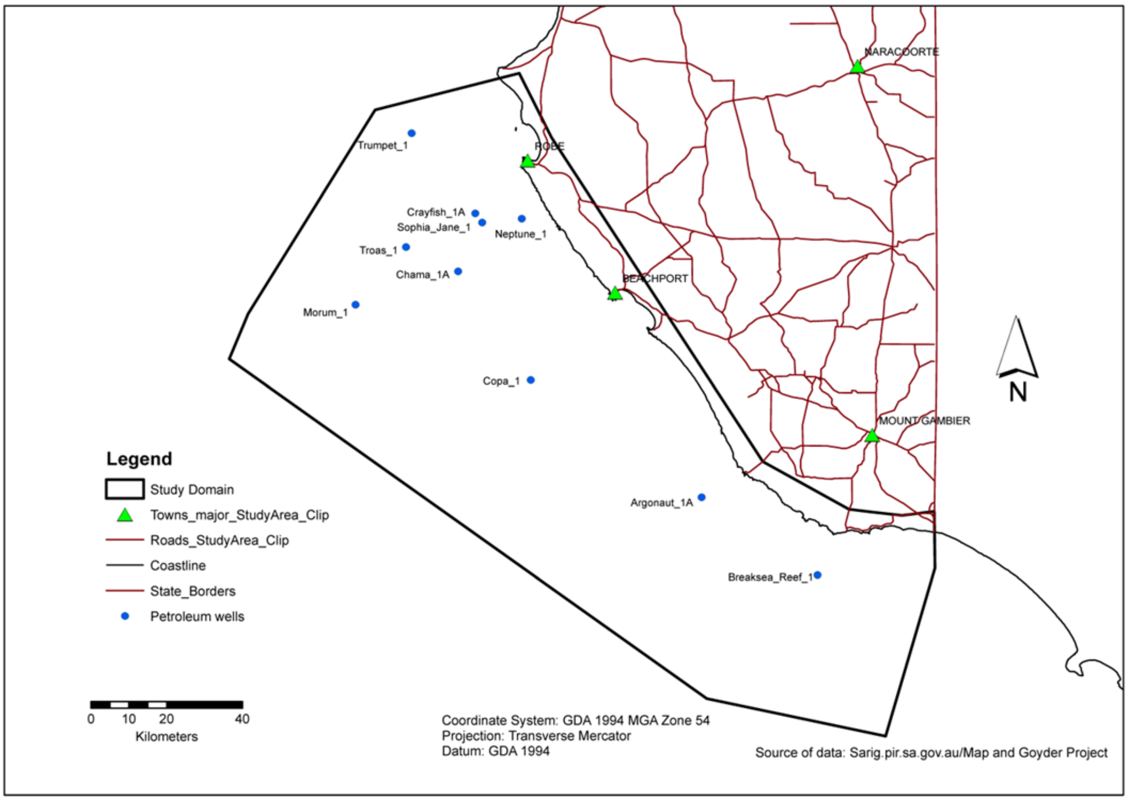


Figure 2.17 Study area of Barandao (2014) showing locations of the offshore petroleum wells (from Barandao, 2014).

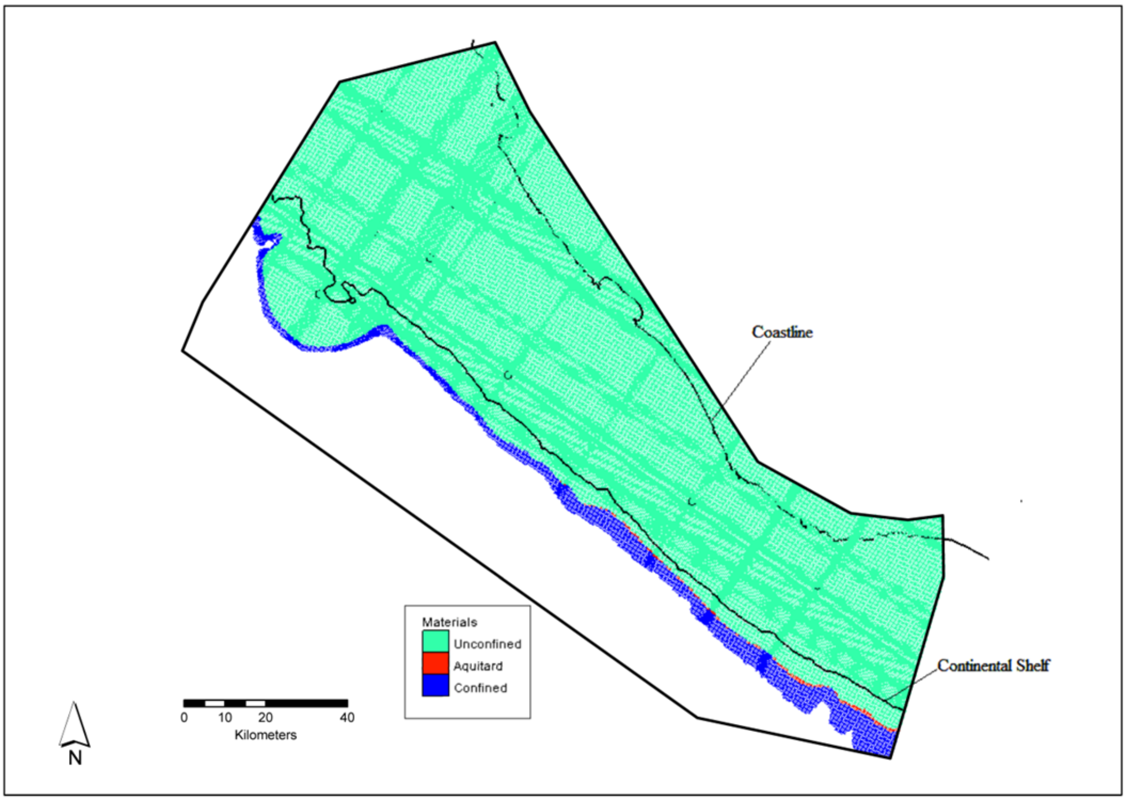


Figure 2.18 Estimated outcrop of the confined aquifer relative to the location of the continental shelf (from Barandao, 2014).

2.10 Water Balance Conceptualisation

Based upon the information provided in the above sections, a conceptualisation of the water balance for the study area over the period 2001-2010 (the time-frame of the MODIS-derived recharge estimate) can be constructed with rough estimates for each water balance component, as shown in Figure 2.19 and Table 2.5.

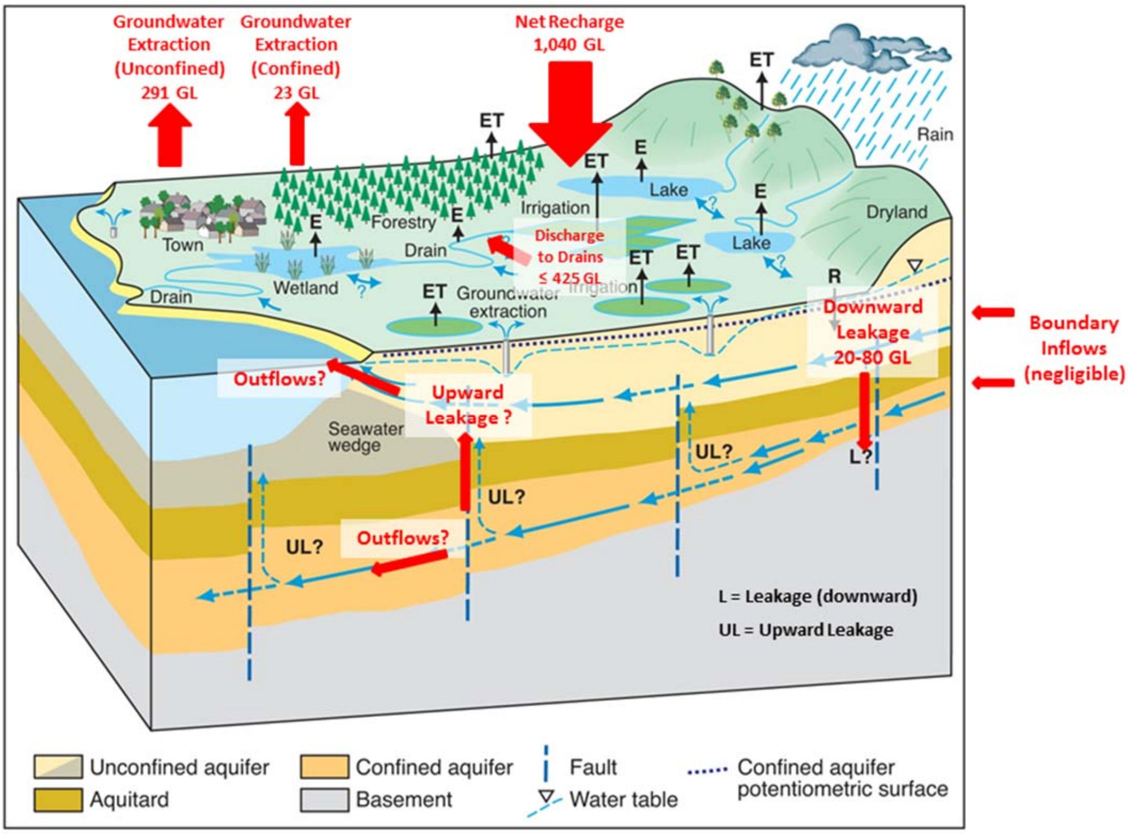


Figure 2.19 Schematic of the water balance conceptualisation showing estimates of water balance components

Table 2.5 Estimates of water balance components

Water Balance Component	Inflow (GL/y)	Outflow (GL/y)
Unconfined Aquifer		
Groundwater fluxes at inland boundary	negligible	0
Net recharge	1,040	
Upward leakage from confined aquifer	?	
Outflows:		
Groundwater extraction		291
Total discharge to drains (coastal outflows + evaporation)		≤ 425
Downward leakage to confined aquifer		20-80
Outflows at coastal or submarine groundwater discharge (SGD)		?
Total	**1,040 (+upward leakage from confined aquifer)**	**736 - 796 (+ coastal outflows)**
Confined Aquifer		
Inflows across inland model boundary	negligible	
Recharge from unconfined aquifer	20-80	
Groundwater Extraction		23
Upward leakage to unconfined near coast		?
Submarine groundwater discharge (SGD)		?
Total	**20-80**	**≤ 23 (+ SGD)**

Table 2.5 suggests that:

- Coastal outflows from the unconfined aquifer could be of the order of 250-300 GL/y.
- Submarine groundwater discharge from the confined aquifer would be much lower than that from the unconfined aquifer and, in fact, could be negligible.
- For the unconfined aquifer, groundwater extraction is a small percentage of recharge.
- The current level of groundwater extraction from the confined aquifer may be close to the volume of water that recharges the aquifer via leakage from the unconfined aquifer each year.
- There are still large knowledge gaps relating to the regional water balance.

The water balance estimates presented above contain a large amount of uncertainty, particularly in the rate of inter-aquifer leakage. The flux of downward leakage from the unconfined aquifer to the confined aquifer could be much larger or much smaller than that estimated above due to large uncertainties in the spatial variability of leakage rates and the area over which this process occurs. Additionally, the rate of upward leakage from the confined aquifer to the unconfined aquifer near the coast (if any) is not known.

3 LEACHM Recharge Modelling

3.1 The LEACHM Model

LEACHM was used, in combination with field based estimates of recharge, to explore unsaturated zone processes leading to recharge. LEACHM is a one-dimensional soil water and chemical fate and transport model for simulating the transport of pesticides (LEACHP), nutrients (LEACHN) and salinity (LEACHC) (Hutson, 2003; Jabro et al., 2011). Water flow is described either by a capacity (tipping-bucket) model or by a mechanistic (Darcy-based Richard's) model. The mechanistic model was used in this work. LEACHM has been compared to other 1D codes (Nolan et al., 2005) and has been used previously as a regulatory model for pesticide registration (e.g. PMRA, 2004) and to estimate recharge in other water resource assessments (e.g. Swancar and Lee, 2003; Ordens et al., 2014).

LEACHG, a GIS-linked version of LEACHM (Hutson et al, 1997) aims to assess regional behaviour. First developed for farm-scale simulations (Hutson et al., 1997) as part of the New York City Watershed project, advances in computer technology have enabled its application to larger and more complex regional simulations. The stand-alone LEACHM input data file consists of sections describing the simulation period, profile geometry and boundary conditions, soil, vegetation, chemical properties, irrigation and chemical management and weather. Each of these data components vary spatially, defined by GIS rasters based on state soil and land use maps, along with spatially interpolated weather data. In addition, features such as water table depth and land surface slope class etc. may also be applied to the model in GIS format. In LEACHG, each of the data file components are selected from a library of input data files linked to raster ID values. For example, if a land use raster cell has an ID of 23, then LEACHG will read data from a library file named Crops.023. Initially, the model reads all relevant rasters, identifies unique combinations of soil, land use and weather, and performs a single simulation of each combination for the defined time period. A complete set of LEACHM output files are generated for each simulation, identified by the raster ID values that are used to name the files. Post-processing generates rasters of any desired output variable, such as drainage from the soil profile, actual evapotranspiration or irrigation applications, produces summaries of water mass balance components both in terms of water depths and volumes, and generates input data files for the groundwater model MODFLOW.

LEACHNG, the nutrient version of LEACHG was used in a previous project to assess the risk of nitrogen and pesticide contamination in the Lower South East (Fleming and Hutson, 2014). In this project LEACHPG, the pesticide version, was used as the chemistry component could be reduced to a single tracer, simplifying the input data and decreasing execution time.

A general schematic of the recharge processes simulated by LEACHM are illustrated in Figure 3.1.

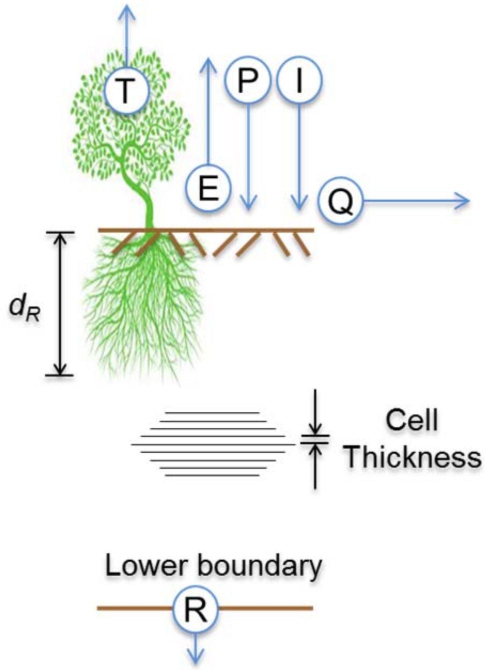


Figure 3.1 Schematic of the LEACHM model applied to recharge estimation, where T is transpiration, E is evaporation from bare soil, P is precipitation, I is irrigation, Q is direct runoff, R is recharge and d_R is the vegetation rooting depth (from Werner et al., 2014).

3.2 Application of LEACHM to the South East

3.2.1 SPATIAL DATASETS USED

Rasters describing soils, land use and weather were the primary spatial information used in the application of LEACHM to the current project. Each of these coverages was simplified in order to limit the number of combinations to be simulated to less than about 2,500. SILO Data Drill weather data was obtained for 37 equal-sized rectangles across the area, and the available soil map was simplified to depict only five textural classes. Land use or vegetation classes were derived from land use maps for 1969, 1983, 1998 and 2008. This allows for the impact of land-use change to be assessed. The 1969 and 1983 land use maps were constructed as part of this project and are considered to be preliminary land use maps for those times (Harrington et al., 2015). The 1998 and 2008 land use maps were obtained from DEWNR.

3.2.2 LAND USE CLASSES FOR TRANSIENT MODELLING

The original land use classes provided in the various land use maps were amalgamated into classes thought to have similar water mass balance characteristics such as plant growth period, transpiration and rooting depth. Simulations were performed for the time periods defined in Table 3.1 for each of these land use maps. In addition, a continuous simulation for the period 1955 to 2013 was carried out using land use classes that reflected temporal sequences in land use change over this period, based upon the application of land use maps to time periods, as shown in Table 3.1, and the development of transient land use classes from the information provided in Tables 3.2 and 3.3.

Table 3.1 Land use maps and periods of application in the LEACHM recharge model.

Model Period	Land Use Map	Comments
1960 – 1982	1969 map	This land use map was constructed by modifying the 2008 land use map based on interpretation of historic aerial photos dating from 1960 to 1983 (Harrington et al., 2015). Photos were not available for northern and Victorian parts of the study area, and the 2008 land use map was used for these areas.
1983 – 1993	1983	Simple modifications were made to the 1969 land use map to reflect major changes in land cover (Harrington et al., 2015), which include: • The expansion of vines in the Coonawarra and Padthaway regions that occurred during the 1980s. Vineyard areas were expanded to match the 1998 map. • The destruction of forest areas following the Ash Wednesday bushfires on 16 Feb 1983. These “burnt out” areas were assumed to have similar recharge characteristics to cleared areas until replanting was completed in the early 1990s.
1994 – 2003	1998	This map included the first of the blue gum plantations, which were established in 1987 to 88 on previously grazed areas. Bluegum plantations expanded significantly between 1990 and 1995/96. In the Border Designated Area Zones 1B, 2B and 3B significant plantation forestry development replaced pasture between 1992 and 2002.
2004 – 2013	2008	The most recent State land use map available.

The available State land use classifications are based on the Australian Land Use and Management Classification (ALUM). However, land use map categories change over time and there is no guarantee that successive land use maps were classified in the same way. Also, the level of detail in classification from 1969 to 2008 is very different. For the purpose of understanding the regional water balance, the land use classifications used should reflect the characteristics of land use and management that influence the soil water balance and hence recharge predictions. Therefore, land use categories were amalgamated into a smaller number of groups, each considered to behave in a hydrologically similar way. As an example, the groupings applied to the 1969 land use map are shown in Table 3.2. The new “burnt out” land use classification introduced in the 1983 land use map (see Table 3.1) was included in the “Grazing modified pastures” land use class as these two classes are likely to have similar recharge characteristics.

Table 3.2 Land use codes allocated to land uses, 1969 land use map

Final amalgamated classes and description	Land use description
Null	Intensive animal and plant production, Mining and waste
Other conserved area	Grazing native vegetation, Land in transition, Native vegetation, Nature conservation, Other minimal use, Other protected areas, Scattered native vegetation
Hardwood production	Hardwood plantation, Production forestry
Softwood production	Softwood plantation
Grazing modified pastures	Cleared or modified pasture, Grazing modified pastures
Cropping	Crop or irrigation, Dryland cropping, Interpreted crop
Seasonal horticulture	Dryland horticulture, Interpreted dryland vineyard, Interpreted irrigation
Irrigated modified pastures	Irrigated pastures
Irrigated cropping	Irrigated cropping
Irrigated perennial vine fruits	Irrigated horticulture
Urban residential	Intensive uses (mainly urban)
Rural residential	Rural residential
Water	Water
Young Forestry (almost closed canopy	Young Forestry (almost closed canopy)
Young forestry (seedling)	Young Forestry (seedling)
Cleared	Cleared for Forestry, Newly Cleared, Recently Cleared

Initially, simulations were performed separately using the 1969 land use map (and classifications in Table 3.2) for the period 1960 to 1975 and the 2008 map for the period from 1970 to 2013. Later, the land use categories were simplified further and applied across the study time period using the 1969, 1983, 1998 and 2008 land use maps as described in Table 3.1, so that the land use classes reflected changing practices over time. To do this, the four land use rasters were analysed to identify the unique combinations of land uses over time. A maximum of about 30 land use combinations is feasible; 30 land use types x 37 weather areas x 5 soil types leads to a maximum of 5,550 combinations to be simulated by LEACHM. Not all of these combinations are realised, as all land uses and all soils do not occur in every weather area. In order to restrict the number of simulations to between about 1,200 and 2,500 (for reasonable processing time), the number of land uses was reduced. The simplified land use categories adopted are shown in Table 3.3. Continuous grazing covered 51% of the area, and 15% of the land area was continuously covered by native vegetation. Six land use combinations cover 88% of the study area and the remaining 12% of the study area is occupied by 22 land use combinations.

Table 3.3 Simplified land use classes adopted for the transient LEACHM simulations.

1960 to 1981	1982 to 1993	1994 to 2003	2004 to 2013	Cumulative % of total area
Grazing	Grazing	Grazing	Grazing	50.7
Natural Vegetation	Natural Vegetation	Natural Vegetation	Natural Vegetation	65.5
Crops	Crops	Crops	Crops	74.6
Water	Water	Water	Water	79.9
Forest	Forest	Forest	Forest	85.2
Natural Vegetation	Natural Vegetation	Grazing	Grazing	87.7
Built	Built	Built	Built	89.6
Grazing	Grazing	Grazing	Forest	91.1
Grazing	Grazing	Forest	Forest	92.2
Grazing	Grazing	Grazing	Irrigated Pasture	93.1
Natural Vegetation	Cleared	Grazing	Grazing	93.8
Natural Vegetation	Natural Vegetation	Forest	Forest	94.6
Forest	Cleared	Forest	Forest	95.3
Irrigated Pasture	Irrigated Pasture	Irrigated Pasture	Irrigated Pasture	95.8
Grazing	Grazing	Irrigated Pasture	Irrigated Pasture	96.4
Grazing	Grazing	Grazing	Crops	96.9
Cleared	Cleared	Forest	Forest	97.4
Grazing	Grazing	Grazing	Irrigated Vines	97.9
Natural Vegetation	Cleared	Natural Vegetation	Natural Vegetation	98.3
Irrigated Crops	Irrigated Crops	Irrigated Crops	Irrigated Crops	98.6
Crops	Crops	Crops	Irrigated Pasture	98.8
Natural Vegetation	Natural Vegetation	Grazing	Forest	99.1
Grazing	Grazing	Grazing	Irrigated Crops	99.3
Grazing	Irrigated Vines	Irrigated Vines	Irrigated Vines	99.5

Natural Vegetation	Natural Vegetation	Crops	Crops	99.7
Natural Vegetation	Natural Vegetation	Natural Vegetation	Grazing	99.8
Irrigated Vines	Irrigated Vines	Irrigated Vines	Irrigated Vines	100.0
Crops	Crops	Crops	Irrigated Crops	100.0

3.2.3 WATER TABLE AND VEGETATION PARAMETERS

LEACHM simulations for all soil, land use and weather combinations were performed both with and without a water table to assess the influence of the lower boundary condition on predictions. Water table lower boundary conditions allow for simulation of the upward flow of groundwater to the unsaturated zone, whereas simulations with a free drainage lower boundary condition neglect any upward flow of groundwater into the unsaturated zone. Two sets of water table simulations were conducted, one set having a water table at 2.4 m (following Fleming and Hutson, 2014) and a second set, using 5 m soil profiles, having the water table at 5 m. A water table lower boundary condition produces recharge estimates that are termed 'net recharge' in this report. This is recharge minus groundwater evapotranspiration. A free-drainage lower boundary condition produces recharge estimates that are termed 'gross recharge'. This is recharge where groundwater evapotranspiration has not been accounted for.

The vegetation parameters applied in the LEACHM model were initially set to those applied by Fleming and Hutson (2014). Those parameters were chosen based upon typical crop requirements and land management practices. Likewise, depths to water table of 2.4 m and 5 m were considered to encompass shallow water tables in the South East. In the current project, comparisons of modelled evapotranspiration with a map of evapotranspiration derived from the MODIS CMRSET dataset (Guerschman et al., 2009; see Section 2.4.1), and assessment of the result in the context of vegetation parameters, led to some adjustments, particularly relating to water table depth and crop coefficients. Likewise, a comparison of LEACHM irrigation applications with actual metered groundwater extraction data at the Management Area scale provided some insight into the representativeness of LEACHM's irrigation applications and whether adjustments to crop parameters were required. The details of these comparisons are reported by Morgan et al. (2015).

A comparison of modelled ET with the CMRSET data, along with the comparison of modelled irrigation with metered irrigation extraction data suggested that modelled irrigation to drip irrigated vineyards was too high. A comparison between the 1D simulations and a 2D LEACHM simulation of drip irrigation, in which the spatial pattern of infiltration under drippers can be better simulated, suggested that the irrigation requirement under drip irrigation may be only 50 to 60% of that under conventional sprinkler or flood irrigation. As this reduction is caused primarily by the reduction in surface evaporation, this was represented in the 1D model by increasing the surface mulch, effective only while the crop is active. This reduced the irrigation requirement of vines and reduced evapotranspiration. In the final simulations, the surface mulch applied to vineyards was increased in a gradual way to represent increasing irrigation efficiencies over time.

The final vegetation parameters used in the LEACHM model are shown in Appendix C.

A highland clearance recharge lag was represented by commencing a set of simulations in 1955, i.e. before land clearing occurred, using a pre-1960 land use map to identify areas that were cleared only during the 1960's. In these areas native vegetation was defined until 1964, after which the land use defined in the 1969 land use map was imposed. By using a 5 m soil profile a time lag between clearing and the increased drainage from the root zone reaching the water table could be represented.

3.3 Results of the LEACHM Modelling

Spatial datasets of gross recharge were developed for MODFLOW that were suitable as inputs for both the steady-state model and the transient model. Gross recharge is defined as unsaturated zone drainage to the water table. Net recharge was not used because groundwater evapotranspiration is calculated within MODFLOW using the EVT package. The spatial distribution of steady-state gross recharge, calculated as the average of the period January 1965 to December 1974, is shown in Figure 3.2. This equates to a total recharge of 3,536 GL/y, with an average rate of 137 mm/y over the study area. Transient gross recharge (monthly averages) for the period January 1970 to December 2013 is shown in Figure 3.3 (note the units of mm/y and GL/y).

Annual average gross recharge was calculated for each year from 1970 to 2013, over which time the average gross recharge is 123 mm/y (3,158 GL/y). The cumulative annual gross recharge deviation from the long-term average gross recharge is also shown in Figure 3.4. The cumulative deviation plot shows a rising trend (above average net recharge and rainfall) for the period 1970 to 1992 and a falling trend for the period 1992 to 2008. From 2008 to present, relatively stable conditions are apparent.

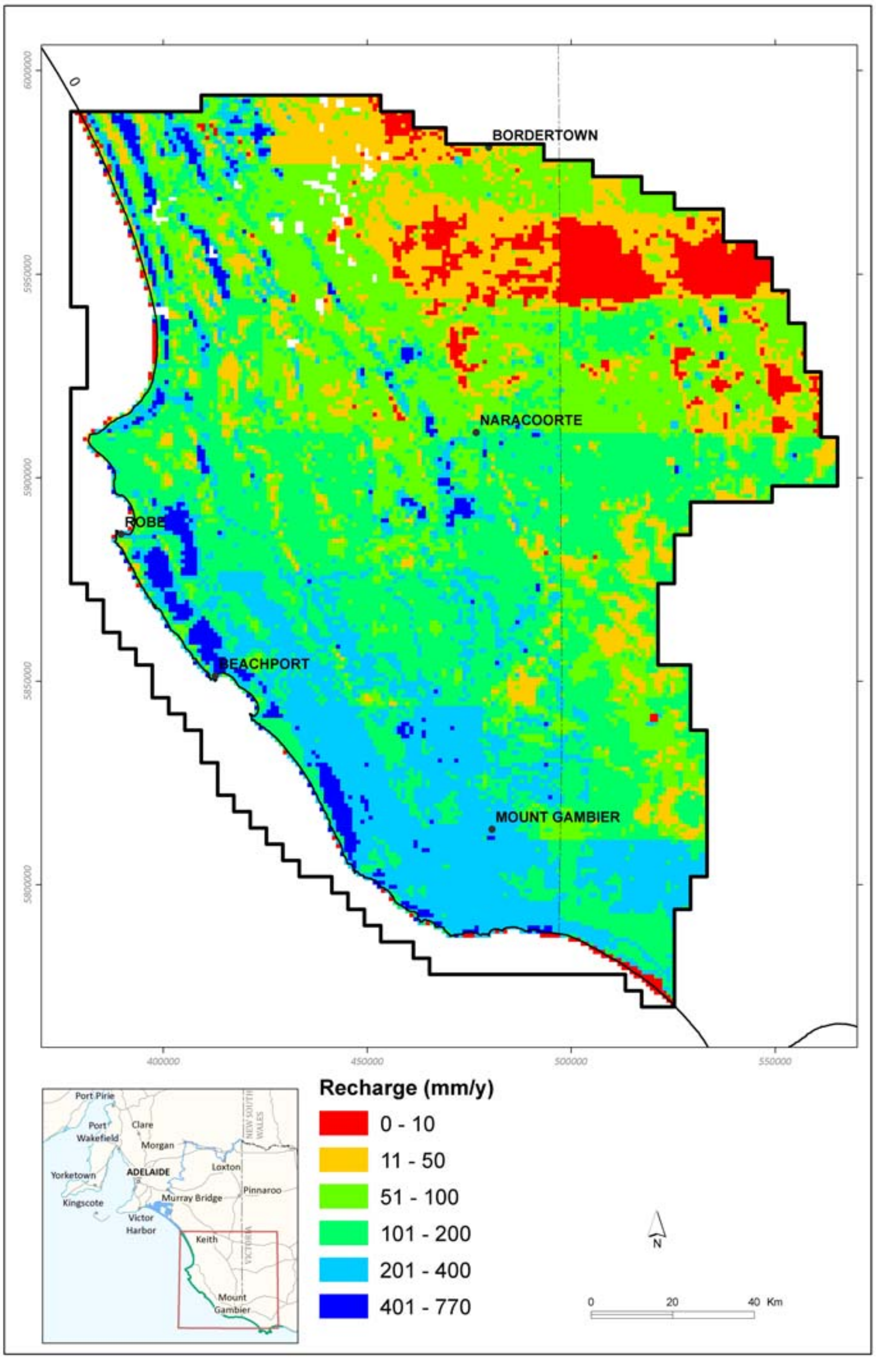


Figure 3.2 LEACHM gross recharge for the steady-state condition (January 1965 to December 1974 decadal average)

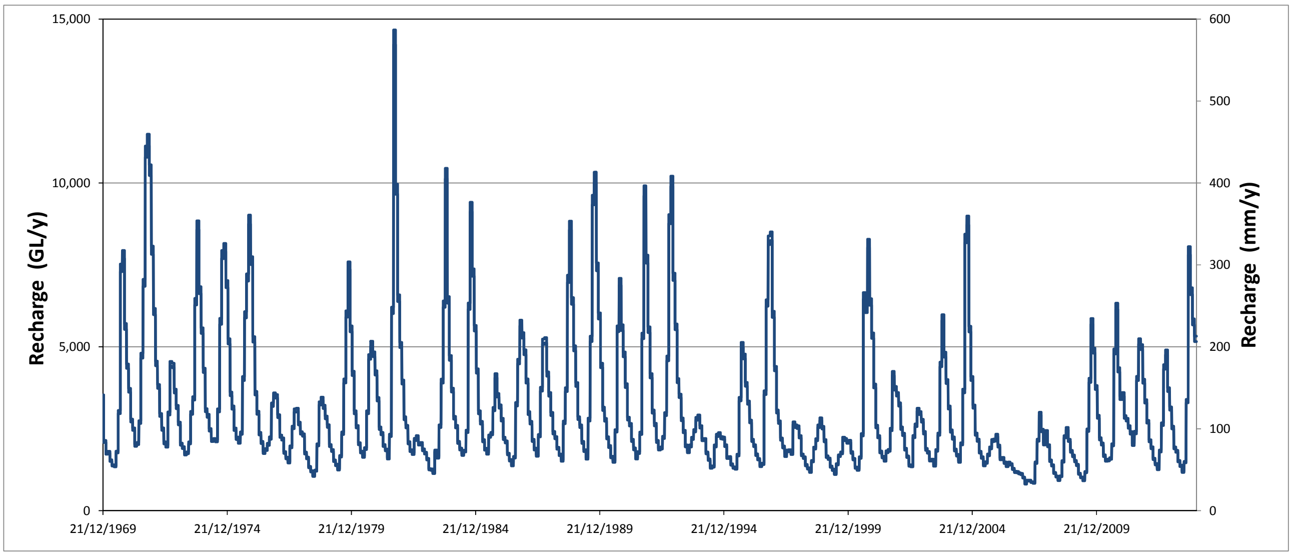


Figure 3.3 LEACHM gross recharge (monthly) for the period January 1970 to December 2013

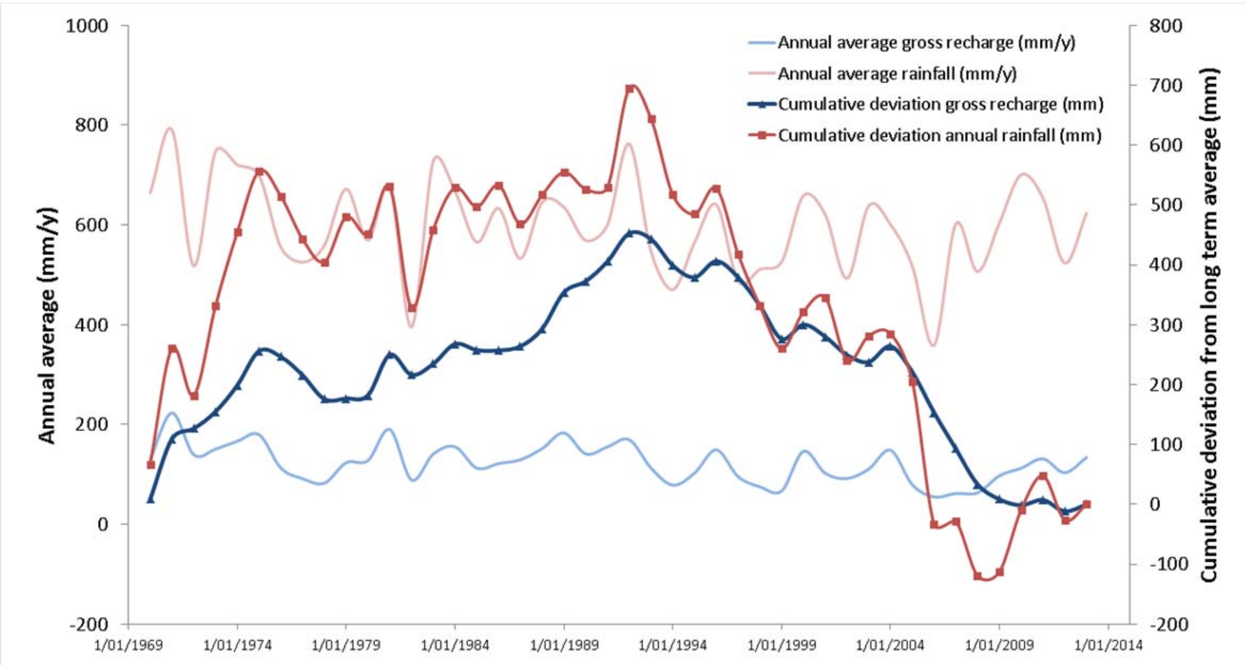


Figure 3.4 Annual average gross recharge and rainfall as well as the cumulative annual average deviation from the long-term average for net recharge and annual rainfall

3.4 Assumptions and Limitations of the LEACHM Model

Due to the assumptions in both the model, in particular, the application of spatial input data, the spatial simulations reflect approximate spatial and temporal variation of soil water balance and drainage from the profile. Assumptions made when applying LEACHM to large regional simulations include:

- Natural systems have large spatial variability which cannot be captured entirely by a discrete number of realizations of a 1D model.
- Plant growth in LEACHM is pre-defined and not explicitly simulated – i.e. plant health and growth does not respond to soil water availability. This means that although transpiration may be limited

when soil water becomes depleted, there is no feedback between soil and weather conditions and current and future plant growth.

- Plant growth parameters, especially crop cover and root growth patterns, the crop coefficient for adjusting reference ET and the extent of surface mulching, have a strong element of subjectiveness in setting their values in LEACHM.
- Equating drainage from the simulated soil profile to recharge can be simplistic. In this work, LEACHM's drainage excluded any surface runoff to quick-flow channels.
- Soil profile variability can have a large significant influence on soil water balances. These simulations have allocated soils to only five profiles which are uniform and neglect soil profile heterogeneities.
- Water tables, when present, are defined at a constant depth, whereas in reality, the depth to the water table is spatially variable and changes in response to seasonal variations of weather and water balance.

4 MODFLOW Model Development

4.1 Code Selection

MODFLOW was used in this study. MODFLOW is a three-dimensional finite-difference code (McDonald and Harbaugh, 1988; Harbaugh et al., 2000; Harbaugh, 2005), and is used widely within the groundwater industry to investigate regional-scale applications where water density variations and the unsaturated zone can be essentially neglected in groundwater flow calculations. The version of MODFLOW used was MODFLOW-NWT (Niswonger et al., 2011), an extension of MODFLOW-2005 (Harbaugh, 2005) that is capable of simulating de-saturation and re-saturation of unconfined aquifers in a robust manner. Input files for MODFLOW were generated using the graphical user interface Groundwater Vistas Version 6.4 (GV; Environmental Simulation Systems, Inc., 2010), which served as both the pre- and post-processing platform.

4.2 Model Architecture and Numerical Options

The model domain covers an area of 42,112 km^2, 224 km north-south by 188 km east-west. The bounding coordinates of the model domain are (MGA Zone 54): E377,300 m, N5,770,000 m in the south-west and E565,300 m, N5,994,000 m in the north-east. The rectangular model grid is orientated north-south. The domain is divided into 188 columns, 224 rows and three layers, which, accounting for inactive cells that are outside the study area and within the study domain representing areas of basement outcropping, incorporates 75,260 active finite-difference cells. All of the cells have a uniform dimension of 1,000 x 1,000 m in the horizontal plane. A coarse grid was used to reduce run times in the transient model. The model domain, grid and boundary conditions for layer 1 and layer 3 is shown in Figure 4.1 and Figure 4.2, respectively. The model domain, grid and boundary conditions of layer 2 are the same as that of layer 3, except that layer 2 has a no flow boundary at the coast.

Both steady-state and transient conditions were simulated. Steady-state models provide an approximation of the long-term groundwater levels under unchanging conditions, and are used to estimate initial conditions for transient simulations. The steady-state model was based on the average conditions during January 1965 to December 1974. That is, the decadal average recharge and groundwater extraction were applied within the steady-state model and decadal average water levels were used as a target during calibration. It is acknowledged that conditions were not unchanging in the South East during this period, however, hydrographs are reasonably stable compared to more recent decades. Water levels for a pre-development period (i.e., pre-1880) are not available. The transient model adopts monthly stress periods to represent seasonal variations in the potentiometric head and stresses. The transient model was used to simulate a period from January 1970 to December 2013, representing 528 stress periods. Each monthly stress period of the transient model has time steps that successively increase in length by 20%, and there are 10 time steps per stress period.

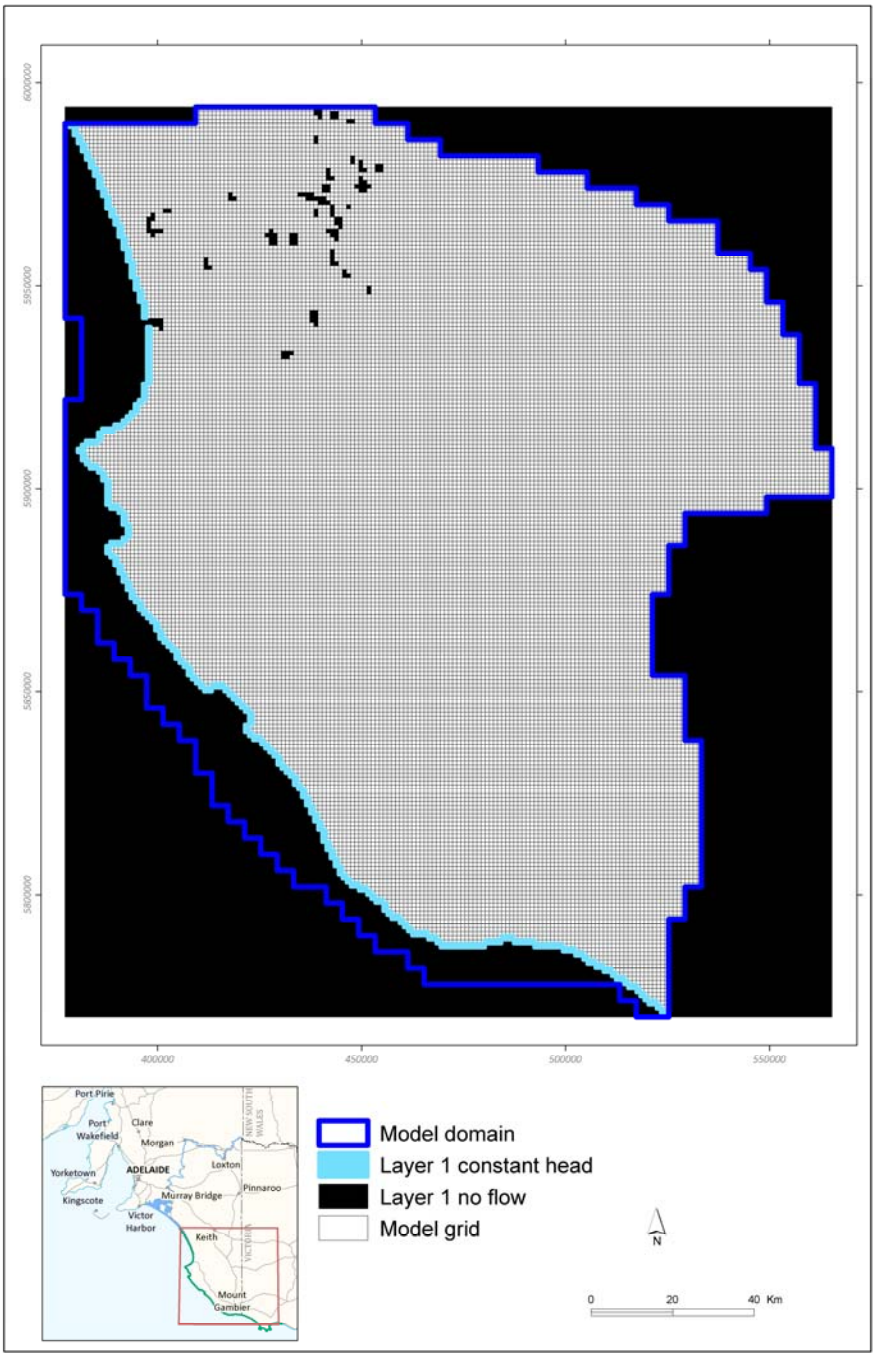


Figure 4.1 Model domain, grid and boundary conditions in layer 1.

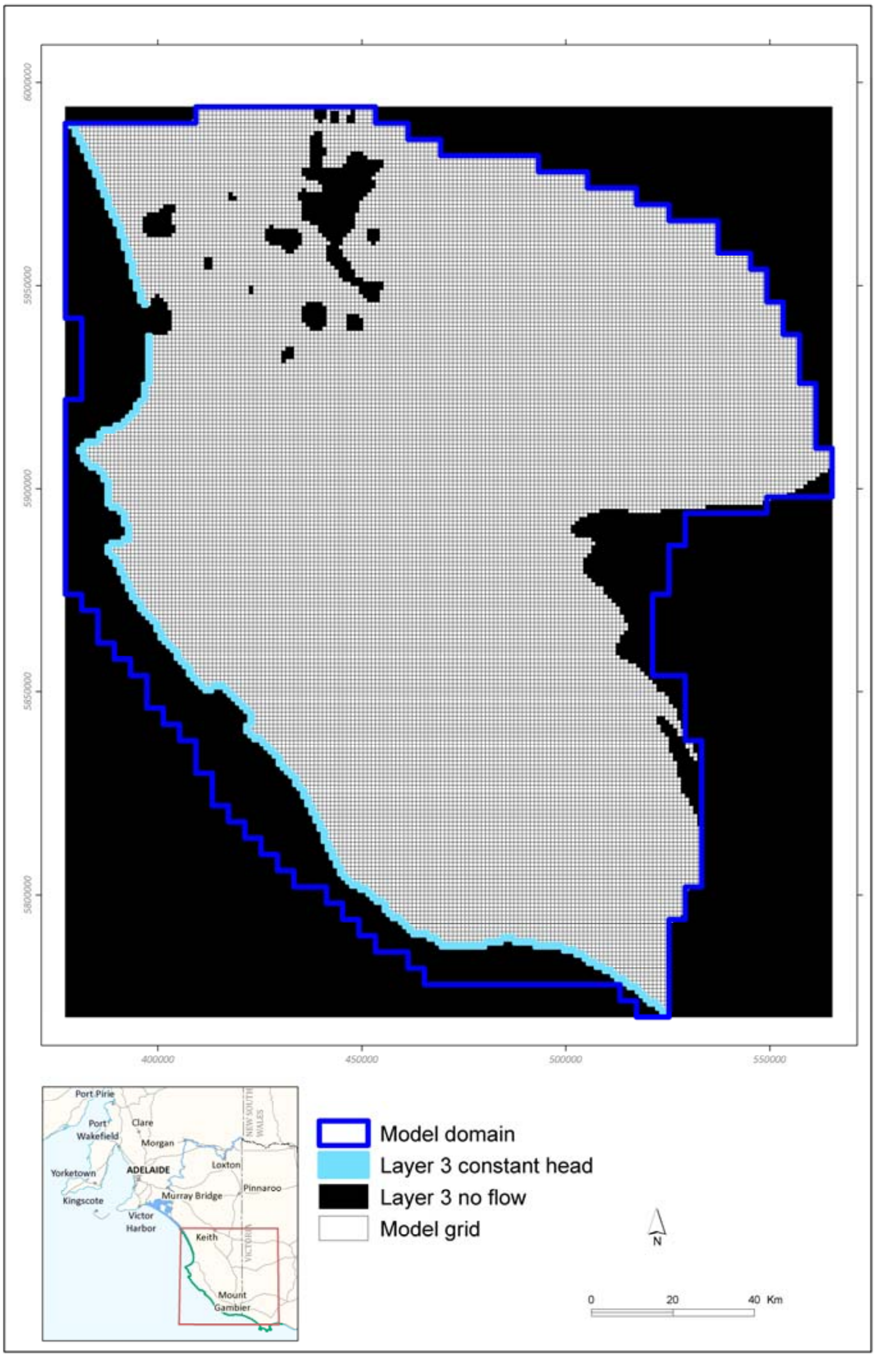


Figure 4.2 Model domain, grid and boundary conditions in layer 3.

The Upstream Weighting Package (UPW) and Newton Solver (NWT), with solver options set to complex, were used for both steady-state and transient simulations. The head change criterion for outer iterations (HEADTOL) was set to 0.0001 m. These options were implemented in the steady-state and transient models.

4.3 Model Layers

The top surface of the model is based on ground surface elevation. A LIDAR-based digital elevation model (DEM) with a 2 m x 2 m cell size was available for the South Australian portion of the study area. This was merged with a satellite-derived DEM with a 25 m x 25 m cell size that covered the Victorian portion of the study area. The resulting merged DEM has a 10 m x 10 m cell size and the cells align with the MODFLOW model cells such that exactly 10,000 DEM cells fit within a MODFLOW model cell. DEM grid statistics were calculated for each MODFLOW model cell using ArcGIS. Statistics include the maximum, minimum, range, mean and standard deviation of DEM values in each MODFLOW model cell.

The DEM range was on average 13.6 m within MODFLOW cells (i.e. a 13.6 m difference, on average, was found between the highest and lowest topographical points of model cells), and varied between -10.7 m and 240 m. The mean DEM value was assigned as the top of layer 1 elevation within the MODFLOW model. The maximum and minimum elevations for the top of layer 1 are 202 m and -6.0 m, respectively.

As described in Sections 1.3.2 and 2.2, the hydrostratigraphy of the study area is complex. It involves two major sedimentary basins: the Otway Basin and the Murray Basin. Various units become very thin or absent in different parts of the domain and the water table passes through a large number of different formations. The extent and thickness of formations are not mapped in detail everywhere in the domain and the interactions between the various aquifers is not well characterised.

A hydrostratigraphic model was developed by DEWNR in collaboration with this project, as detailed within Section 2.2. Stratigraphic layers were grouped into model layers according to their properties as aquifers or aquitards. Model layer 1 (set as Layer Type 1 in the model) includes the Pleistocene/Pliocene Padthaway and Bridgewater Formations as well as the Tertiary Gambier Limestone aquifer. These aquifers are hydraulically connected, except in very small areas where the clayey Coomandook Formation is believed to form a local aquitard, and together form a Quaternary/ upper to-middle Tertiary unconfined aquifer. Layer 2 (set as Layer Type 0) represents an upper-mid Tertiary aquitard. Layer 3 (set as Layer Type 0) was constructed to include units that are considered to form the Tertiary Confined Sand aquifer. These are the Lower Mepunga Formation, the Dilwyn Sand, the Pember Mudstone and the Pebble Point Formation. It has been found in previous modelling studies that there is insufficient data (stratigraphic and hydraulic property) to allow representation of these units as separate model layers in a meaningful way. The geological units represented by these layers are not continuous due to basement outcropping. Layer surface elevations located at the centre of groundwater model cells were used as input to the groundwater model.

4.3.1 EVALUATION OF MODEL LAYER THICKNESSES

Maps of model layer thicknesses were developed using ArcGIS to:

1) Ensure that manipulation and contouring of the data had not resulted in negative layer thicknesses.
2) Develop isopachs for comparison to local expert knowledge of aquifer thicknesses across the study area.

All layers are thickest in the south. Layer 1 is up to 550 m thick in the south and, on average, 100 m thick over the model domain (Figure 4.3). The unconfined aquifer (layer 1) is absent in areas of the north and thin (i.e., less than 10 m) in areas to the north-west of Mt Gambier and in the south-east of the model domain. Layer 2 is up to 150 m thick with an average thickness of 20 m (Figure 4.4). Layer 3 is up to 1,300 m thick with an average thickness of 220 m (Figure 4.5). The aquitard (layer 2) and confined aquifer (layer 3) are absent across extensive areas of the north and east of the model domain. No negative layer thickness values are apparent. Model cells are set as inactive cells in areas where the aquifer or aquitard is absent.

4.3.2 EVALUATION OF SATURATED THICKNESS OF LAYER 1

The saturated thickness of Layer 1 was evaluated to:

1) Identify areas where Layer 1 may be dry in the model.
2) Compare areas where the water table is above the land surface with mapped surface water features.
3) Through (1) and (2) identify any areas of the hydrostratigraphic model that may contain errors.

The datasets used in the evaluation were:

1) Unconfined aquifer observation well data for September 2011 (arbitrarily selected) (Figure 4.6).
2) The top of layer 2 elevation (i.e., base of unconfined aquifer) at a 1 km x 1 km MODFLOW grid spacing.
3) The top of layer 1 elevation (i.e., surface elevation taken from the mean DEM value in each MODFLOW cell) at a 1 km x 1 km MODFLOW grid spacing.

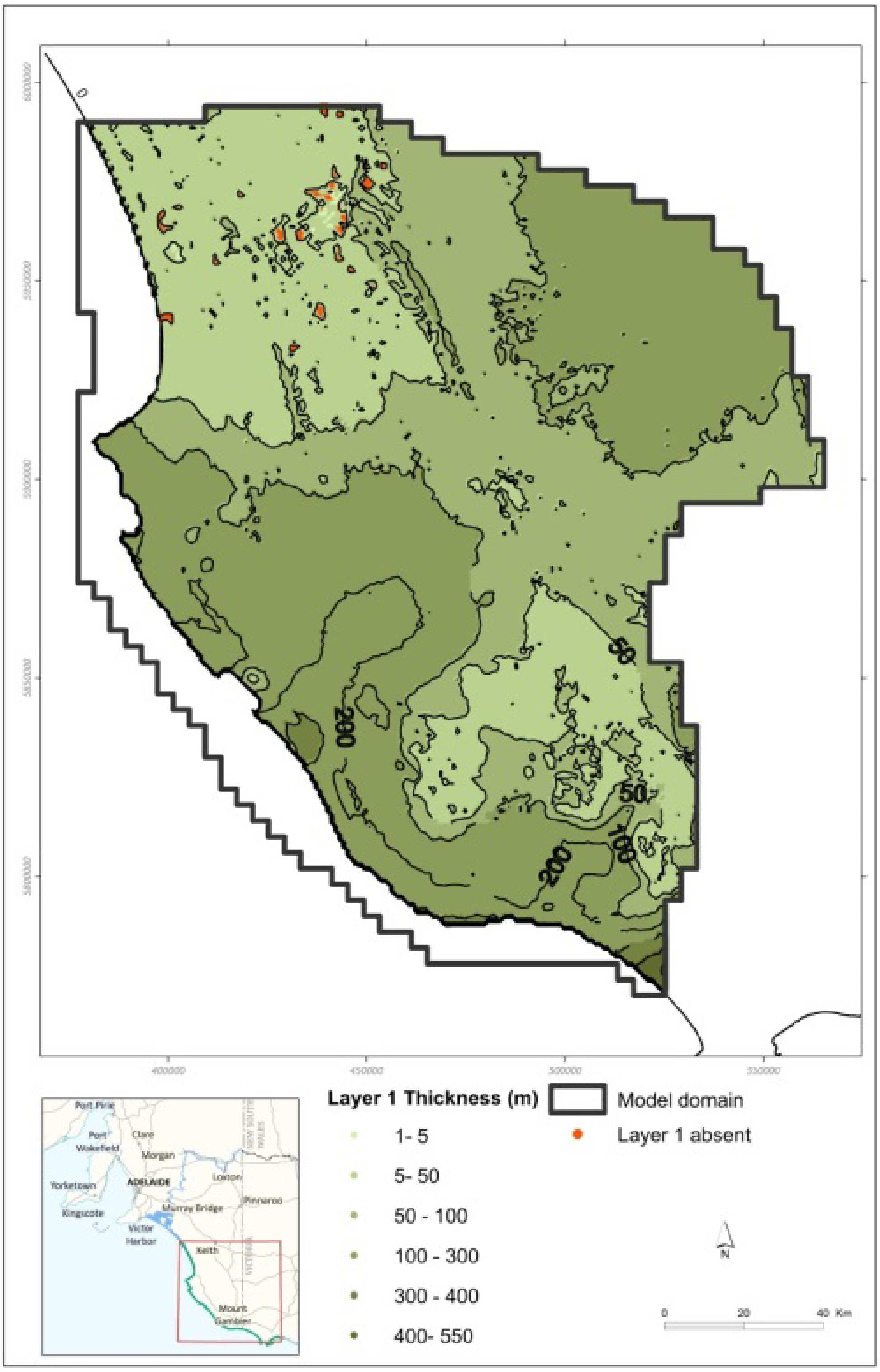


Figure 4.3 Model layer 1 thickness.

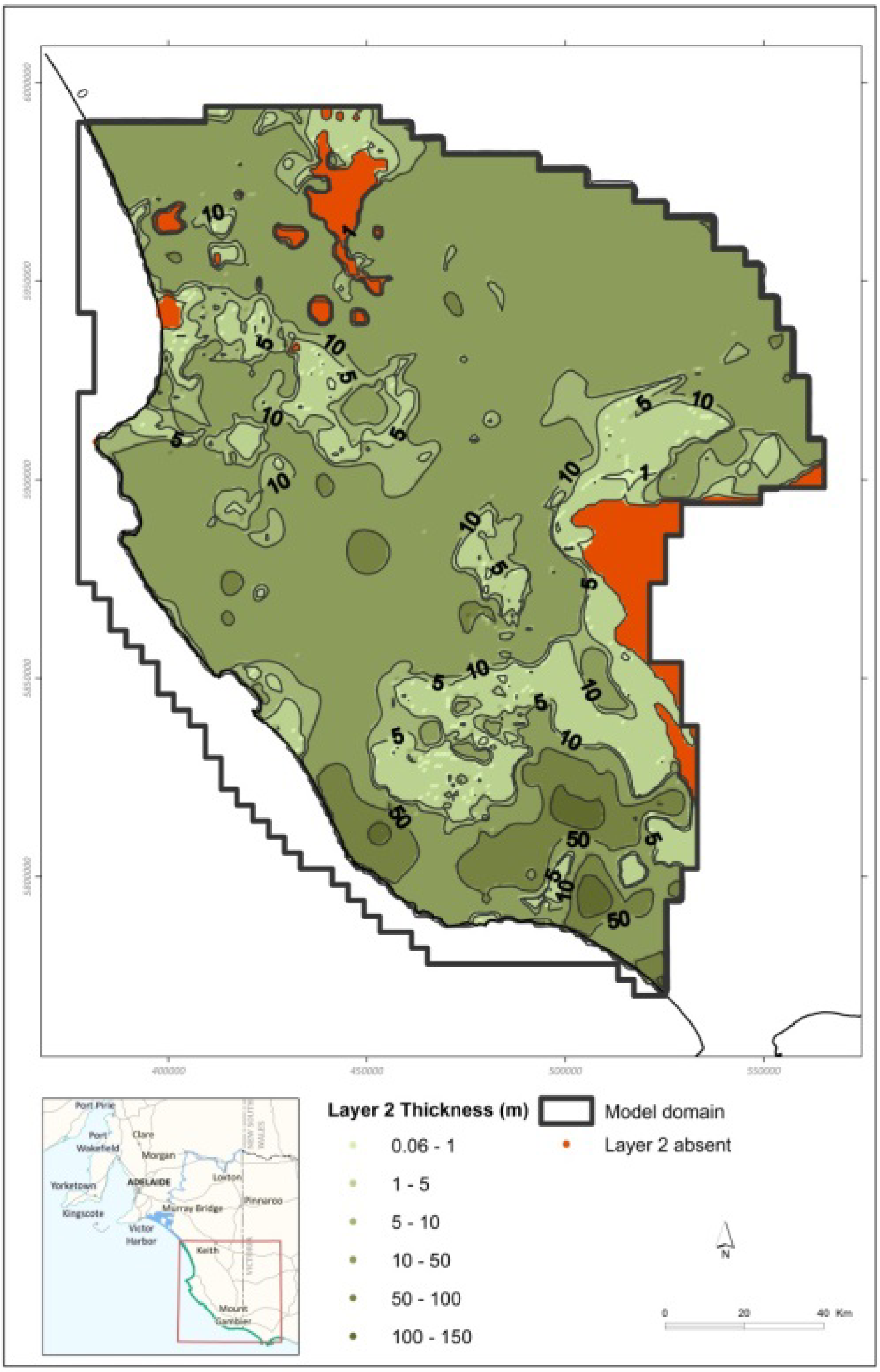


Figure 4.4 Model layer 2 thickness.

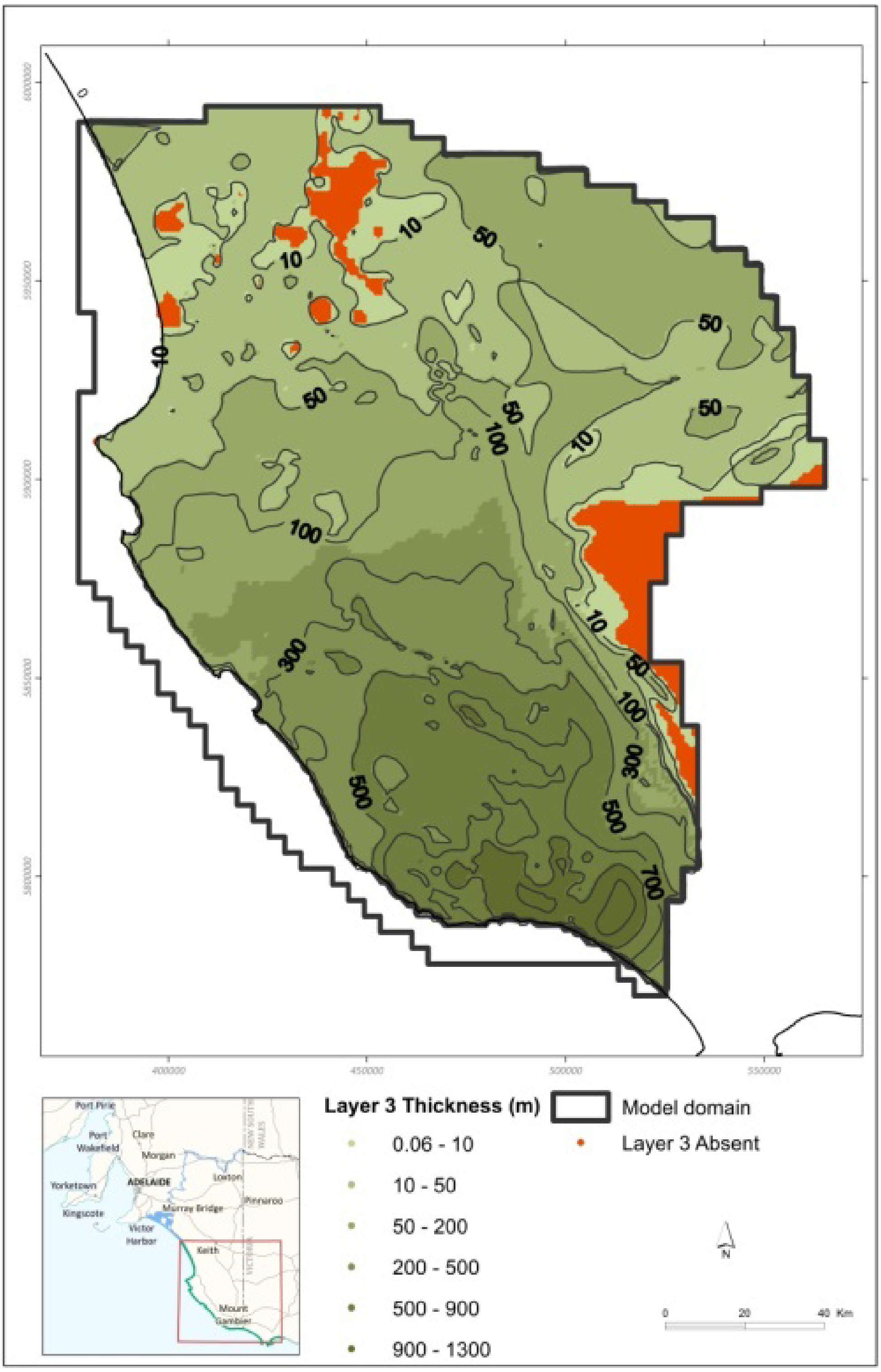


Figure 4.5 Model layer 3 thickness.

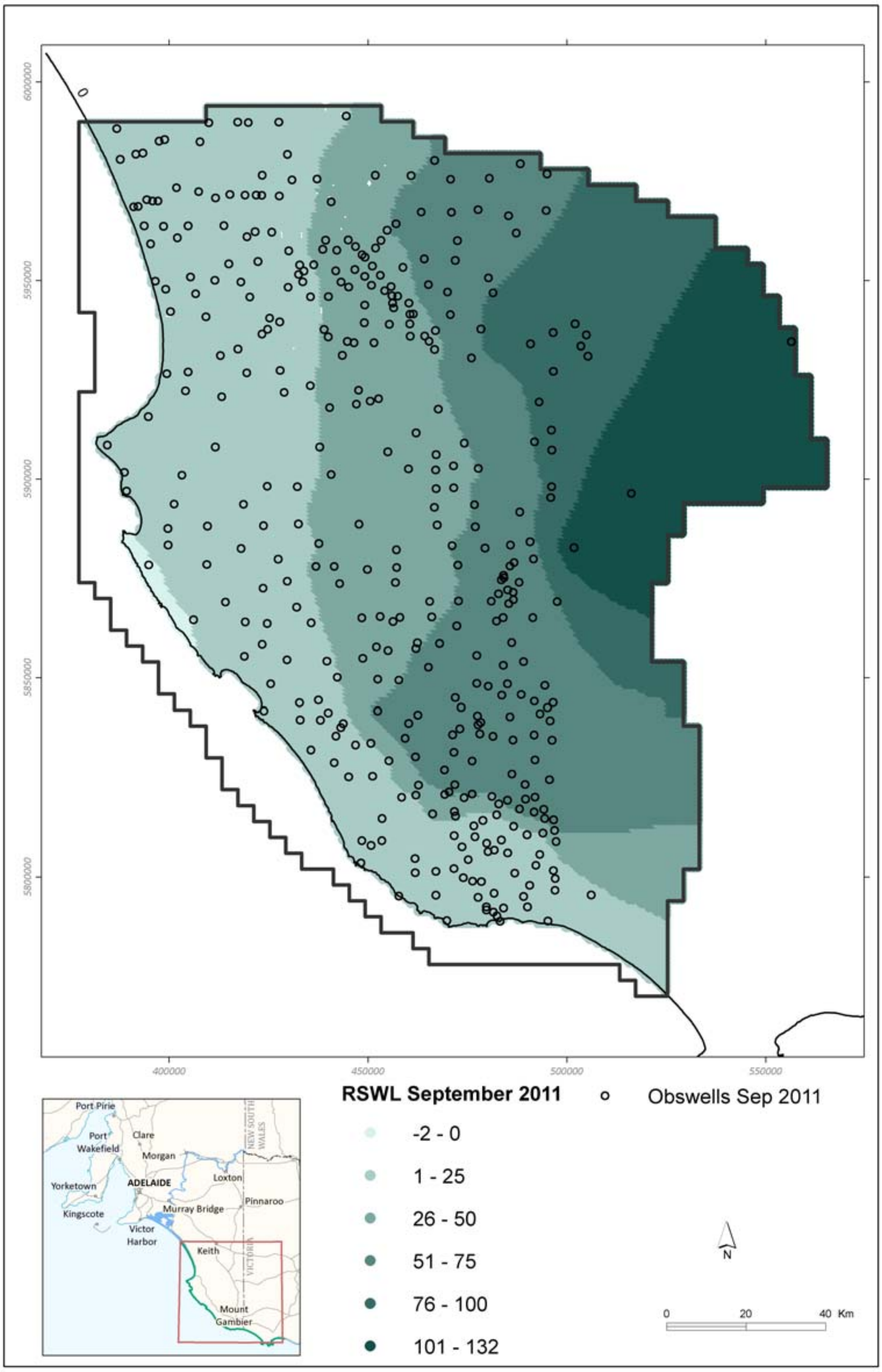


Figure 4.6 Interpolated RSWL (m AHD) for the unconfined aquifer (September 2011).

Figure 4.7 shows the calculated saturated thickness of Layer 1, with dry areas indicated in pink. The analysis indicates two areas in the model domain where the unconfined aquifer may be dry. The first occurs in the north of the model domain, adjacent areas of basement outcrop. The second area, located in the south of the model domain, was investigated more closely. Interpolation of the water table surface was not likely to be a major source of error in this region, as there were data points close to the dry area. DEWNR staff have made some observations in this area, and agree that the saturated thickness of the aquifer can be less than 10 m, although complete dryness has not been observed. This area of potential dryness in the unconfined aquifer has been noted for consideration in the interpretation of groundwater model results. Figure 4.8

shows the depth to water table in Layer 1, with areas where the water table is above land surface identified in pink and red colours. It should be noted that the accuracy of the water table surface is dependent on the reliability and spatial distribution of measurements, which are sparse in places (e.g. in Victoria). Figure 4.9 shows the depth to water table map, with an overlay of the mapped waterbodies for the region. This figure shows that many of the areas where the water table is calculated to be above the ground surface correspond to mapped surface water bodies. However, there are some pink and red areas that do not correspond to mapped surface water bodies, particularly: (a) in the first inter-dunal corridor to the east of Beachport and Robe, and (b) at the base of the Naracoorte Ranges, to the north-west of Naracoorte. Adding an overlay of the man-made surface drainage system and other watercourses for the South Australian portion of the study area (Figure 4.10) identifies the reason why there is no mapped standing water in the GIS layer at (a) when the water table is inferred to be above ground level in the model. This area is drained by a complex system of man-made drains, which will be included as separate features in the groundwater flow model. However, the areas where the model indicates the water table to be above land surface at (b) is not explained by mapped surface water or man-made drainage features. This area is not known to be inundated and the discrepancy is most likely due to interpolation of observation well data between the high elevation Naracoorte Ranges and the adjacent flats, but this area has been identified for close scrutiny of the results of the groundwater flow model. The red area in the south-east (Victorian) portion of the study area is known to correspond to the Glenelg River valley.

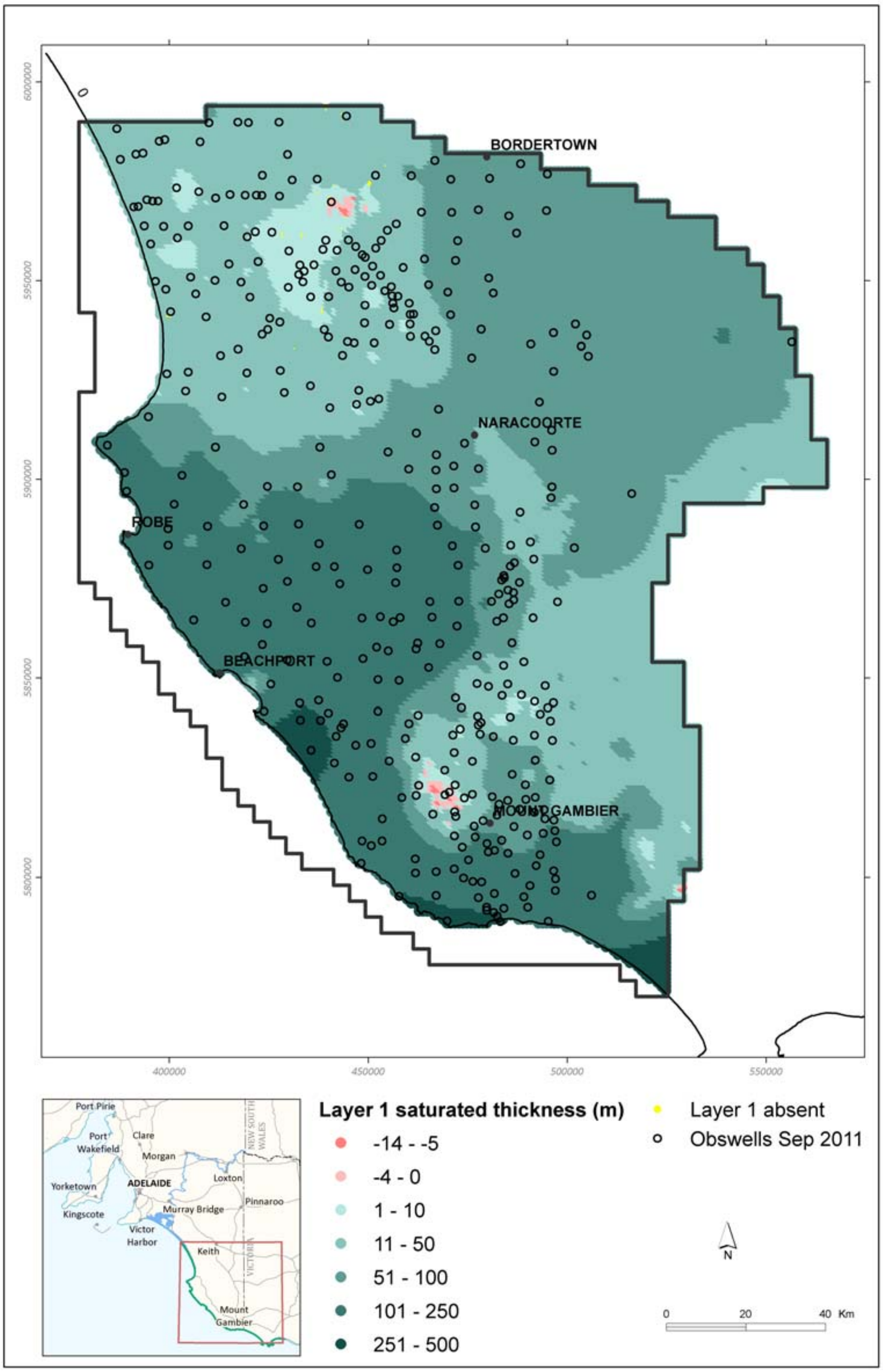


Figure 4.7 Layer 1 saturated thickness, showing dry cell areas as pink.

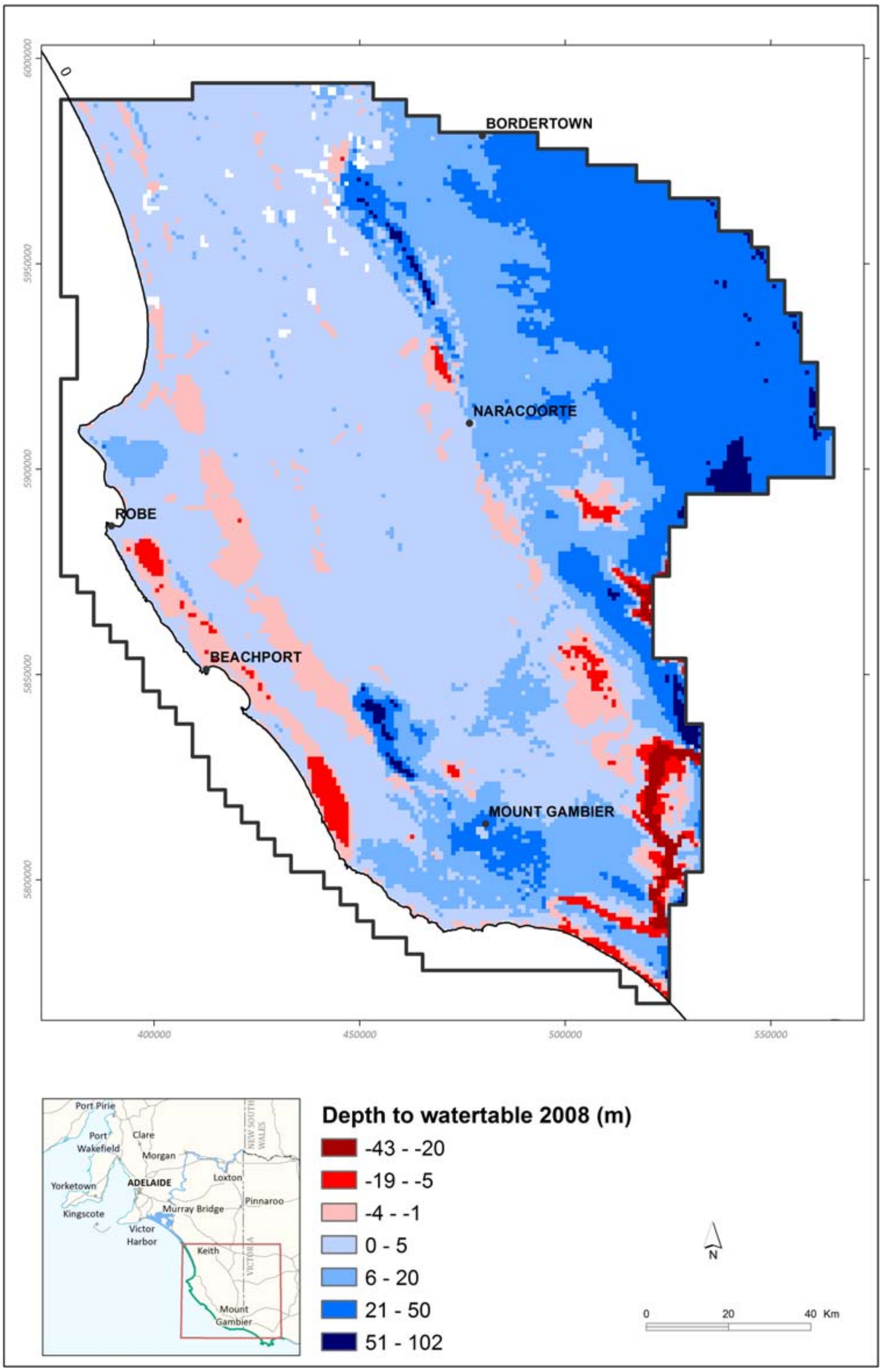


Figure 4.8. Layer 1 depth to water table, showing areas where water table is above land surface.

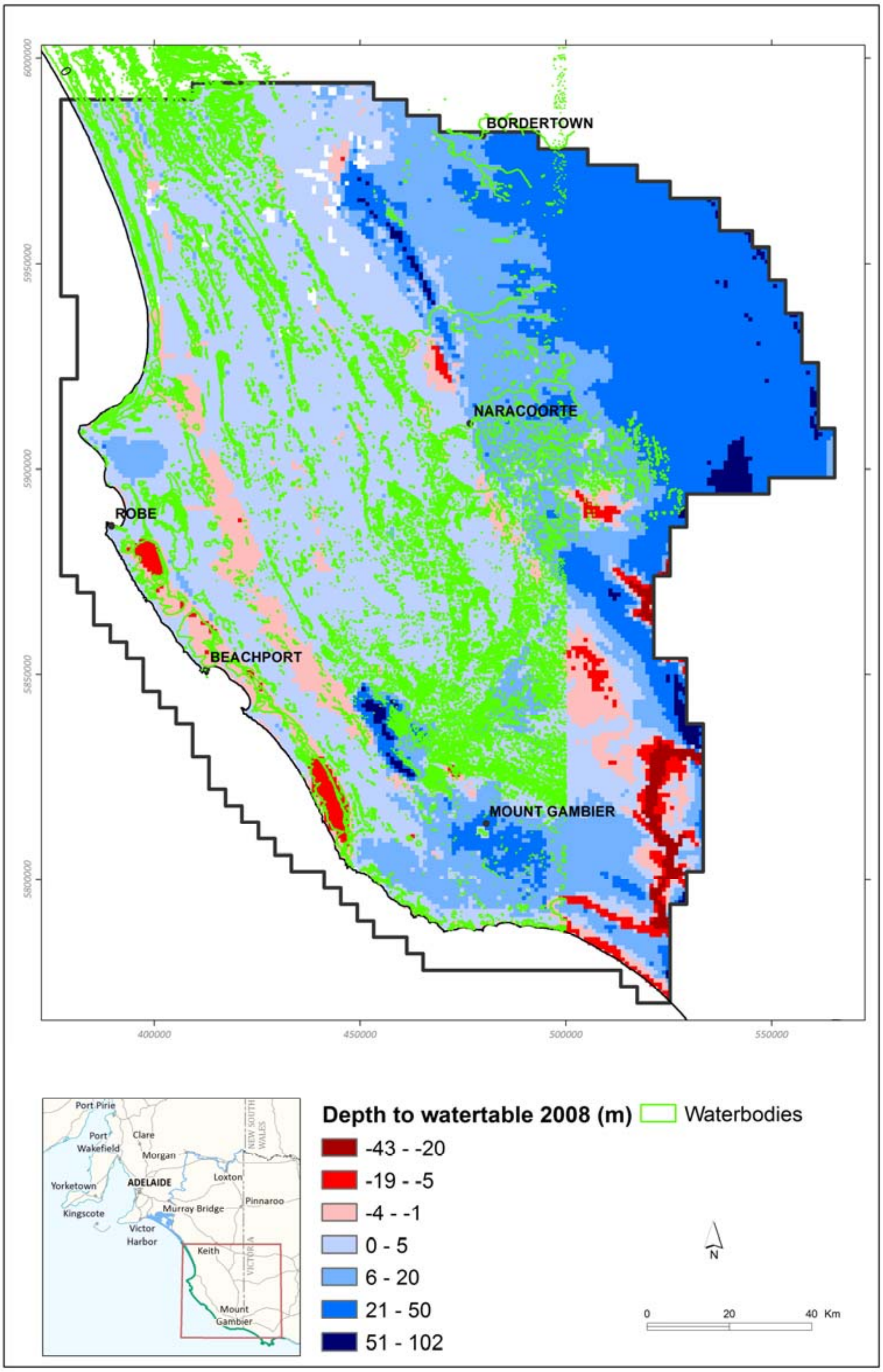


Figure 4.9. Layer 1 depth to water table, showing areas where water table is above land surface and outlines of mapped waterbodies.

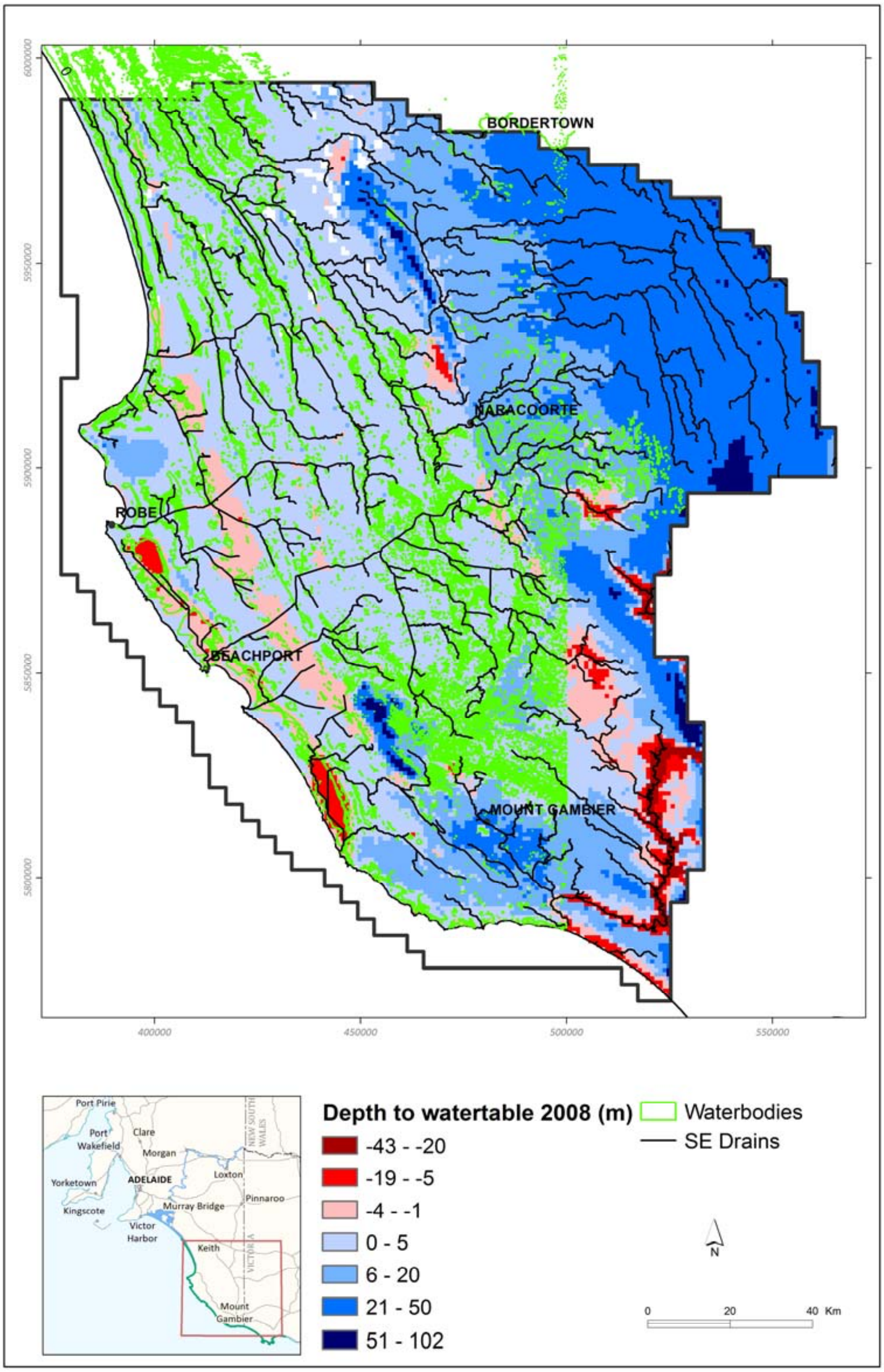


Figure 4.10 Layer 1 depth to water table, showing areas where the water table is above land surface and with outlines of mapped waterbodies, with man-made drains and watercourses also shown.

4.4 Aquifer Hydraulic Parameters

Aquifer hydraulic parameters within layer 1 are subdivided into five zones based on the distribution of geology. The hydrostratigraphic model developed as part of this project (see Section 2.2) was used to identify areas in layer 1 where the Quaternary sediments (i.e., the Bridgewater Formation and Padthaway Formation) comprise more than 70% of the layer thickness of layer 1. These areas were then used to guide zonation, shown in Figure 4.11. The location of the Tartwaup Fault is not well known and flow across this fault is not well characterised. The Tartwaup Fault is not thought to be a linear structure (although drawn as a linear feature in Figure 4.11), but a group of smaller parallel faults. A simple method was used to include the Tartwaup Fault in the model, which involved the addition of a hydraulic conductivity zone at a location that was determined using the fault position shown in Figure 1.1 and measured head contours, which indicate an area of larger hydraulic gradient close to the fault (Figure 2.3). The inclusion of an additional conductivity zone for the Kanawinka Fault was not found to improve model calibration and hence this feature was not included. Layer 2 is treated as a single unit of lower hydraulic conductivity. Layer 3 was divided into four zones (see Figure 4.12) that were developed by amalgamating hydraulic conductivity zones used by Brown (2000) in the Tertiary Confined Sand aquifer model, as well as by considering measured head contours.

Only a handful of pump test data are available in the study area as shown in Figure 2.3 (Layer 1) and Figure 2.4 (Layer 3). Table 4.1 lists the hydraulic parameter bounds/limits that were imparted during calibration. Please refer to Section 2 of this report for the source of observation values listed in Table 4.1.

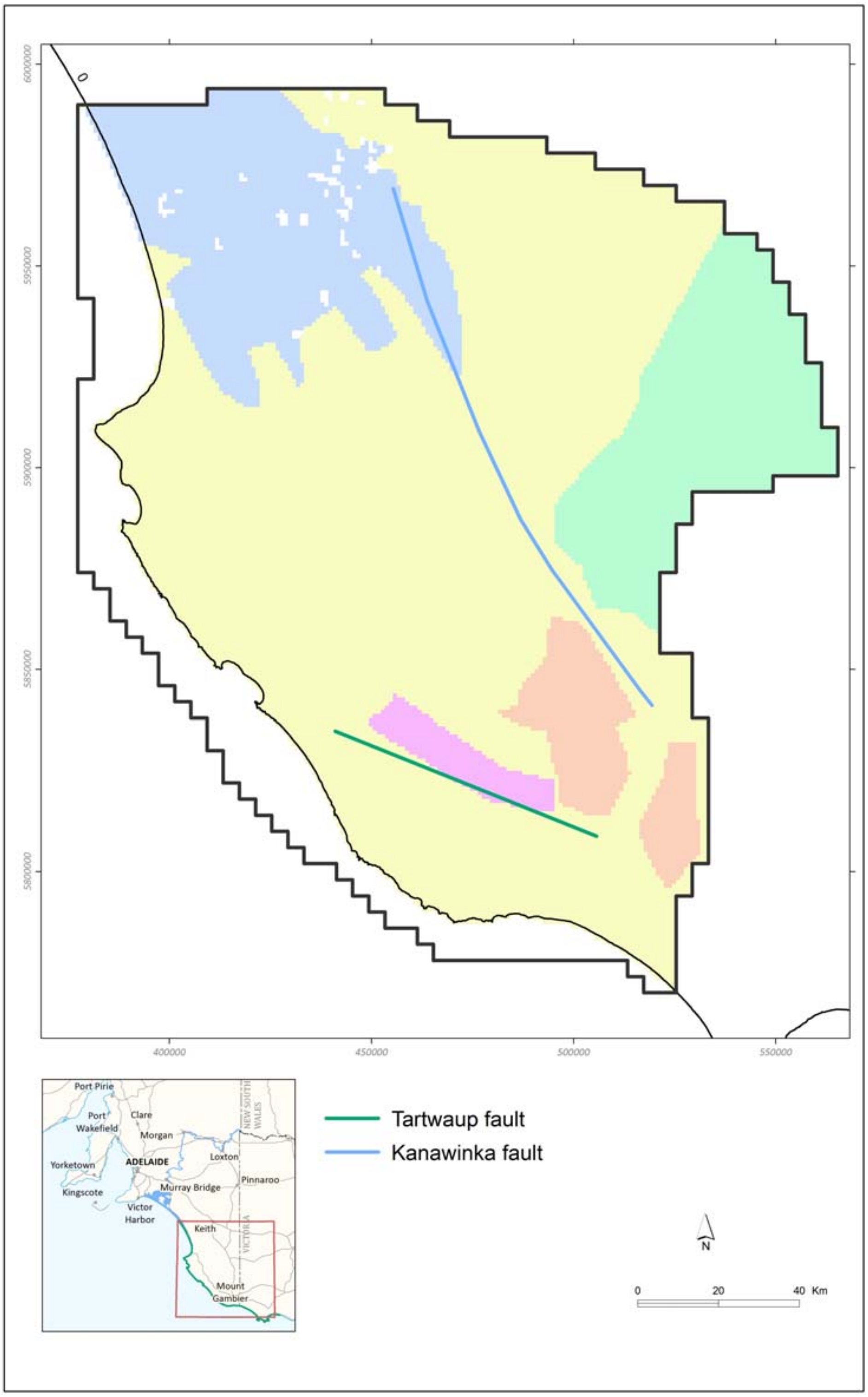


Figure 4.11 Model hydraulic conductivity zones for layer 1

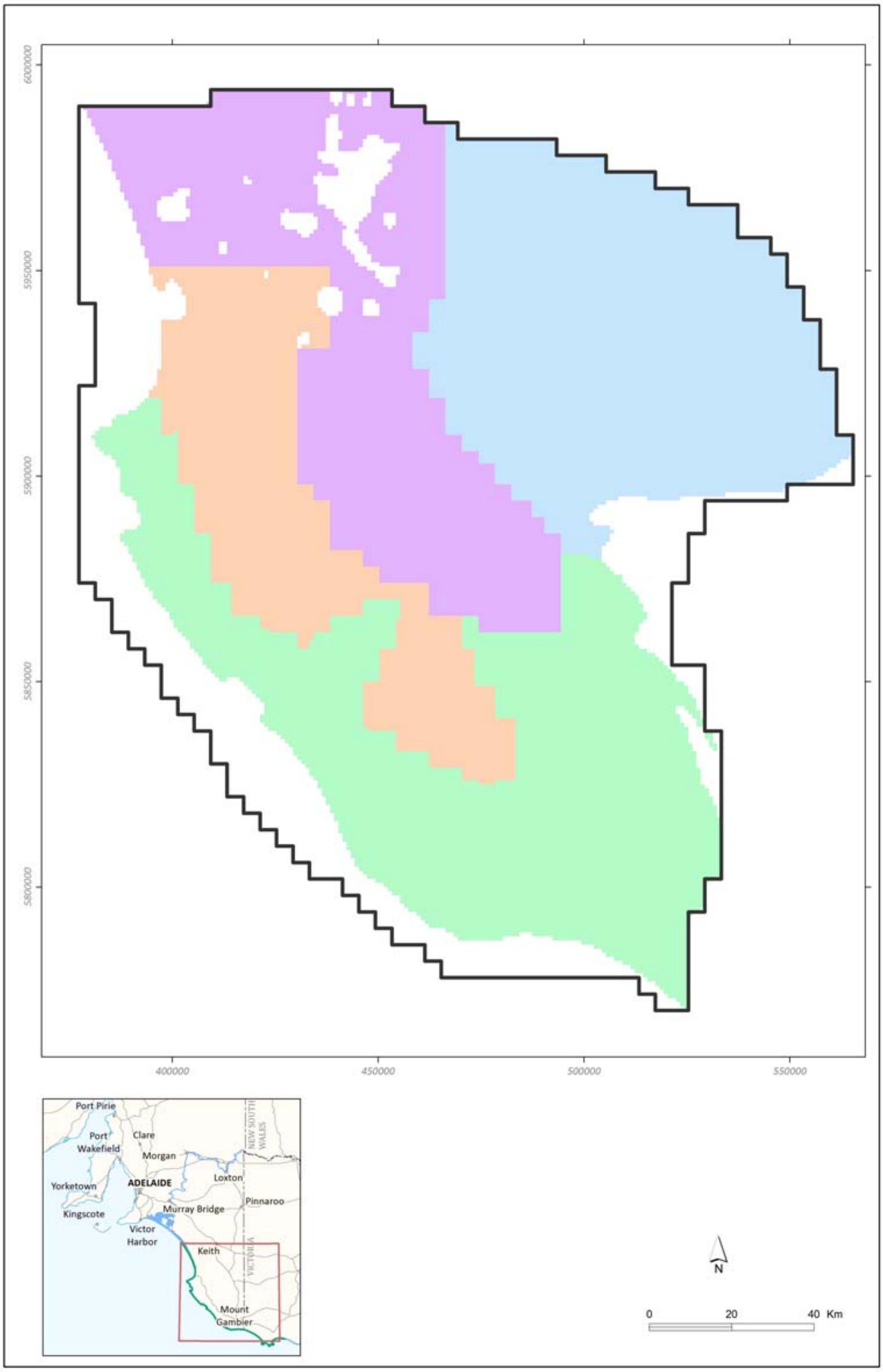


Figure 4.12 Model hydraulic zones and parameters for layer 3

Table 4.1 Parameters tested in the model

Aquifer	Parameter	Units	Observations	Tested values
Layer 1	K_h	m/d	80 – 1,800 (Padthaway Formation) 16 – 1,200 (Bridgewater Formation) 0.5 – 7 (Gambier Limestone)	0.1 - 2,000
	S_y	-	NA	0.0001 - 1
Layer 2	K_v	m/d	0.0007 – 0.27	0.0001 – 10.0
	S	-	NA	2 x 10^{-5} *Ss* of 10^{-6}
Layer 3	K_h	m/d	13 – 226	0.1 - 2,000
	S	-	1.2 x 10^{-5} – 0.00065	2.2 x 10^{-6} – 0.022 *Ss* of 10^{-8} – 10^{-4} m^{-1}

4.5 Boundary Conditions

No-flow boundary conditions were applied along the non-coastal boundaries. Potentiometric contours are generally perpendicular to these boundaries and therefore this is considered appropriate. Future work should consider using a general head boundary in areas where potentiometric contours are not perpendicular, such as along the north- eastern boundary.

Along the coast, a density-corrected specified head (Dirichlet) boundary was used in layers 1 and 3. A no-flow boundary was applied in layer 2 along the coast. The density correction in layer 1 and layer 3, to account for the density of seawater that imposes the coastal hydraulic head conditions, was implemented by extending the stratigraphy offshore by 1 grid cell using the layer thickness at the coast. The density-corrected specified head was then calculated using the formula (Environmental Simulations, Inc., 2010):

$$\Delta h = \Delta\rho \frac{C_i}{C_{\max}}(h_i - z_i) \qquad (1)$$

Here Δh is the head correction added to the boundary head, $\Delta\rho$ is the fractional increase in density of 0.025, h_i is the boundary head at cell *i* (i.e., 0 m AHD), C_i is the concentration at cell *i* (i.e., 35 g/L), C_{max} is the maximum saltwater concentration (i.e., 35 g/L). The resulting coastal head values are shown in Figure 4.13 and Figure 4.14.

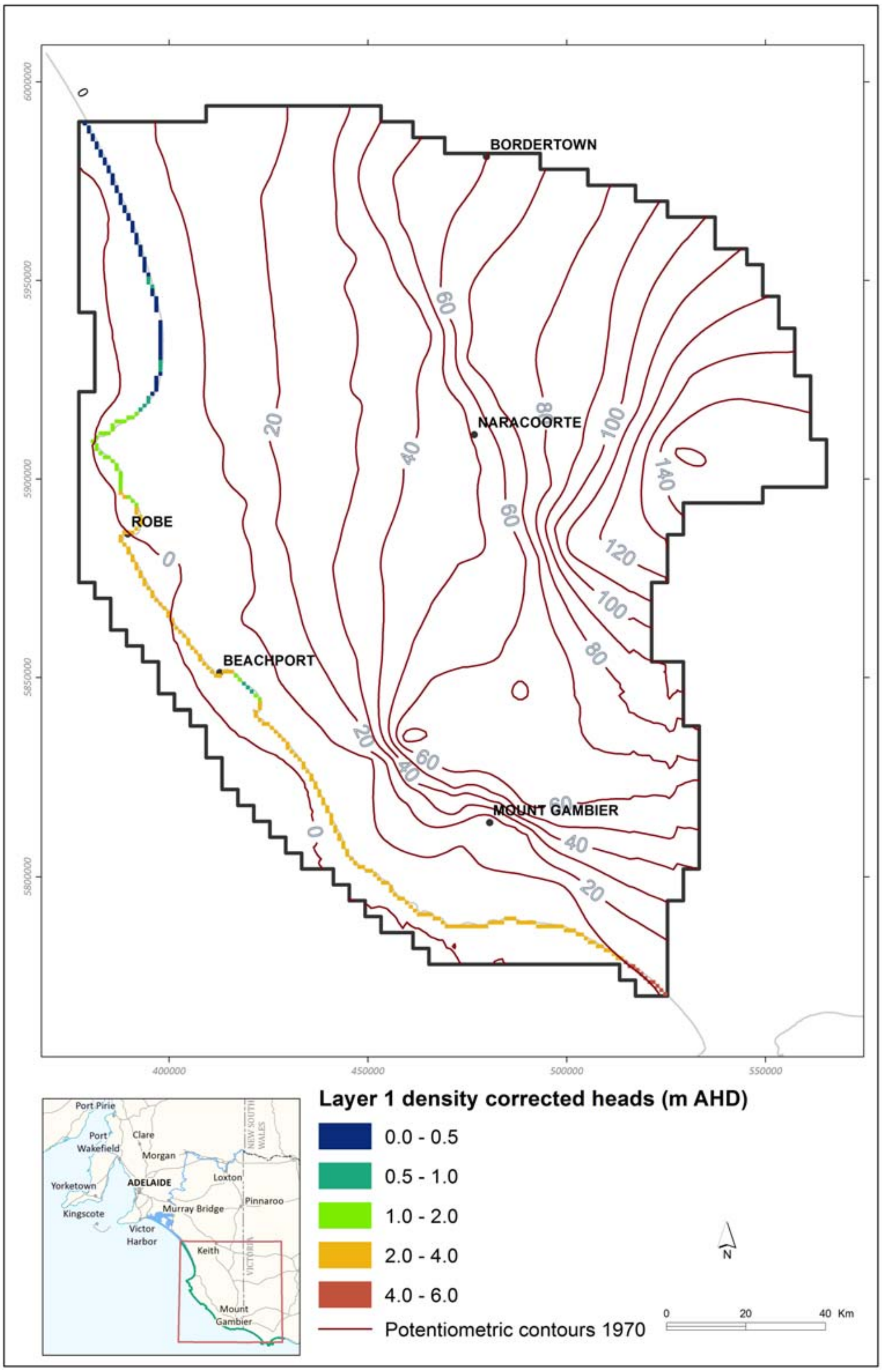


Figure 4.13 Density corrected coastal heads in layer 1.

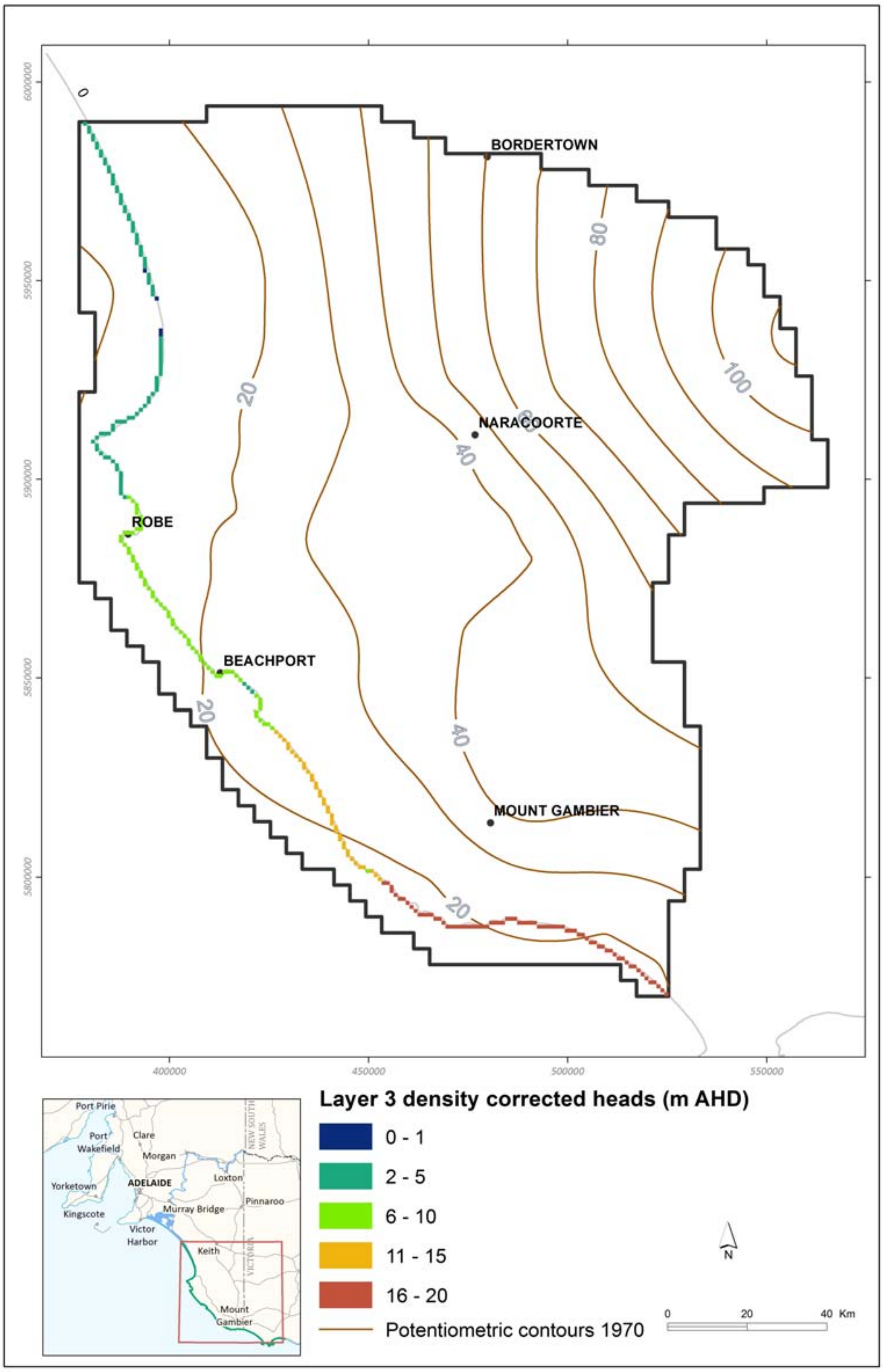


Figure 4.14 Density-corrected coastal heads layer 3.

4.6 Drains

As described in Section 2.7, the majority of the drains in the lower South East were constructed prior to 1970, while drains in the upper South East were constructed between 1998 and 2010 (Figure 2.12). Drains were implemented into the model at stress periods corresponding to the start of the drain construction year (Figure 4.15). Drain elevation was available for each model cell, as described in Section 2.7. The average drain elevation is 28 m and ranged between -4 m and 88 m. Because of the fact that each 1 km x 1 km model cell may contain numerous small drains, the drain conductance was calculated in each cell using the formula $C = LwK_v/m$, where C [L^2/T] is the drain conductance, L [L] is the total length of drain in the model cell, w [L] is the average width of the drain in the model cell, K_v [L/T] is the vertical hydraulic conductivity of the base of the drain sediments, and m [L] is the thickness of the drain sediments. Values of L and w were available for each drain, as described above in Section 2.7. The K_v/m ratio was unknown and following testing during the steady-state model calibration a value of 0.1 /d was selected. This value resulted in drainage fluxes at steady-state of 245 GL/y (see Section 5.1) which are less than the estimate of total groundwater flux to the drains presented in Section 2.7.2, which is 425 GL/y and considered an upper limit. For a K_v/m ratio of 0.1 /d, the average conductance value was 613 m^2/d and ranged between 1.03 and 5283 m^2/d.

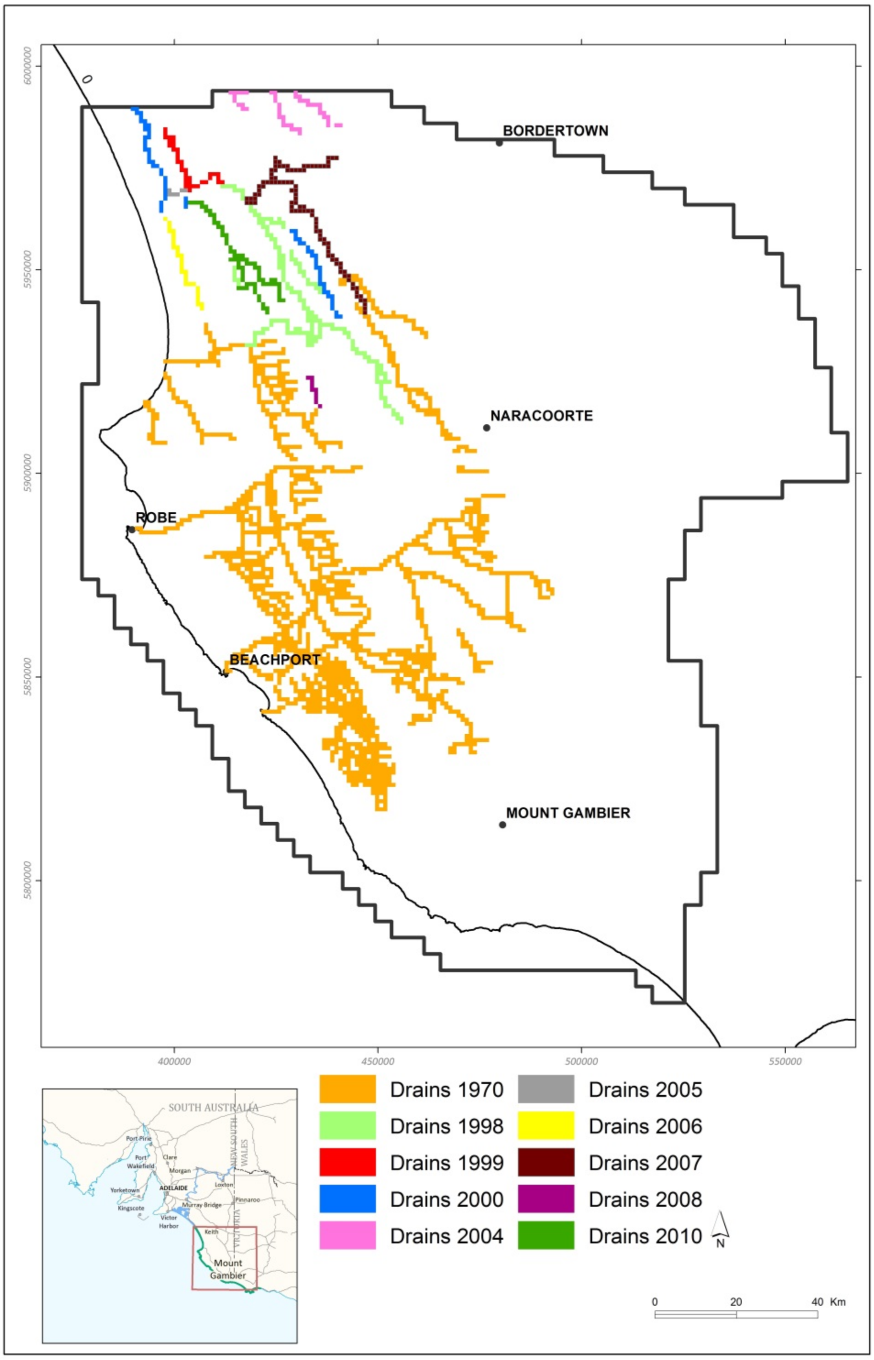


Figure 4.15 Drains and construction dates as implemented within the MODFLOW model.

4.7 Recharge

The gross recharge values obtained from the LEACHM unsaturated zone model with a 5 m soil profile presented in Section 3 were implemented into the model using the RCH package, with recharge applied to the topmost model layer only. Recharge was imported into the groundwater model using a MODFLOW recharge file (i.e., a .rch file) that was developed outside of the graphical user interface using data from the LEACHM modelling described in Section 3.

4.8 Groundwater Extraction

Groundwater extraction for the steady-state model was derived from the average pumping rates during January 1965 to December 1974 for wells that were constructed prior to 1975 (see Section 2.5). For the transient model, groundwater extraction was assumed to commence in January of the year that a well was constructed. If the groundwater licence type was ‘irrigation’, ‘holding’, ‘recreation’ or ‘lucerne equivalent’, the extraction was assumed to be seasonal and the total annual extraction was distributed over the period from October to March of each year. Zero extraction was assumed to occur from April to September of each year. All extraction in Victoria (see Section 2.5.5) was assumed to be seasonal. All other licence types (‘Intensive animal keeping’, ‘Industry – dairy’, ‘Aquaculture’, ‘Public water supply’) were assumed to be non-seasonal. Public water supply wells were assumed to commence in 1970 and average annual extraction volumes were equally distributed over all months (see Section 2.5.2).

Assumed groundwater extraction rates from the Kimberley Clark pulp and paper mills at Millicent and Tantanoola were based on anecdotal evidence about historical pumping up until 2003, after which reported extraction rates were used (as shown in Table 2.3) and assumed to be non-seasonal. Extraction of 20 ML/d from the Kimberley Clark wells was implemented in the steady-state model.

Leakage from confined aquifer bores (see Section 2.5.6) was implemented as extraction that commenced in 1980 and ceased in January of the year when rehabilitation occurred, which was between 2000 and 2010 in all cases. Extraction was assumed to be non-seasonal.

Total groundwater extraction rates implemented in the model are shown in Figure 4.16. Figure 2.8 and Figure 2.9 show the current locations of extraction wells in the unconfined and confined aquifers respectively.

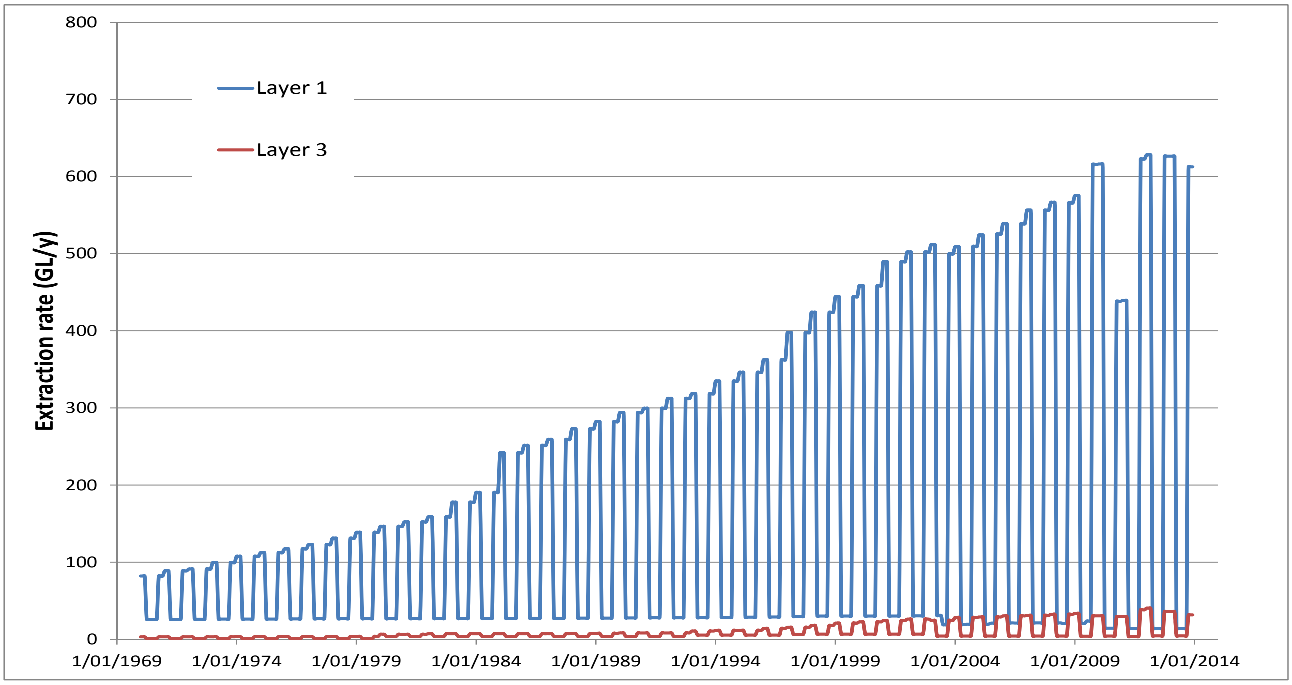


Figure 4.16 Rates of groundwater extraction implemented within the model.

4.9 Evapotranspiration

Groundwater evapotranspiration (ET) was calculated using the MODFLOW EVT package. The MODFLOW EVT package calculates groundwater ET using the following algorithm:

$$ET = 0 \qquad \text{if } DTW \geq ED$$

$$ET = PET \qquad \text{if } DTW \leq 0$$

$$ET = PET*(ED-DTW)/DTW \qquad \text{if } 0 < DTW < ED$$

Here, DTW [L] is depth to water table from the ET surface elevation (generally based on the topographic surface elevation) in each MODFLOW grid cell (see Figure 4.17), ED [L] is extinction depth below which ET does not occur, and PET [L^3/T] is the potential ET.

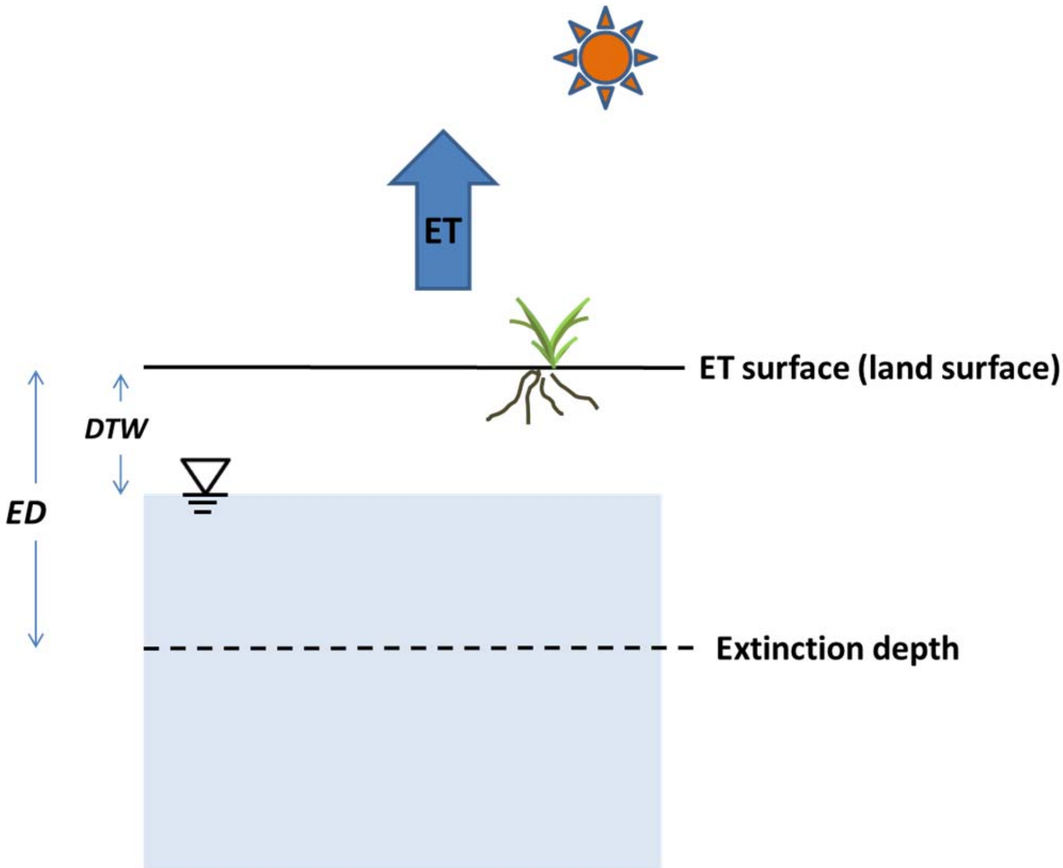


Figure 4.17 Conceptual model of evapotranspiration used in MODFLOW

As described in Section 4.3, the topographic surface was obtained from a LIDAR-derived Digital Elevation Model (DEM) with a 2 m horizontal resolution (Wood and Way, 2010). As the LIDAR-derived DEM only exists for the South Australian portion of the model domain, a DEM derived from satellite data with a 30 m horizontal resolution (Gallant et al., 2011) was used for the Victorian portion of the study area. The LIDAR DEM data was up-scaled to a 10 m x 10 m cell size and the satellite derived DEM was down-scaled to a 10 m x 10 m cell size prior to being merged to form a single DEM dataset for the whole model domain. Grid statistics were obtained using the new DEM dataset values in each MODFLOW cell, including maximum, minimum, mean, median and standard deviation of DEM values.

When applying the EVT package algorithm in each MODFLOW cell, a new approach was employed that incorporates local scale topographic variation into regional scale MODFLOW cells. In this approach, the maximum DEM value in a model cell is considered to be the ET surface (Figure 4.18). DTW was calculated as the maximum DEM value minus the water table elevation and ED is the DEM range (i.e., maximum minus minimum DEM). This approach results in ET being scaled from PET to zero based on the relative area within the MODFLOW cell that is inundated. For example, if the water level in a MODFLOW cell is higher than the maximum DEM value in that cell, then the entire MODFLOW cell is inundated and ET = PET. If half of the MODFLOW cell is inundated, ET = 0.5 * PET.

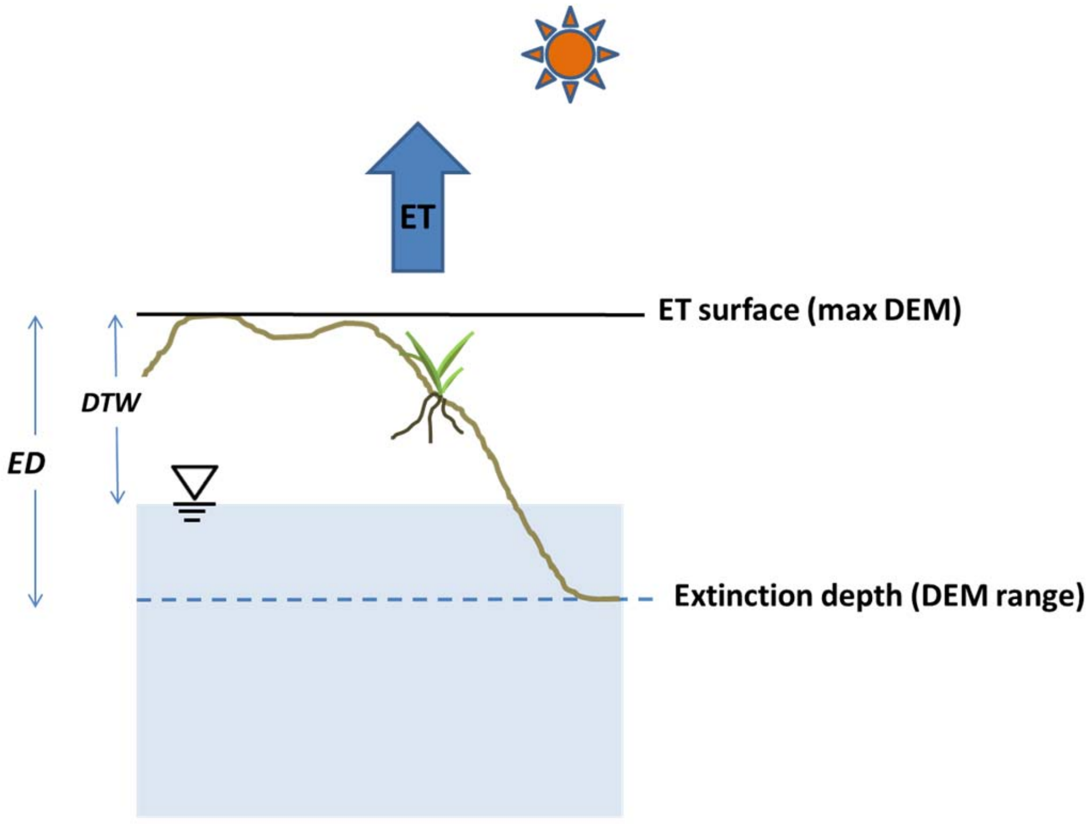


Figure 4.18 Conceptual model for evapotranspiration used within the modified extinction depth approach

Average monthly PET is employed in the transient model and is taken from SILO Data Drill weather data from 37 equal-sized rectangles across the area.

5 MODFLOW Model Calibration

Following the development of prototype steady-state and transient MODFLOW models, model calibration was undertaken using a sequential approach, as described by Knowling et al. (2015). Steady-state calibration was used to estimate the aquifer hydraulic conductivity of layers 1, 2 and 3. Hydraulic conductivity was parameterised using zones shown in Figure 4.11 and Figure 4.12. Transient calibration was used to estimate aquifer storage parameters. Uniform storage parameters were used for each layer. An automated model calibration procedure was undertaken for the steady-state model using the parameter estimation software PEST (Doherty, 2005). PEST modifies model parameter values to minimise an objective function based on the sum of squared weighted residuals (i.e. the difference between model predictions and corresponding field observations). An estimate of groundwater discharge to the drains (i.e., ≤ 425 GL/y, see Section 2.7.2) was used to adjust drain conductance values. Transient calibration was undertaken using a manual approach because the model run-time of 15 hours precludes the use of PEST. The approach taken during manual calibration was to minimise the sum of squared weighted residuals and obtain a good visual match between measured and modelled hydrographs.

In the absence of extensive water-level data at the transient model's starting date of 1/1/1970, a steady-state simulation is the best approach to capture the water surface behaviour at the start of the simulation, and is a common approach used widely in numerical modelling studies. Here, the steady-state simulation is not representative of pre-development conditions, but rather average conditions for the period 1/1/1965 to 31/12/1974. Obviously, alternative starting conditions might be obtained under different assumptions; however, for the purposes of developing a preliminary groundwater model of this region, a steady-state prediction of the initial conditions is deemed the best approach. Testing the effects of the initial conditions on the transient models' predictions is an area for future work.

The groundwater model has been developed as a regional-scale water balance model and hence the focus of model development has not been on calibration to observed heads, but rather to the inclusion of regional-scale processes to best represent key processes affecting the water balance, such as recharge, drains and groundwater ET. As such, the calibration is considered preliminary and requires further efforts before the model is suitable for use as a management tool, particularly for applications such as predicting changes in potentiometric heads in response to pumping.

5.1 Steady-State Model Calibration

Observation bores with more than five head measurements between January 1965 and December 1974 were selected for use in the steady-state calibration. Specifically, the decadal average of the observed head in these wells was used. Due to limited data in the Upper South East, a 20-year period between January 1965 and December 1984 was used. There is a total of 270 steady-state head targets in layer 1 (Figure 5.1) and 60 head targets in layer 3 (Figure 5.2). An equal weighting was applied to all targets during calibration. Head observations in layer 2 are not available. Optimal horizontal hydraulic conductivity parameter values, determined using PEST, are shown in Figure 5.1 and Figure 5.2 for layers 1 and 3, respectively. The optimal horizontal hydraulic conductivity value for layer 2 was found to be 0.001 m/d. These values are within the range of observed values. A ratio of horizontal to vertical hydraulic conductivity of 10 was applied in all layers. Figure 5.3 shows the steady-state model comparison between observed and modelled groundwater heads. The calibration goodness-of-fit statistics for heads include a root-mean-square error (RMSE) of 5.4 m, a scaled root-mean-square error (SRMS) of 3.6% and a coefficient of determination (R^2) of 0.96 for both layer 1 and layer 3.

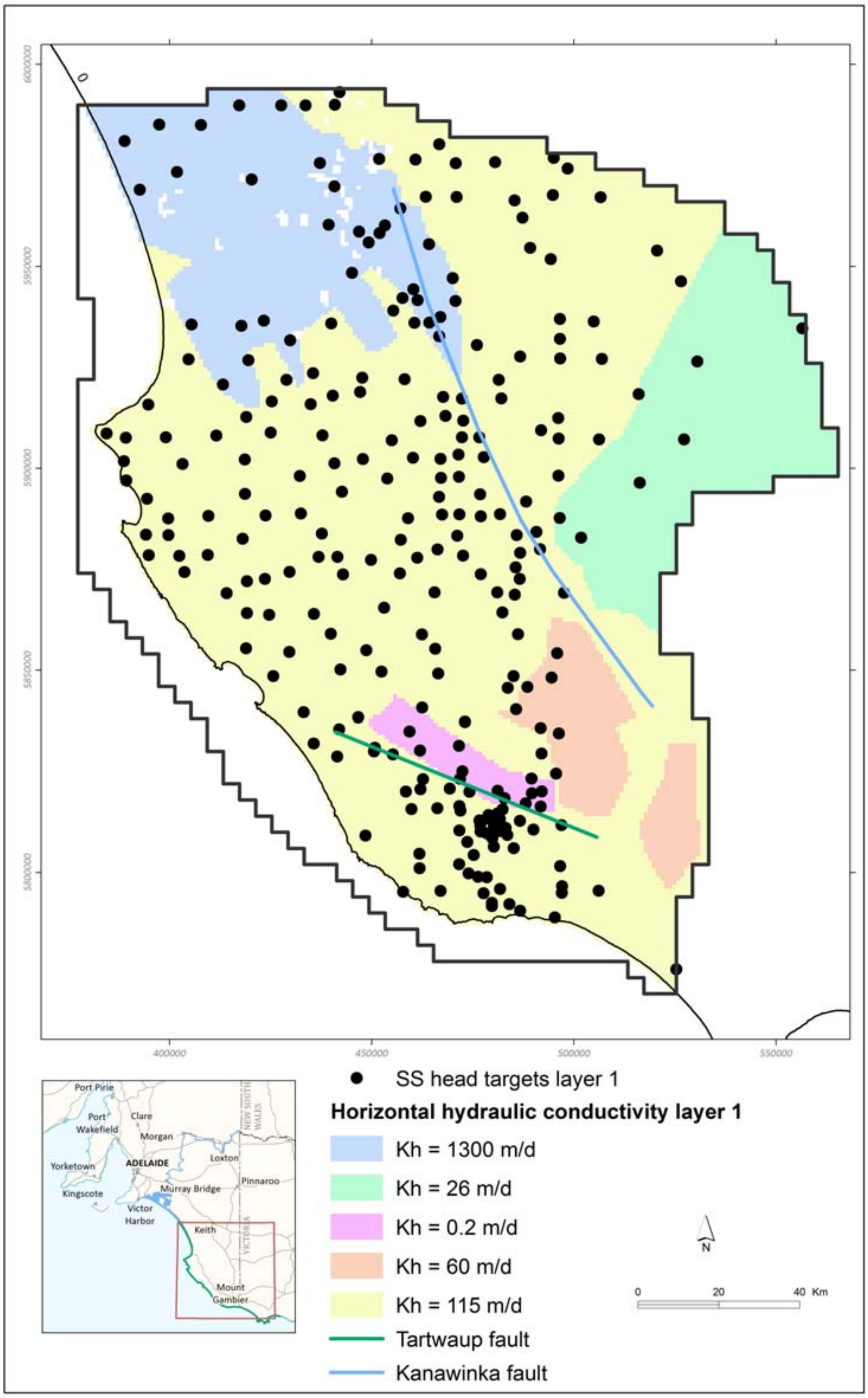


Figure 5.1 Location of observation bores used as steady-state head targets in layer 1, and calibrated hydraulic conductivity parameter values.

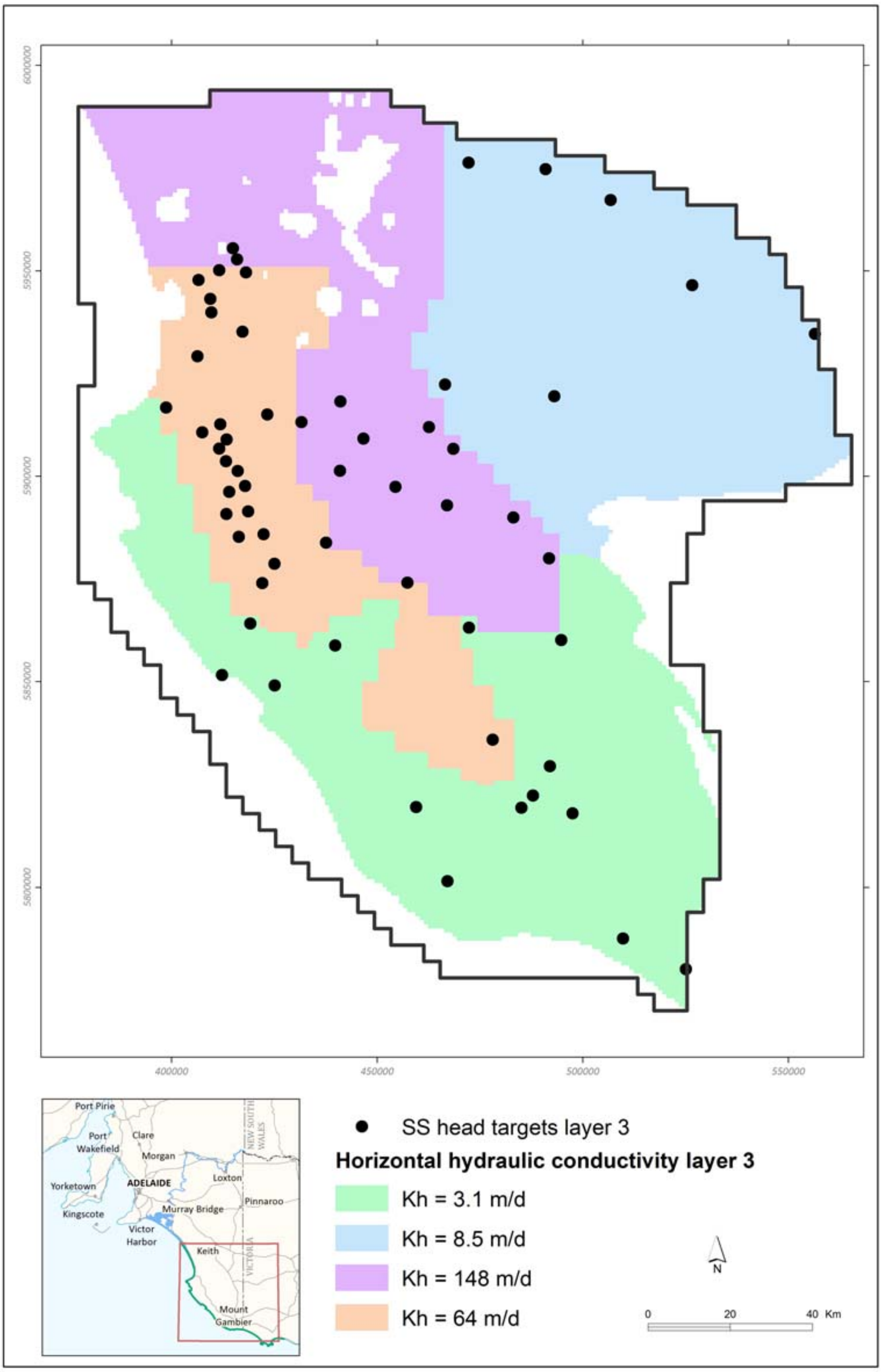


Figure 5.2 Location of observation bores used as steady-state head targets in layer 3, and calibrated hydraulic conductivity parameter values.

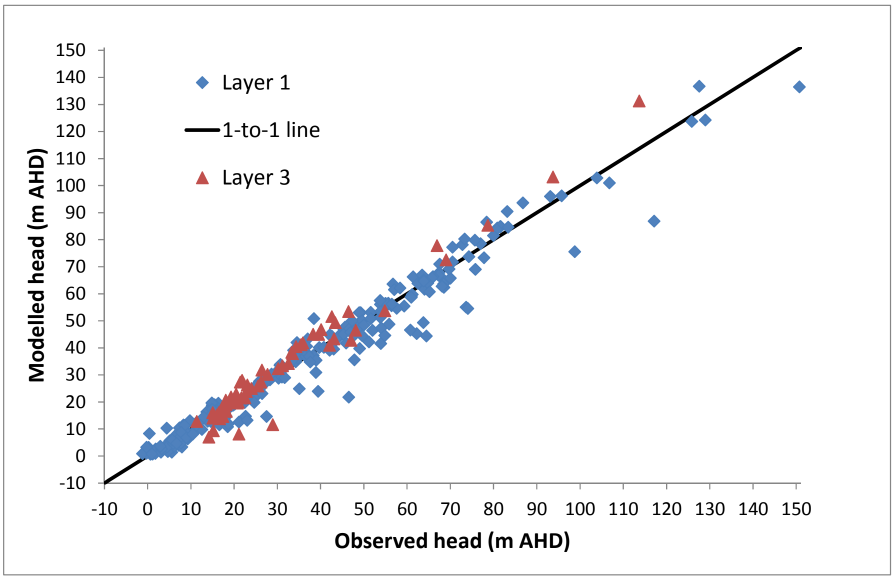


Figure 5.3 Steady-state calibration scatter plot.

The steady-state head residuals for layer 1 and layer 3 are shown in Figure 5.4 andFigure 5.5, respectively. In layer 1, areas with head residuals greater than 10 m (i.e., measured heads are more than 10 metres higher than modelled heads) occur in the regions of the Tartwaup fault and the Kanawinka Fault, as well as in the Victorian highlands. In layer 3, the head residuals generally trend from negative values in the north east to positive values in the south west. As described in Section 2.3.2, layer 3 is thought to have hydraulic conductivities that decrease to the south, and the pattern of head residuals conforms to these understandings.

The comparison of observed and modelled head contours for layer 1 and layer 3 are shown in Figure 5.6 and Figure 5.7, respectively. There is a reasonably good match between modelled and measured head contours in layer 1 and layer 3. Observed head contours in layer 3 (confined aquifer) in the north east of the model domain do not cross the model boundary at right angles, which suggests there may be inflows at this boundary, although this is based on very limited data. The potentiometric head contours in Figure 5.4 are based on Victorian observation well data provided by the Victorian Department of Sustainability and Environment (DSE), although future work could include the acquisition of any additional head data for the Victorian portion of the model domain if it exists and, if deemed warranted, the use of a general head boundary to allow flows into the model.

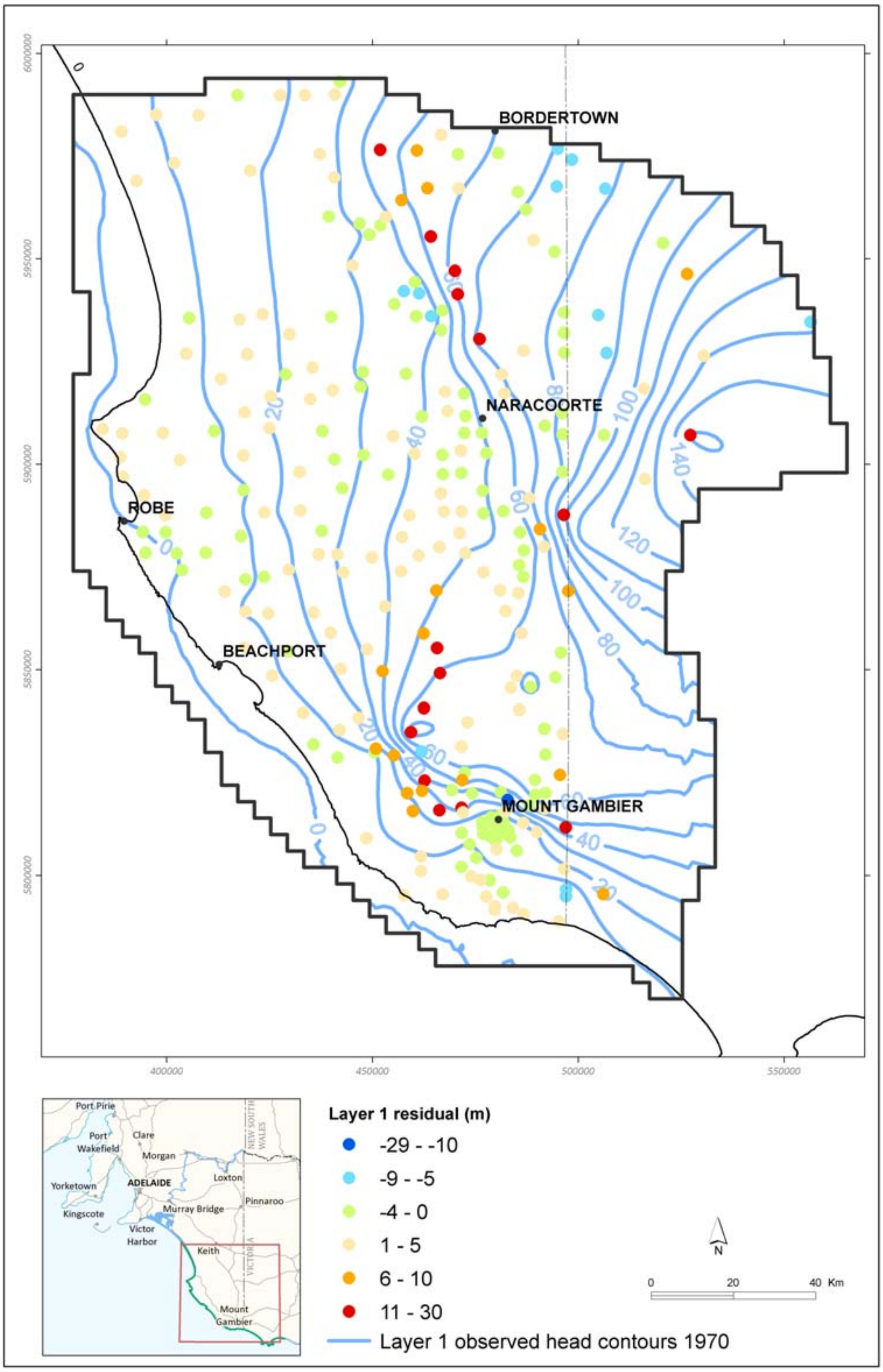


Figure 5.4 Layer 1 head residuals (negative residuals indicate that modelled heads are higher than measured heads).

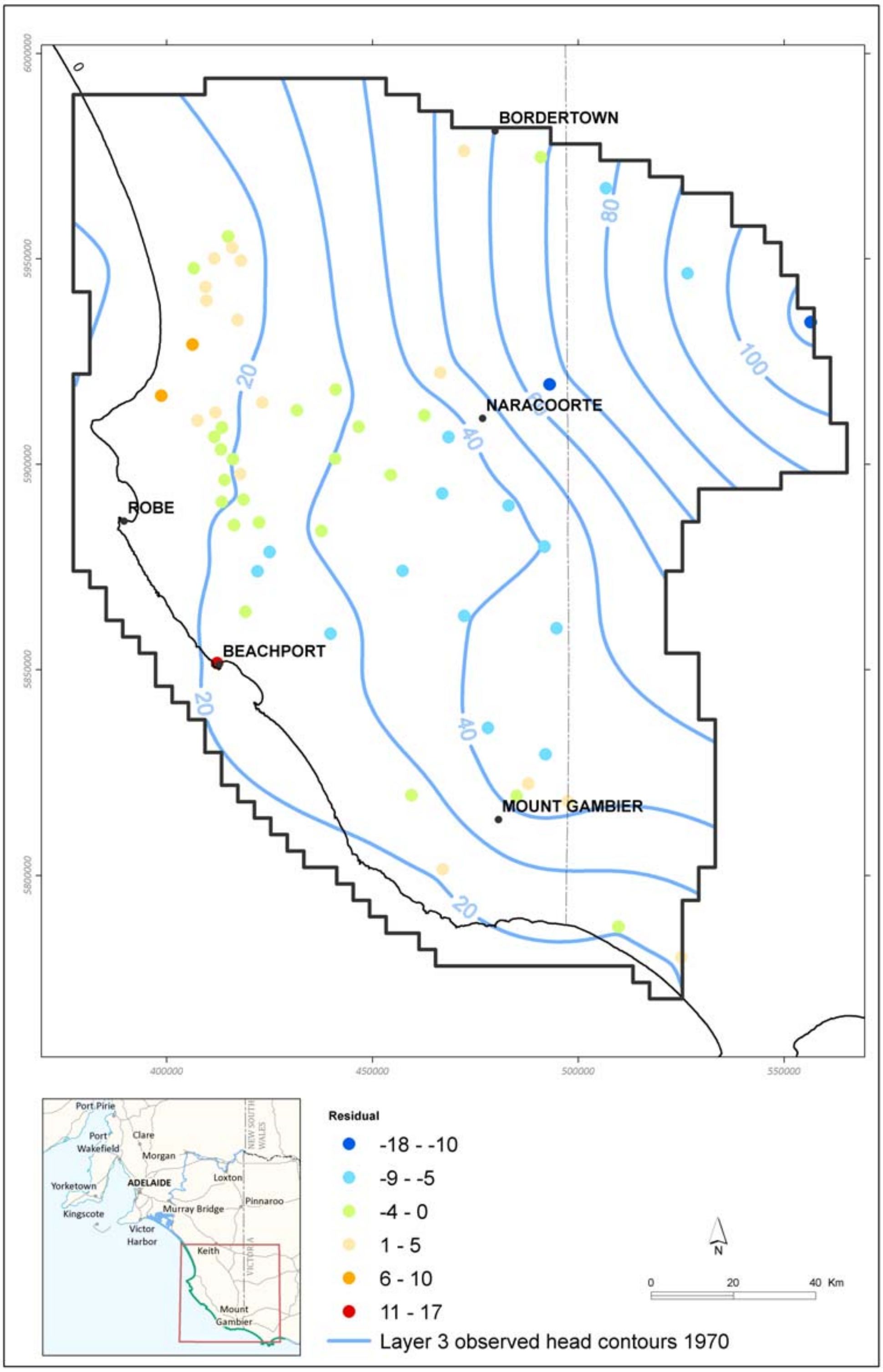


Figure 5.5 Layer 3 head residuals (negative residuals indicate that modelled heads are higher than measured heads).

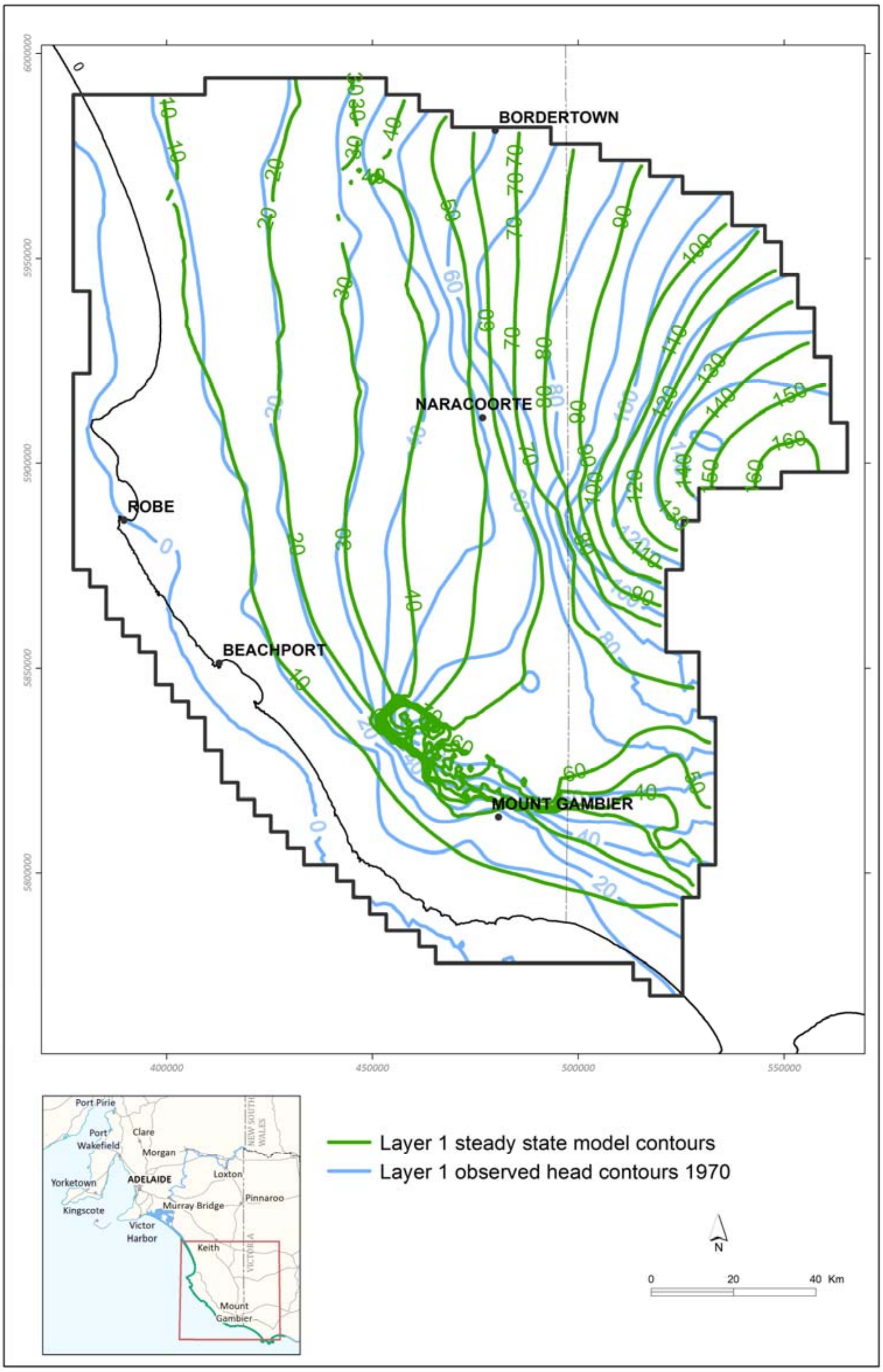


Figure 5.6 Comparison of modelled and observed head contours for layer 1.

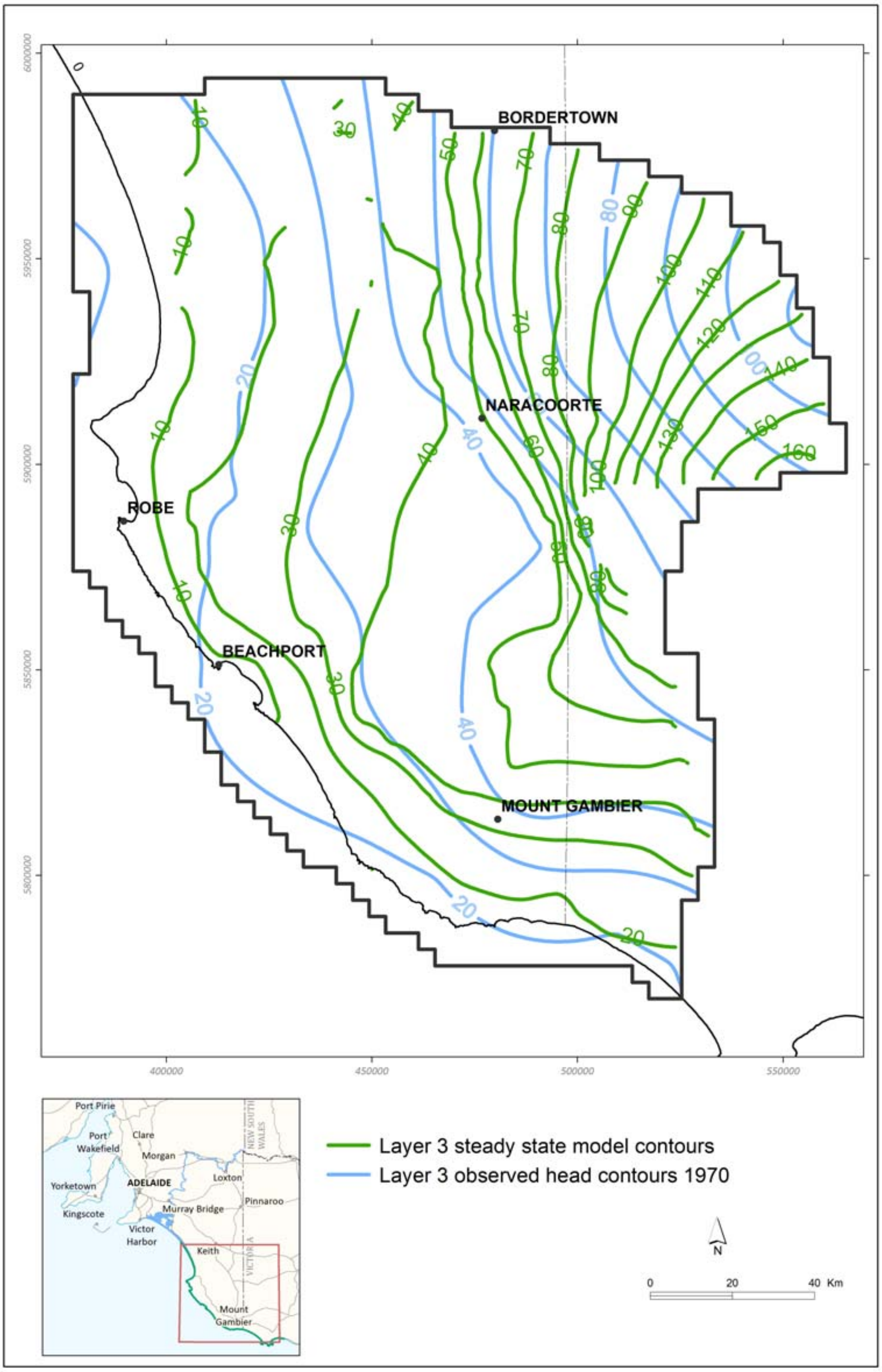


Figure 5.7 Comparison of modelled and observed head contours for layer 3.

The overall model water balance was used as a further check on model calibration results. The steady-state water balance for this simulation is shown in Table 5.1. The analysis in Section 2.7.2 estimated the maximum groundwater discharge to the drains to be in the order of 425 GL/y for the period 2000 to 2013. Therefore a flow to drains of 245 GL/y is considered reasonable. A net recharge (i.e., gross recharge minus evapotranspiration) of 1890 GL/y is equivalent to a spatially averaged net recharge of 73 mm/y over the model domain. This is reasonable when compared to spatially averaged net recharge values for the 2001 to 2010 period (a period of low rainfall) reported by Crosbie et al. (2015) of 20 mm/y (from the chloride mass balance method), 40 mm/y (using remotely sensed ET data and a mass balance approach), and 73 mm/y (water table fluctuation method).

Table 5.1 Steady-state water balance estimates.

	Water Balance Component	GL/y	mm/y
Inflows	Gross recharge	3,536	137
	Coastal boundary	4.0	0.2
Outflows	Evapotranspiration	1647	64
	Extraction	40	1.5
	Drains	245	9.5
	Coastal boundary	1,610	62
	Extraction	40	1.5

Coastal boundary flows occur primarily in layer 1 (over 95%) with a net outflow of 1,546 GL/y and 60 GL/y in layers 1 and 3, respectively.

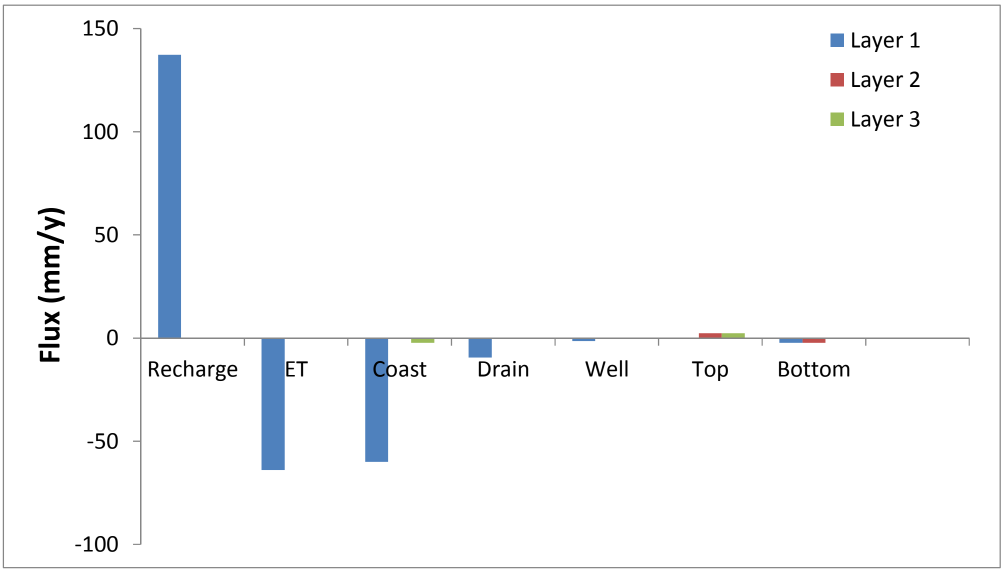


Figure 5.8 Fluxes in model layers

The steady-state model predicts a flow from layer 1 to layer 3 (through layer 2) of 317 GL/y. This value is higher than the rough estimate given in Section 2.3.3 of 20 – 80 GL/y based on the point-scale isotopic analyses of Harrington et al. (1999). However, given the uncertainty associated with both estimates, it is considered reasonable that values of a similar order of magnitude were obtained. The model predicts an upward flow from layer 3 to layer 1 (through layer 2) of 255 GL/y, which means there is a net flow of 62 GL/y from layer 1 to layer 3 across the model domain. The velocity vectors through the base of layer 1 predicted by the steady-state model suggest a pattern of inter-aquifer leakage that is more complex than previously thought based upon observed head differences and trends in groundwater hydrochemistry and isotopes (see Section 2.3.3), particularly in the north of the model domain (Figure 5.9). However, in general, the locations of downward flow and upward flow agree with measured head differences between layer 1 and layer 3 (Figure 2.5). The line of zero head difference, which is the line along which the hydraulic gradient between the unconfined and the confined aquifer changes from downwards to upwards, is shown on Figure 5.9 for reference.

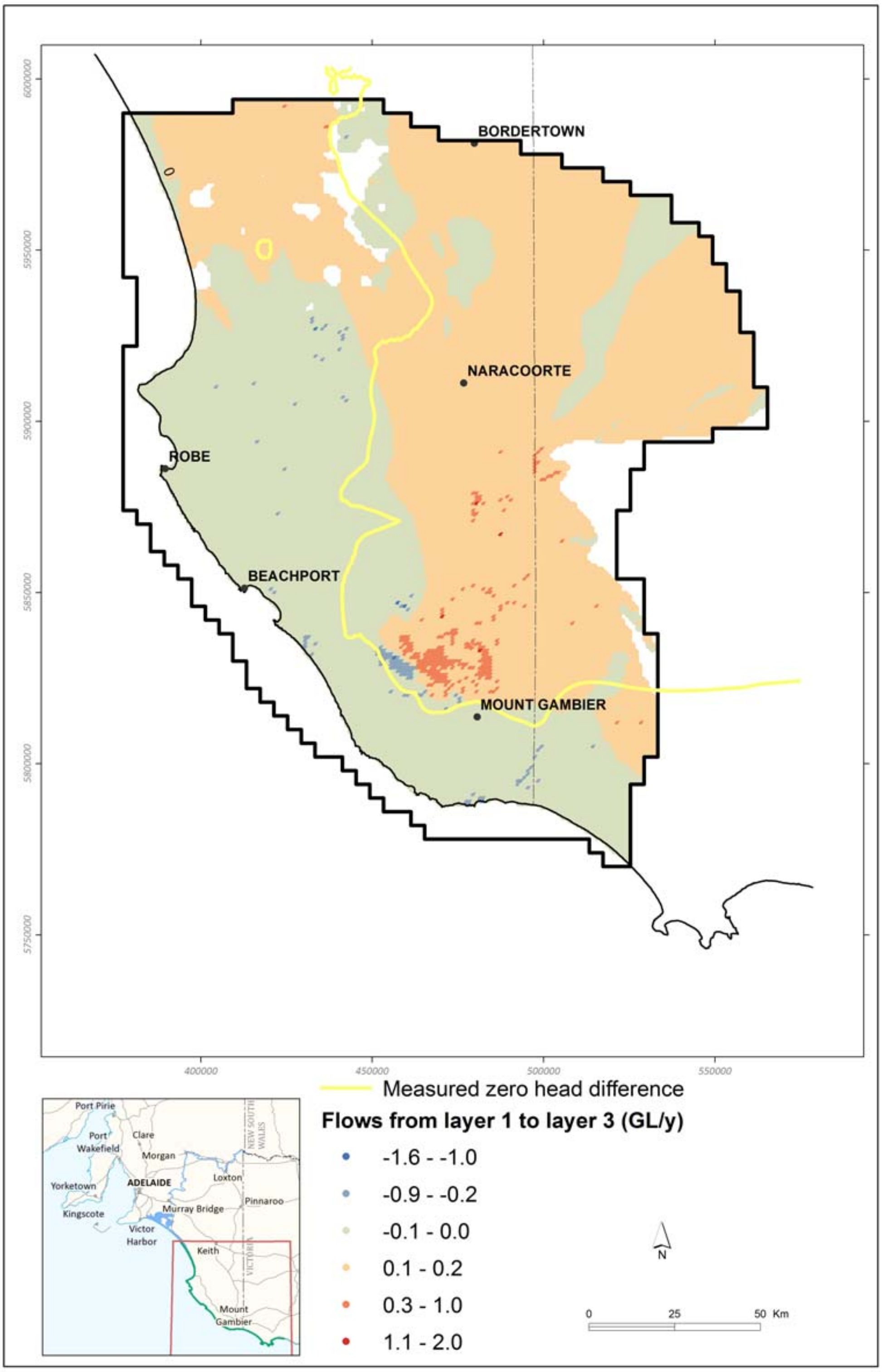


Figure 5.9 Flows from layer 1 to layer 3 (positive values indicate downward flow).

5.2 Transient Model Calibration

Observation bores from layer 1 and layer 3 were selected to represent various hydrogeological conditions and processes within the study area, as outlined in Table 5.2. The locations of the 57 selected observation bores for transient calibration are shown in Figure 5.10 and Figure 5.11. The selected observation wells have long term observation data and calibration was carried out using differences from the average water level.

Table 5.2 Observation bores selected as transient head targets.

Observation bores	Layer and hydrogeological condition
BOW004, DUF006, ROS009, WEL002, NVL001	Layer 1, interdunal flats
BLA041, MTB007, RID010, WLM010, MNC005, PRK002, 100533	Layer 1, coastal plain
HIN038, HIN010, KON001, MAC035	Layer 1, coastal plain near extractions
PEN002, MON008, MON035, NAN009, SHT012	Layer 1, coastal plain beneath forestry
BMA010, GGL007, HYN001, BIN053, PAR033, GLE108, TAT028, WLL007, 60610	Layer 1, highlands
BRA023, LKG013, WAT012	Layer 1, near coastal lakes and below sea level
BLA082, BLA005, GAM008	Layer 1, near Blue Lake
JOA011, MIN017, PEN025, MAC057, MAC077, 101239, 46217, BIN049, TAT027, KEN017, LAN018, RIV065, MRB011	Layer 3, regional
CNM078, CNM080, JOY019, ROS013, ROS021, LAC023, MTB017, BOW022, BOW024	Layer 3, near extraction

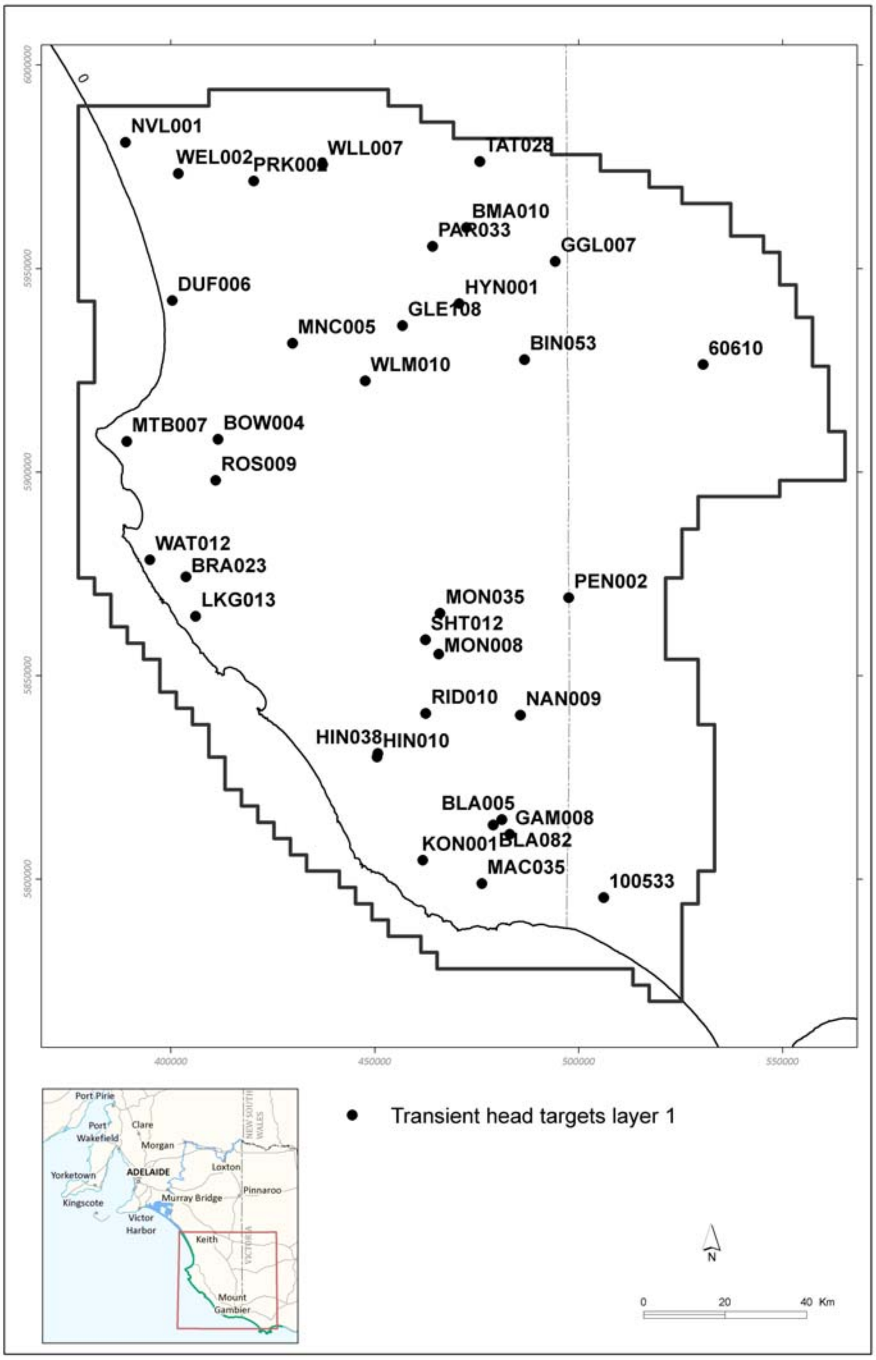


Figure 5.10 Locations of observation bores selected as transient head targets in layer 1.

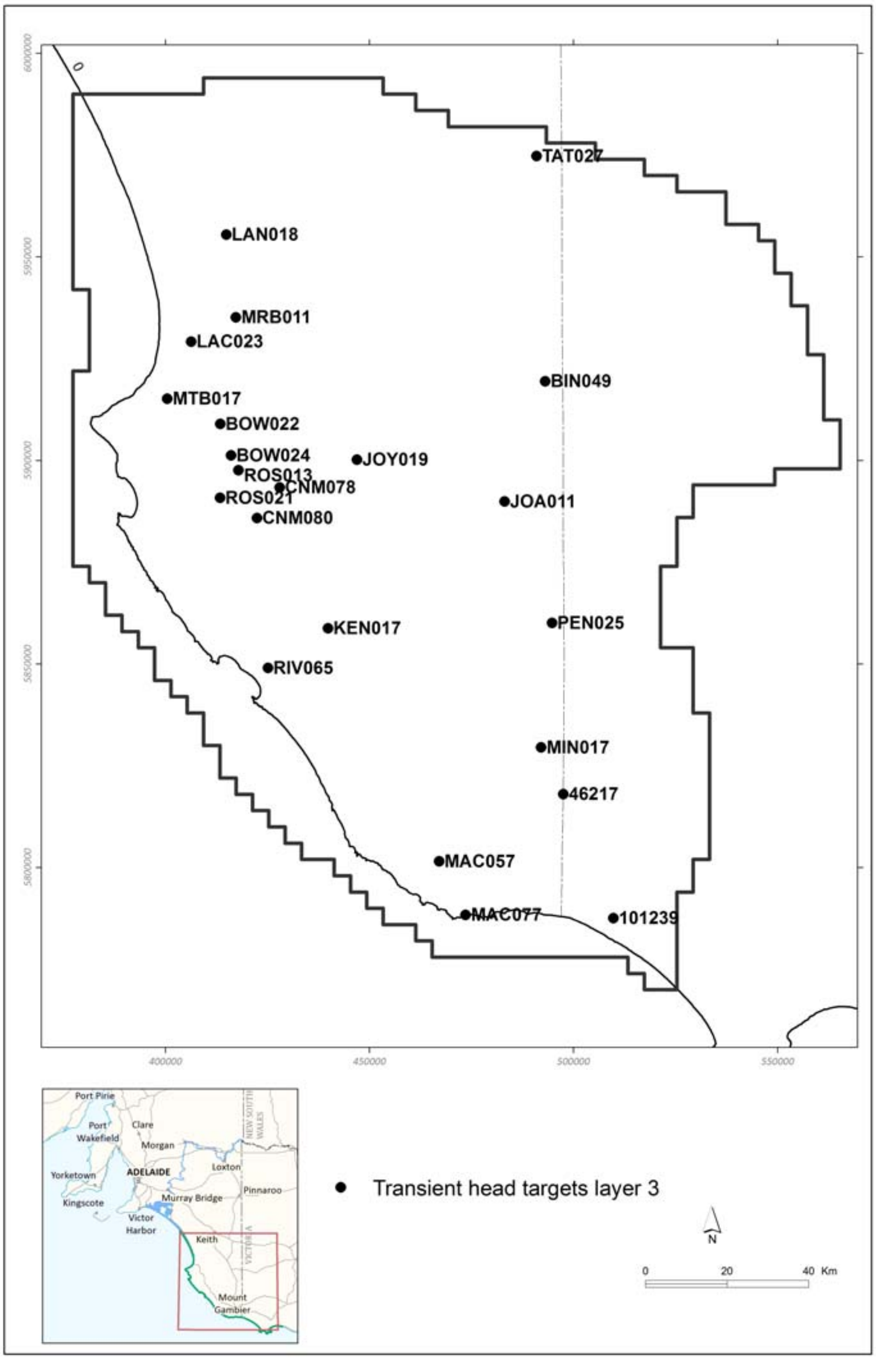


Figure 5.11 Locations of observation bores selected as transient head targets in layer 3.

Figure 5.12 shows the transient model comparison between observed and modelled groundwater heads. The RMSE and SRMS from the transient calibration are 6.5 m and 5.0 %, respectively. The calibrated S_y value in layer 1 was found to be 0.1. The calibrated S_s value in layer 3 was found to be 10^{-7} m^{-1}. These values are considered appropriate as they are within the range of observed data listed in Table 4.1.

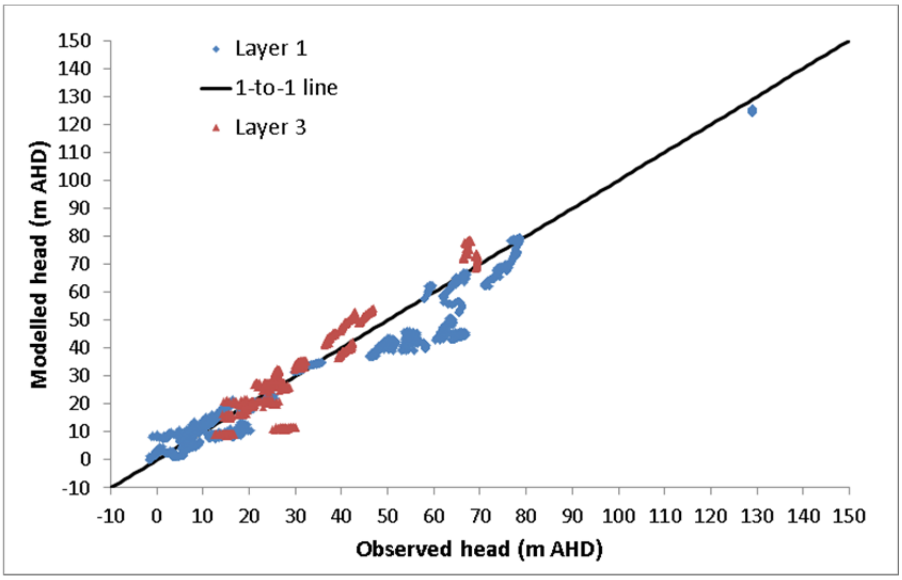


Figure 5.12 Transient model comparison between observed and modelled heads.

Modelled and measured hydrographs are shown in Figure 5.13 to Figure 5.20. The hydrographs have been grouped according to hydrogeological conditions and processes that they represent, as outlined in Table 5.2. Differences between modelled and measured heads at the start of the transient simulation tend to persist throughout the simulation period in most hydrographs. These differences may, at least in part, be due to the use of the 1965 to 1975 period as steady-state when in fact this is not a pre-development period (i.e., changes to the hydrology of the system were occurring). It is difficult to define a pre-development period for the South East because changes to the hydrology began as early as the 1860s, when the first drains were constructed around Millicent.

The transient hydrographs show a good match between short-term (i.e., seasonal) head changes in the majority of cases. This indicates that seasonality of recharge, groundwater evapotranspiration and extraction are being represented with reasonable accuracy in the model. Long-term trends in head also match reasonably well, indicating that long-term climate, extraction, irrigation and land use change impacts are generally well represented including, for example, the rise in water levels following the 1983 Ash Wednesday bushfires, which destroyed extensive areas of plantation forestry and native vegetation, with the resulting increase in recharge being obvious in hydrographs around that area (see hydrograph NAN009 in Figure 5.16). However, differences in long-term modelled and measured head trends do occur in hydrographs close to the Kimberley Clark pulp and paper mills and South Australian highlands. A number of hydrographs have a steeper decline in modelled heads than measured heads for the period since 1990, especially in forested areas. Further comments on this are provided below.

Modelled heads in the interdunal flats are both higher (by up to 5 m in the case of DUF006) and lower than measured heads (Figure 5.13). However, the short and long-term trends in modelled and measured head exhibit a good match.

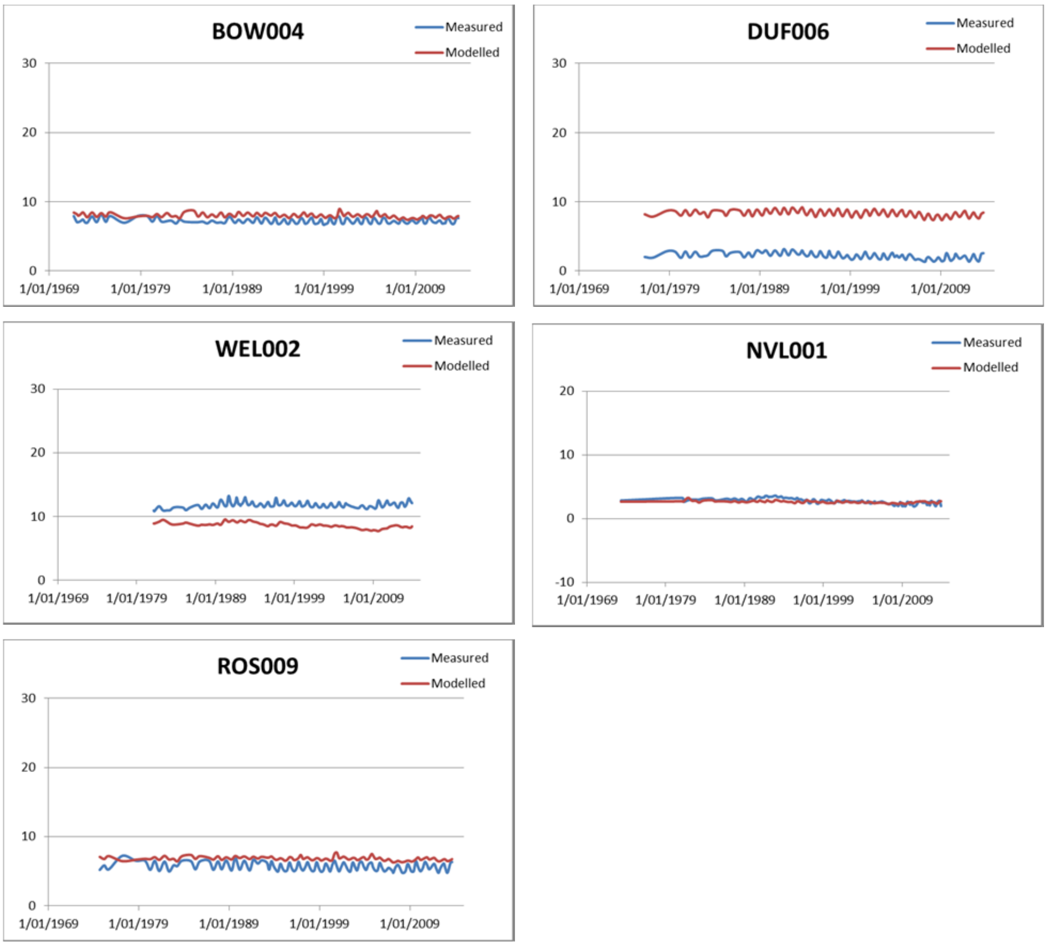


Figure 5.13 Hydrograph comparison between modelled and measured heads in layer 1, interdunal flats.

Modelled heads are both higher and lower than measured heads in the coastal plain of layer 1 (Figure 5.14). RID010 has the greatest difference in heads and is located north of the Tartwaup Fault, which is an area identified in the steady-state model as having relatively large differences between modelled and measured heads. The short and long-term trends in modelled and measured heads match reasonably well. Modelled heads have a steeper declining trend in the years 2000 to present, particularly in RID010.

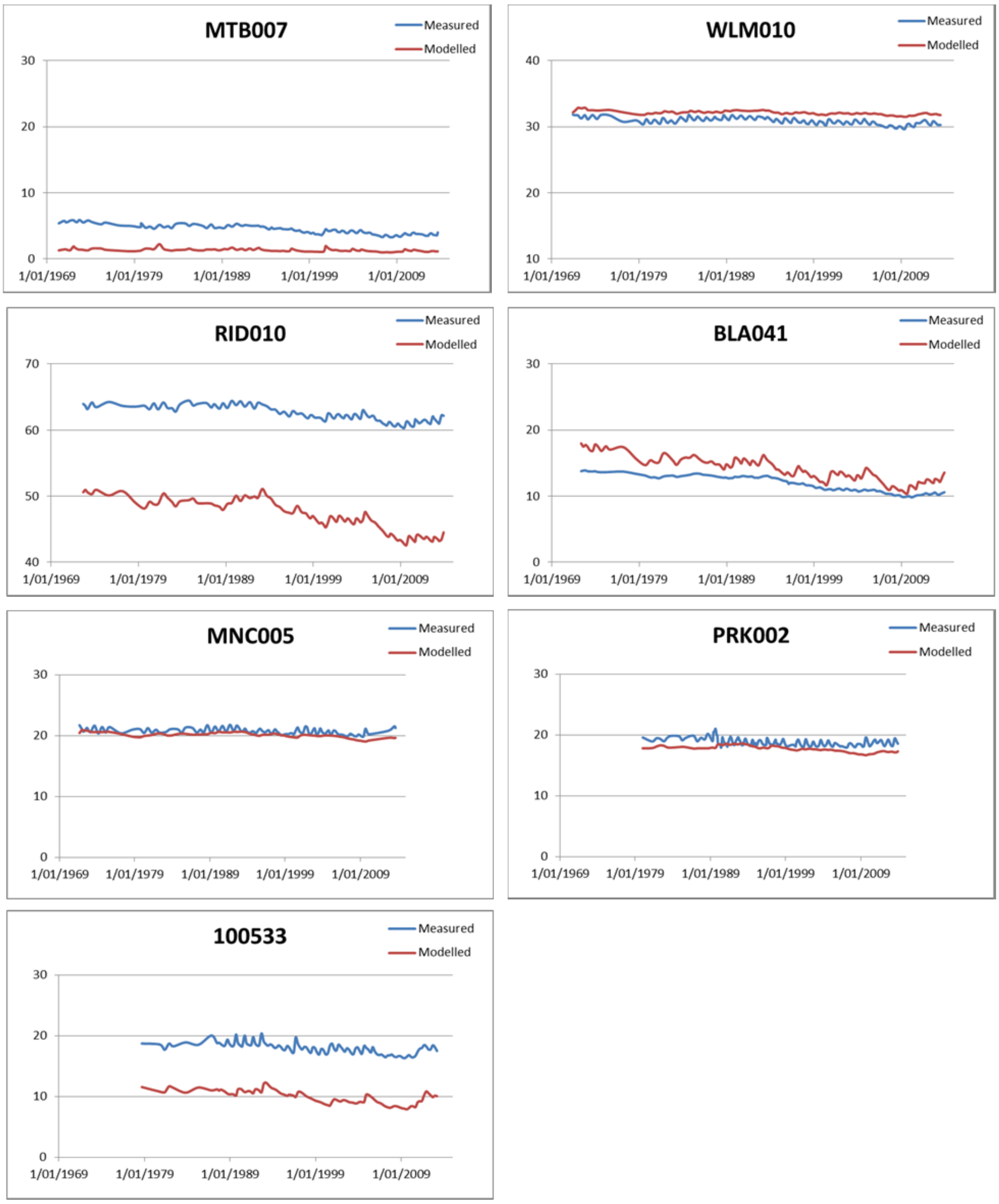


Figure 5.14 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain.

Hydrographs HIN038 and HIN010 are close to the Kimberley Clark pulp and paper mill (Figure 5.15).Modelled and measured hydrographs for HIN010 exhibit large differences from 1990 to the present. As detailed in Section 4.8, groundwater extraction from the Kimberley Clark pulp and paper mills was based on anecdotal evidence about historical pumping prior to 2003, with an extraction rate of 60 ML/d assumed between 1990 and 2003, after which time metered extraction rates were available and were employed within the model. The HIN010 hydrographs suggest that the rate of extraction is likely to have been larger than 60 ML/d during the 1990s.

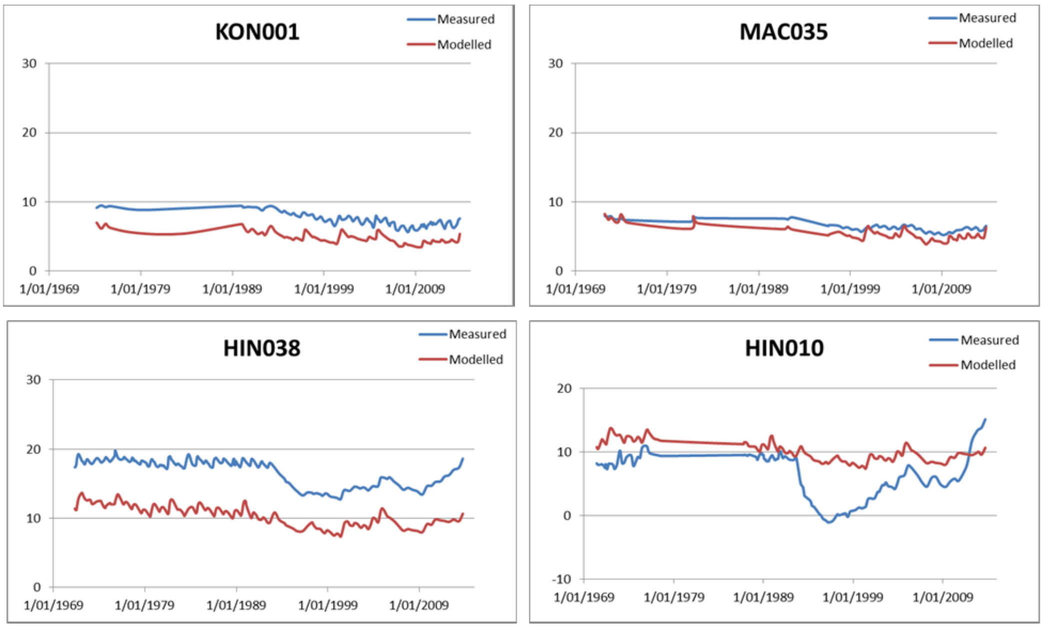


Figure 5.15 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain near extractions.

Modelled heads are consistently lower than measured heads on the coastal plain near forestry areas (Figure 5.16). There is a reasonable match between short and long term trends. NAN009 shows that the model is somewhat able to reproduce changes in head associated with forestry areas being burnt in the 1983 Ash Wednesday fire event. However, the trend in head decline after around 1990 is steeper than measured head declines in NAN009 and MON008.

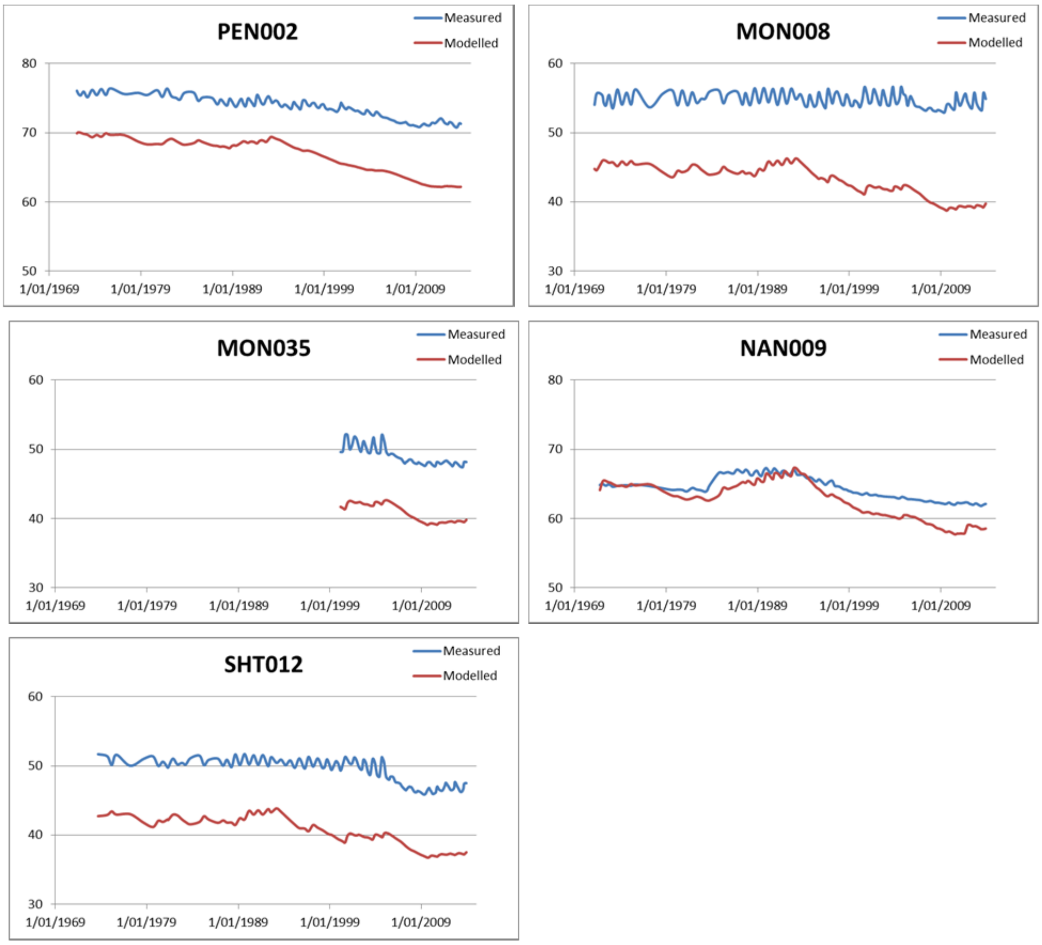


Figure 5.16 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain near forestry.

Modelled heads are both higher and lower than measured heads in the highland area. In BMA010, GGL007 and PAR033 the measured heads increased between around1970 and 1990, then levelled off or declined. This is thought to be due to a lag in recharge reaching the watertable after land-clearing; that occurred in the highland areas in the 1960s. The current recharge model has attempted to incorporate this effect, in a preliminary way, as described in Section 3. Further work is required however, as the modelled hydrographs fail to exhibit the required rising trend, although the match is an improvement on earlier iterations of the recharge model where land clearing was not included. The use of a spatially variable soil column length (it is currently set to 5 m where in fact the depth to the watertable is about 20 m in the highland area) may improve the simulation of the recharge lag, however this is outside the scope of the current project.

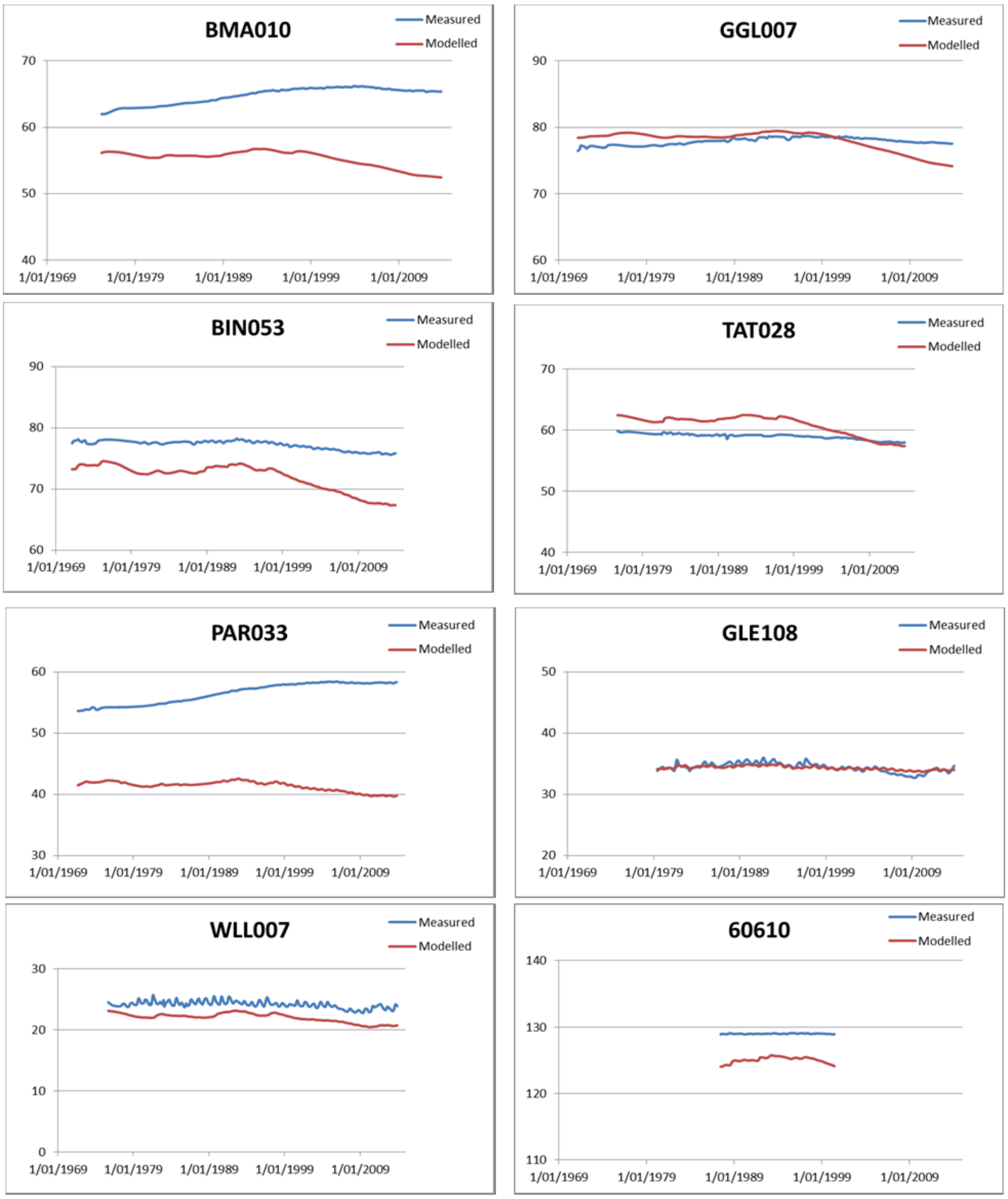


Figure 5.17 Hydrograph comparison between modelled and measured heads in layer 1, highlands.

Modelled heads are higher than measured heads in the coastal lakes and Blue Lake region hydrographs. There is a very good match in seasonal head trends for the coastal lake hydrographs (Figure 5.18). The magnitude of changes in modelled heads are larger than measured heads for the Blue lake hydrographs suggesting a higher Sy value may be needed in this region. Future work that uses a non-uniform approach to representing storage in each layer would improve the transient model calibration, but is outside the scope of the current project given available data and time constraints.

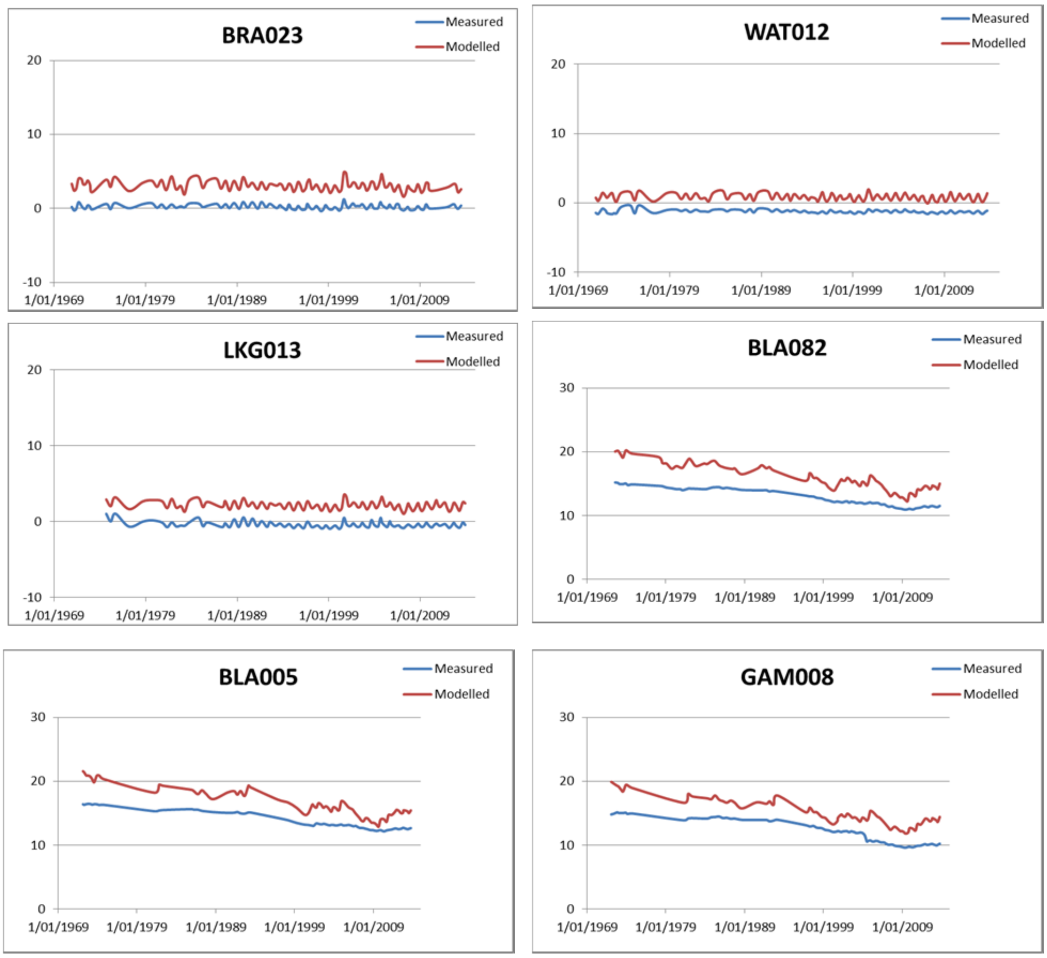


Figure 5.18 Hydrograph comparison between modelled and measured heads in layer 1, near coastal lakes (BRA023, WAT012, LKG013) and near Blue Lake (BLA082, BLA005, GAM008).

The match between modelled and measured heads in layer 3 is variable across hydrographs, with, for example, a good match in 101239, MAC057 and LAN018 and a head difference of about 20 m in RIV065 (Figure 5.19 and Figure 5.20). In layer 3 the residuals are largest at the coast near Robe, where the density corrected heads are less than the measured heads, this discrepancy is likely due to the offshore extension of the aquifer. The head difference in RIV065 occurs because the density corrected heads at the coast are less than the measured heads and this discrepancy is likely associated with the offshore extension of the confined aquifer off-shore. Short-term head trends are similar in the majority of hydrographs. Modelled heads have a steeper long-term decline than measured heads after around 1990 in a number of hydrographs, especially BIN049. For the hydrographs near to extraction wells (Figure 5.20) the seasonal change in measured heads is not matched by the model, as expected because the model averages extraction impacts out over a 1 km x 1km cell size. The rise in measured hydrographs in recent years is thought to be due to rehabilitation of leaky confined wells in the area. This rising trend is not matched by the model, despite that reductions in extraction from rehabilitated wells was included within the model.

Figure 5.19 Hydrograph comparison between modelled and measured heads in layer 3 regional bores.

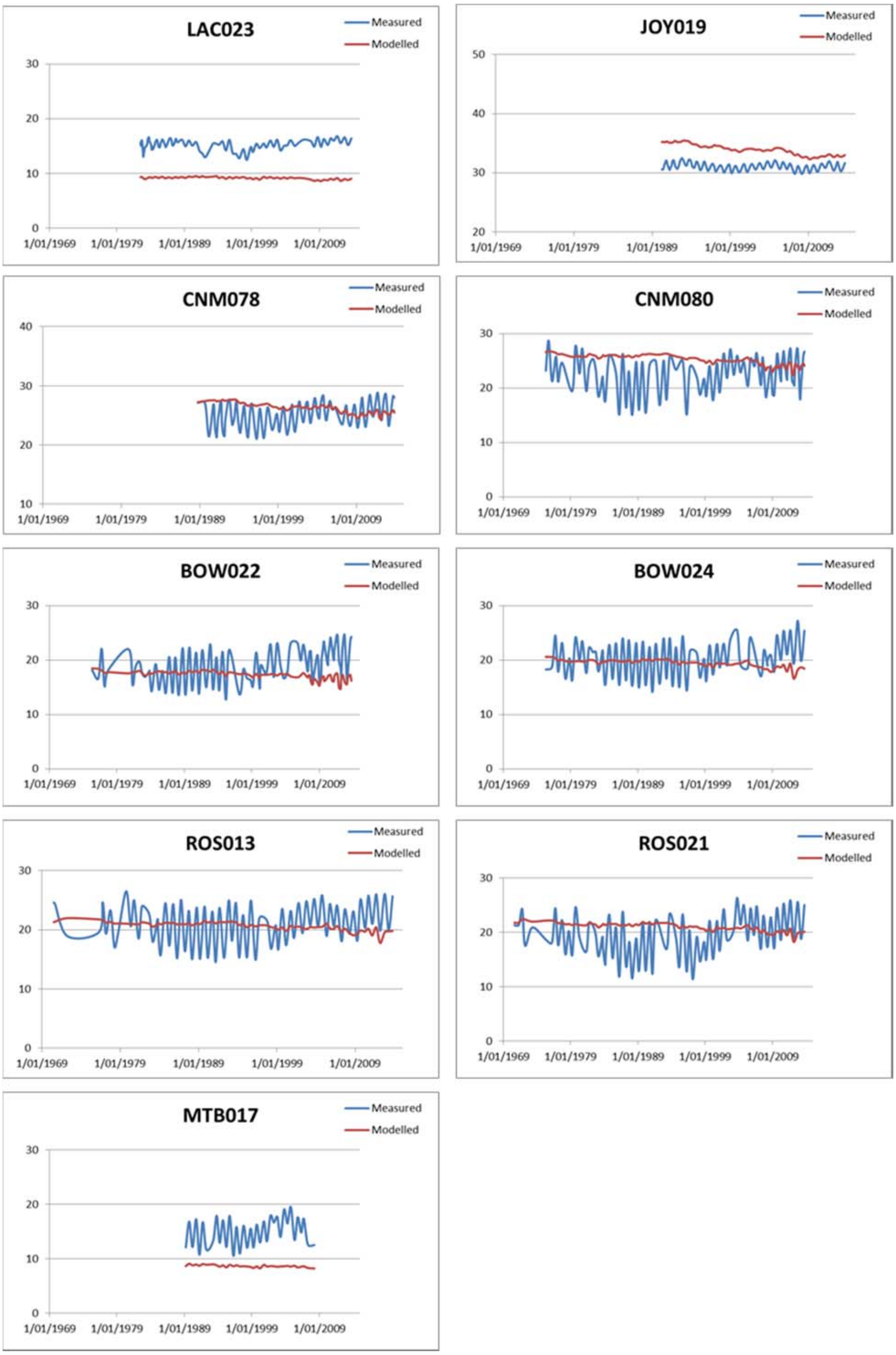


Figure 5.20 Hydrograph comparison between modelled and measured heads in layer 3 near extraction bores.

6 MODFLOW Water Balance Results

6.1 Water Balance for the Model Domain

Figure 6.1 shows the transient water balance for all layers over the model domain. The largest fluxes in the system are recharge, evapotranspiration and net coastal flux. Evapotranspiration, net coastal flux, flux to drains and change in net storage have seasonal trends (although this is difficult to see for the drains). The water balance at steady-state and the annual average water balance in 1983, 1993, 2003, 2013 is shown in Table 6.1. In 2003 and 2013, the flows to the drains estimated by the model are 224 GL/y and 223 GL/y, respectively. These values are considered reasonable as they are less than the sum of measured drain discharge to the sea and estimated evaporation from the drains, which is 425 GL/y (see Section 2.7.2) and considered to be an upper limit for drain losses. The decadal average net recharge (i.e., gross recharge minus groundwater ET) obtained from the model is 1248 GL/y (spatial average of 48 mm/y). This compares well to the estimate of Crosbie et al. (2015) for the same period, which is 40 mm/y.

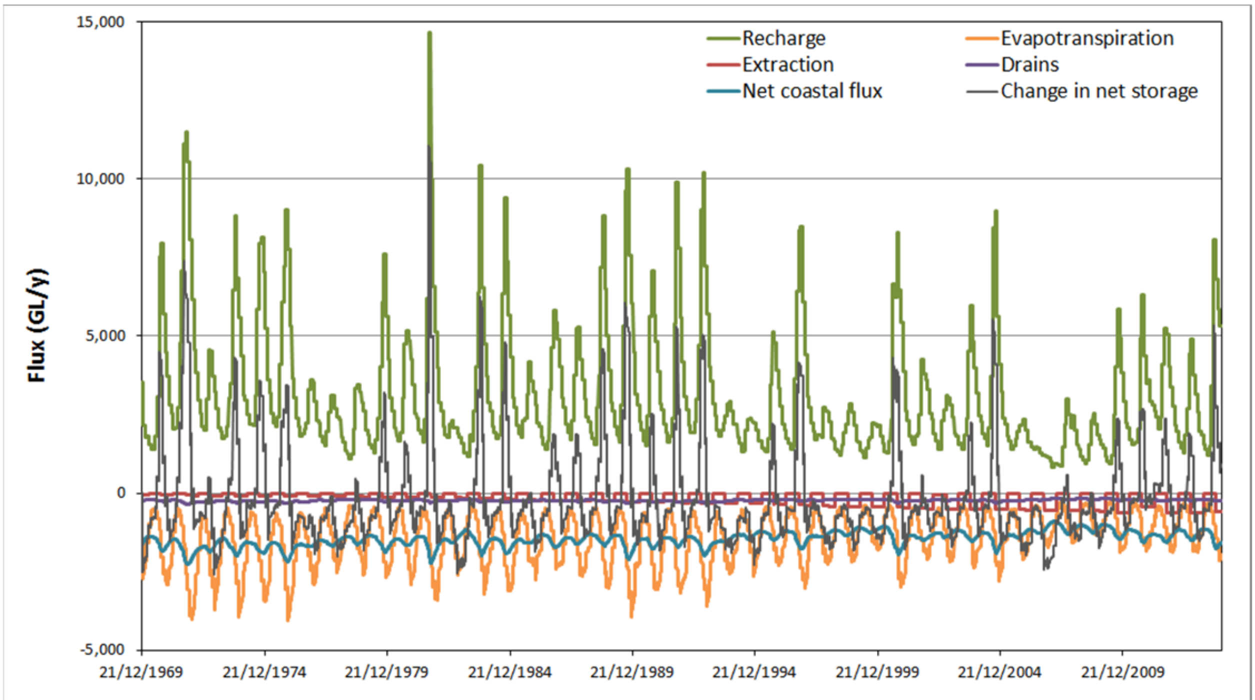


Figure 6.1 Modelled transient water balance.

Table 6.1 Modelled water balance at steady-state(1965-1974) and the annual average water balance in 1983, 1993, 2003, 2013. Please note that there is a high degree of uncertainty in the magnitudes of the water balance components presented in this table and an appropriate assessment of this uncertainty should be carried out before they are used for management purposes.

	Water balance component	Steady-state (GL/y)	1983 (GL/y)	1993 (GL/y)	2003 (GL/y)	2013 (GL/y)
Inflows	Gross recharge*	3,537	3,633	2,909	2,855	3,454
	Coastal boundary	4	9	5	9	11
Outflows	Evapotranspiration	-1,648	-1,435	-1,857	-1,212	-1,101
	Extraction	-40	-89	-174	-265	-316
	Drains	-244	-229	-269	-224	-223
	Coastal boundary	-1,609	-1,499	-1,591	-1,326	-1,379
	Net storage change	0	389	-976	-162	445
	Error	0	0	0	0	0

6.2 Water Balance for the Lower Limestone Coast Prescribed Wells Area

The Lower Limestone Coast Prescribed Wells Area (LLC PWA), shown in Figure 6.2, is the area of interest for this study.

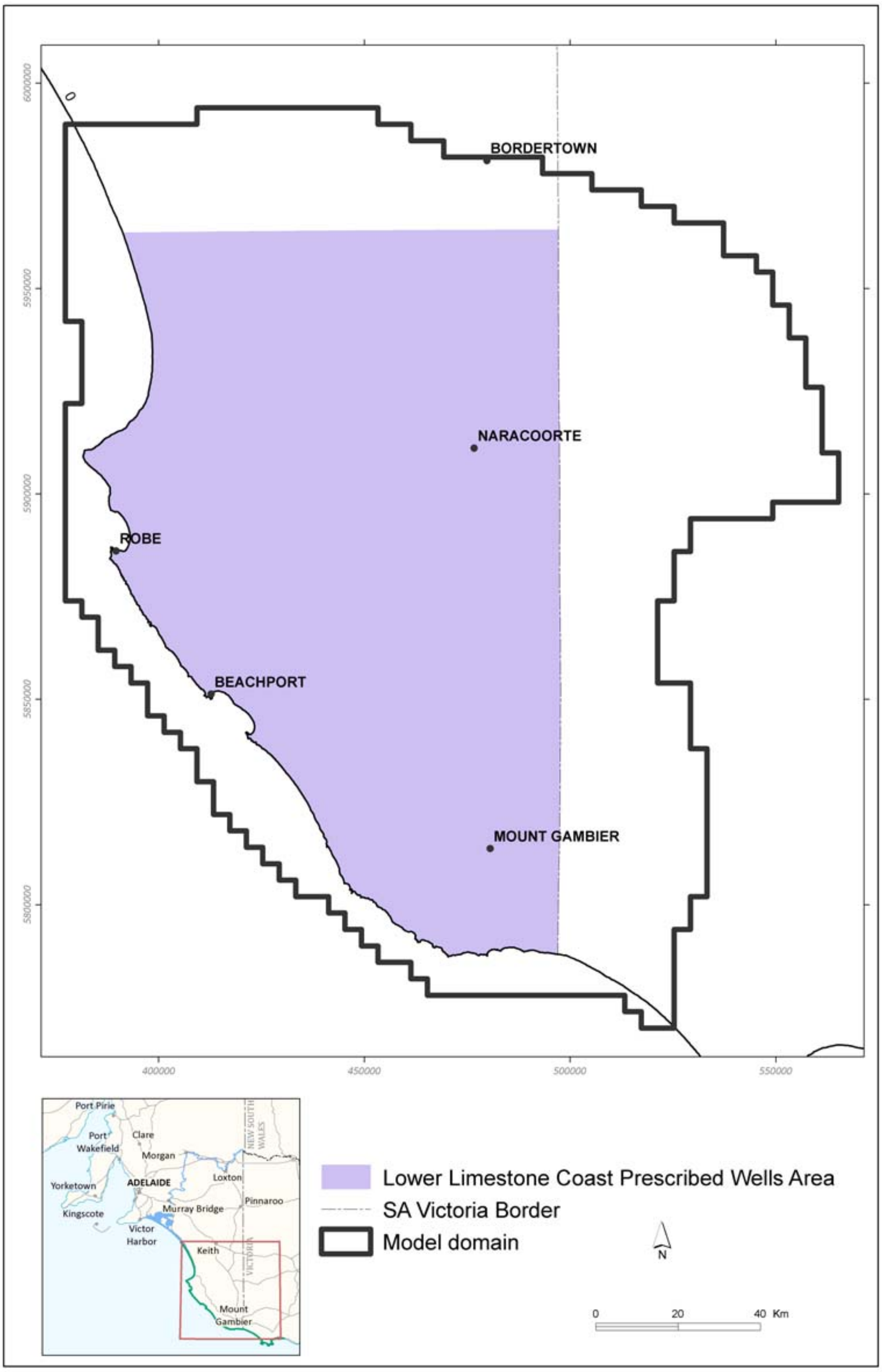


Figure 6.2 Lower Limestone Coast Prescribed Wells Area

Figure 6.3 shows the transient water balance for all layers for the LLC PWA. The water balance at steady-state and the annual average water balance in 1983, 1993, 2003, 2013 for the LLC PWA is shown in Table 6.2.

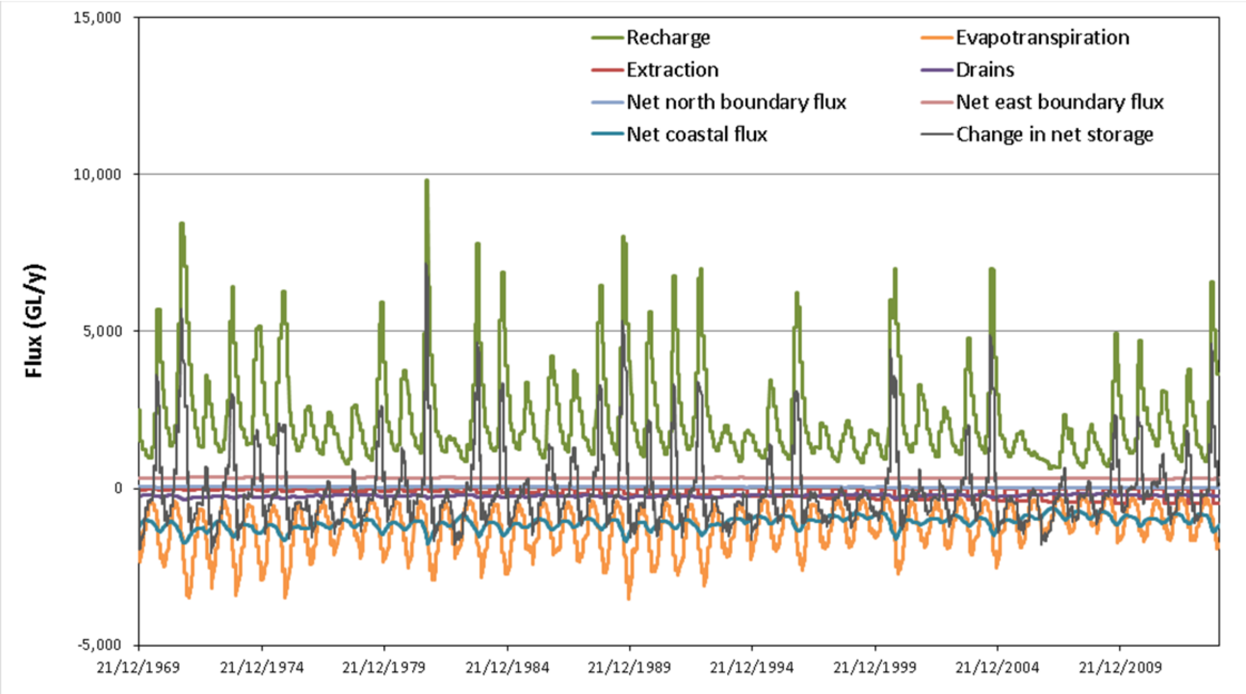


Figure 6.3 Modelled transient water balance for the LLC PWA.

Table 6.2 Modelled water balance at steady-state and the annual average water balance in 1993, 2003, 2013 for the LLC PWA. Please note that there is a high degree of uncertainty in the magnitudes of the water balance components presented in this table and an appropriate assessment of this uncertainty should be carried out before they are used for management purposes.

	Water balance component	Steady-state (GL/y)	1983 (GL/y)	1993 (GL/y)	2003 (GL/y)	2013 (GL/y)
Inflows	Gross recharge*	2495	2754	1952	2238	2553
	Coastal boundary	4	8	4	8	10
	Eastern boundary	351	348	353	324	313
	Northern boundary	60	61	62	51	45
Outflows	Evapotranspiration	-1408	-1246	-1600	-1084	-986
	Extraction	-33	-68	-126	-199	-249
	Drains	-244	-229	-269	-222	-218
	Coastal boundary	-1200	-1137	-1176	-1008	-1026
	Eastern boundary	-9	-9	-11	-6	-3
	Northern boundary	-15	-15	-16	-16	-14
	Net storage change	0	467	-825	86	425
	Error	0	0	0	0	0

The model provides an estimate of fluxes across the South Australia - Victoria border and into the LLC PWA (i.e., across the eastern boundary). At steady-state, the modelled inflow from Victoria is 351 GL/y (see Table 6.2). The majority of this occurs in layer 1 (310 GL/y). The model suggests that flows from Victoria are reasonably constant over the period of the transient simulation, as shown in Figure 6.3. Net outflows across the northern boundary of the LLC PWA are small, being 45 GL/y at steady-state and 31 GL/y in 2013.

Figure 6.4 shows a comparison of the cumulative annual average deviation from the long-term average of net storage change, net recharge (i.e., gross recharge minus evapotranspiration) and rainfall in the LLC PWA. There is a close relationship between net recharge and storage change, and both of these plots can be seen to follow the rainfall cumulative deviation trend.

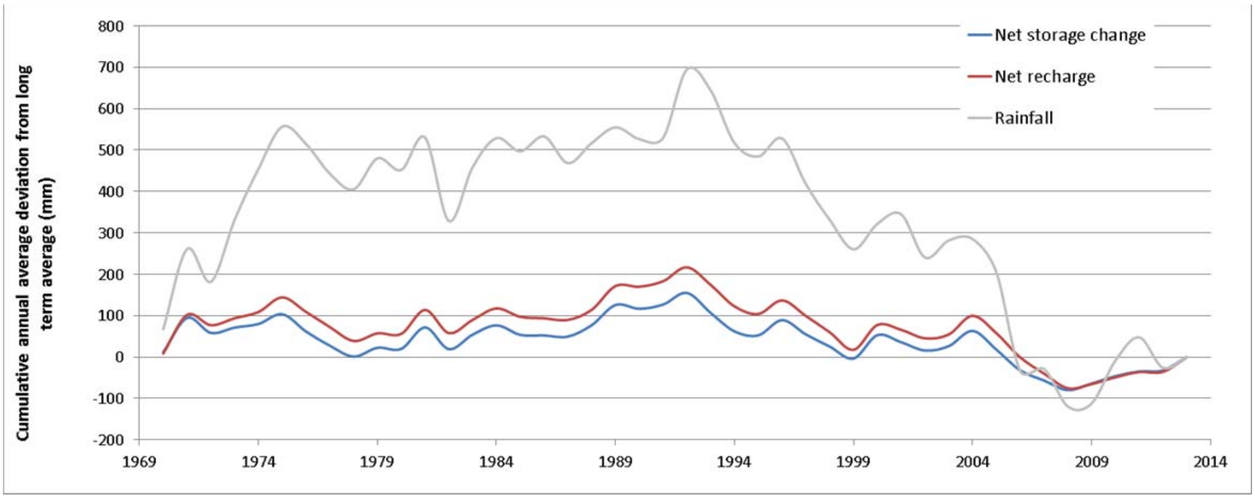


Figure 6.4 Cumulative annual average deviation from the long-term average for change in net storage, net recharge, and rainfall in the LLC PWA

7 Sensitivity and Uncertainty Analysis

The sensitivity of model outputs to changes in key hydraulic parameters, that are poorly constrained, was carried out using a manual approach. This involved changing a single model parameter, re-running the model to obtain a new set of heads and fluxes and observing the effect of the change. The purpose is to determining how sensitive the model is to each parameter (Barnett et al., 2012). The baseline simulation is the calibrated steady-state model. Sensitivity to changes in (gross) recharge, drain conductance and hydraulic conductivity of layer 1, 2 and 3 was assessed.

Uncertainty associated with the use of FAO56 potential ET, as opposed to pan potential ET was assessed by applying pan PET values as ET rates within the steady state model. Efforts to assess uncertainty associated with the use of the modified extinction depth approach to calculating groundwater ET (that has been applied within the SE model) were hampered by non-convergence occurring within the steady state model when traditional extinction depth approaches (i.e., using a mean DEM value for the ET surface and a spatially extinction depth of 2 m) were used. For each parameter tested via the sensitivity and uncertainty analysis, the main water budget outputs and the model error statistics are given (Table 7.1).

Table 7.1 Sensitivity and uncertainty analysis results

Parameter variation	Recharge (GL/y) *(mm/y)*	ET (GL/y) *(mm/y)*	Net coastal flux (GL/y) *(mm/y)*	Drain fluxes (GL/y) *(mm/y)*	SRMS (%)	RMSE (m)
Base Case	3536 *137*	1647 *64*	1606 *61*	245 *9.5*	3.6	5.4
Recharge x 2	7073 *275*	4025 *156*	2589 *100*	412 *16*	5.3	8.1
Recharge x 0.5	1768 *68*	614 *24*	979 *38*	137 *5.3*	11	7.0
Drain Conductance x 10	3536 *137*	1188 *46*	1450 *56*	859 *33*	3.6	5.5
Drain Conductance x 0.1	3536 *137*	1816 *70*	1649 *64*	31 *1.2*	3.6	5.4
K Layer 1 x 10	3536 *137*	342 *13*	3113 *121*	45 *1.7*	16	24
K Layer 1 x 0.1	3536 *137*	2776 *108*	483 *19*	238 *9.2*	7.1	11
K Layer 2 x 10	3536 *137*	1610 *62*	1634 *63*	253 *9.8*	4.4	6.1
K Layer 2 x 0.1	3536 *137*	1707 *66*	1552 *60*	237 *9.2*	3.5	5.3
K Layer 3 x 10	3536 *137*	1150 *45*	2141 *83*	206 *8.0*	6.4	9.8
K Layer 3 x 0.1	3536 *137*	1768 *69*	1486 *58*	243 *9.4*	4.1	6.3
Pan Potential ET	3536 *137*	1799 *70*	1482 *58*	216 *8.4*	3.6	5.4

The sensitivity analysis indicates that increasing the recharge by a factor of 2 increased groundwater ET (by 140%), increased net coastal fluxes (by 60%) and increased drainage fluxes (by 68%). Increasing recharge reduced the goodness-of-fit, with SRME increasing from 3.6% to 5.4%. Reducing the recharge by a factor of 2 reduced the groundwater ET (by 63%), reduced net coastal fluxes (by 39%) and reduced drainage fluxes (by 44%). Reducing recharge by a factor of 2 worsened the goodness-of-fit significantly, with the SRMS increasing from 3.6% to 11%.

Increasing the drain conductance by a factor of 10, increased drainage fluxes significantly (from 245 GL/y to 859 GL/y, an increase of 250%) and reduced both groundwater ET and net coastal fluxes. Conversely, reducing drain conductance by a factor of 10 reduced drainage fluxes (from 245 GL/y to 31 GL/y, a reduction of 87%) and increased both groundwater ET and coastal fluxes. The changes in drain conductance had minimal impact on the model goodness-of-fit. Therefore, the calibration process is not able to inform drain conductance on the basis of the current observation dataset.

Increasing the *K* of layer 1 worsened the SRMS significantly (from 3.6 to 16%) and had a large impact on the water balance, with net coastal fluxes increasing from 1606 GL/y to 3113 GL/y, ET reducing from 1647 GL/y to 342 GL/y and drain fluxes reducing from 245 GL/y to 45 GL/y. Reducing the *K* of layer 1 also worsened the SRMS (from 3.6 to 7.1), and reduced net coastal fluxes and increased ET and drainage fluxes. Increasing *K* had a larger impact on the SRMS and the water balance than did reducing *K*.

Increasing the *K* of layer 2 worsened the SRMS (from 3.6 to 4.4%) and increasing the *K* led to a small improvement in SRMS (from 3.6 to 3.5%). Changing the value of *K* had a small effect on water balance components.

Increasing the *K* of layer 3 worsened the SRMS (from 3.6 to 6.4%) and increased the net coastal flux from 1606 GL/y to 2141 GL/y, and reduced ET from 1647 GL/y to 1150 GL/y and drain fluxes from 245 GL/y to 206 GL/y. Reducing the K of layer 3 also worsened the SRMS (from 3.6 to 4.1), and reduced net coastal fluxes and increased ET and drainage fluxes. Increasing *K* had a larger impact on the SRMS and the water balance than did reducing *K* in layer 3. The SRMS and water balance are more sensitive to *K* values in layer 1 than in layer 2 or layer 3.

As expected, the use of pan potential ET instead of FAO56 potential ET resulted in an increase in groundwater ET (from 1647 GL/y to 1799 GL/y) and a decrease in net coastal flux and drainage fluxes. The change is relatively small in water balance elements and therefore the choice of pan or FAO56 potential ET is not considered to be a large source of uncertainty in the model.

8 Discussion and Conclusions

The regional water balance model consists primarily of a three layer transient MODFLOW groundwater flow model, which has been developed for a large area of the South East of South Australia, including the LLC PWA, and extending across the SA-Vic border. This is the first model to include details of both the unconfined and confined aquifers in this region, and that covers the entire regional groundwater flow system. The groundwater model is complemented by a recharge model that has undergone significant validation and testing (Morgan et al., 2015). New data sets were developed as part of the project and these have been implemented in the groundwater and recharge models, including hydrostratigraphy, man-made drains, groundwater extraction and historical land use. The groundwater and recharge models therefore act as databases of the latest climate, soils, land use, and hydrogeological data for the region.

The regional groundwater flow model described here includes all available information on the conceptual model, including hydrostratigraphy, current and historical groundwater extraction and man-made drains. A particular focus of the project was on the quantification of rainfall recharge. Despite being a very large component of the regional water balance, a suitable spatial and temporal rainfall recharge dataset that had been validated against real measured recharge data did not yet exist for the study area. For the initial model scenarios reported here, spatially and temporally variable rainfall recharge input data was developed using the Richard's Equation-based LEACHM unsaturated zone model (Hutson, 2003), implemented in a GIS framework, following previous work in the South East by Fleming and Hutson (2014). The recharge and evapotranspiration outputs of the unsaturated zone model were compared against datasets based on the CSIRO MODIS reflectance based scaling evapotranspiration (CMRSET) algorithm (Guerschman et al. 2009) that had been evaluated as part of Phase 1 of the Regional Water Balance project (Crosbie and Davies, 2013; Crosbie et al., 2015). This resulted in a series of improvements to the recharge model used by Fleming and Hutson (2014), and an improved confidence in the use of its outputs in the regional groundwater flow model (Morgan et al, 2015).

A new method for representing groundwater ET with the MODFLOW EVT package was employed within the groundwater model and involved the use of a modified extinction depth approach, as outlined in Morgan et al., (2015). This new approach scales groundwater ET in each MODFLOW cell by the relative area of the cell that is inundated. The approach was validated through comparison with CSIRO MODIS datasets described above. Traditional methods for applying the EVT package, that involve the use of a spatially uniform extinction depth of 2 m (somewhat arbitrarily selected) and an ET surface determined using an approximation of the ground surface elevation in the cell e.g., using the mean DEM value in the model cell, failed to converge within the South East model. This convergence failure is thought to be due to large changes in calculated groundwater ET fluxes between time steps that occur in shallow water table environments such as the South East. The modified extinction depth approach overcomes this problem because it smooths out the changes in groundwater ET between time steps.

Aquifer hydraulic parameters within layer 1 of the groundwater model were subdivided into five zones based on the distribution of geology and the approximate location of the Tartwaup Fault. Layer 2 was treated as a single unit of lower hydraulic conductivity. Layer 3 was divided into four zones that were developed by amalgamating hydraulic conductivity zones used by Brown (2000) in the Tertiary Confined Sand aquifer model, as well as by considering measured head contours. The steady-state model takes less than a minute to run and calibration was carried out using PEST. The transient model takes about 15 hours to run and therefore calibration of storage parameters was carried out using a manual trial and error approach. Storage parameters were implemented using a single zone in each layer. There was limited spatial hydraulic property data for the study area and hence only a small number of zones have been employed during calibration. Recalibration using more complex methods, such as pilot points, is recommended when additional hydraulic parameter data becomes available.

Despite the relatively simple nature of the groundwater model's parameter distributions, the calibration statistics are relatively good (steady-state model root-mean-square error (RMSE) = 5.4 m and scaled root-mean-square error (SRMS) = 3.6%; transient model RMSE = 6.5 m and SRMS = 5.0%). While the regional-scale measures of fit are relatively good, there are areas in the model with up to a 19 m discrepancy between measured and modelled heads.

The transient model produces reasonable water balance results, based upon comparison with estimates of net recharge (i.e., gross recharge minus groundwater ET), drainage fluxes, coastal discharge fluxes and inter-aquifer leakage. For the 2001 to 2010 period the model produces a spatially averaged net recharge (i.e., gross recharge minus groundwater ET) of 48 mm/y, which compares well to the estimate by Crosbie (2015) of 40 mm/y for the same period. Also, the model estimates drainage fluxes of around 250 GL/y for the entire simulation period, which compares well to the sum of measured drain flows to the sea and estimates evaporation from the drains, which is 425 GL/y (and considered an upper limit). Modelled coastal discharge fluxes can be compared with an estimate obtained from an environmental tracer study carried out during Phase 1 of this project (Lamontagne et al., 2015). That study estimated coastal groundwater discharge in the near-shore zone between Port MacDonnell and the SA/Victorian border to be 50 to 150 GL/yr. Extrapolation of this along the entire coastline of the study area results in a value of 250 to 750 GL/yr. The modelled value is 1368 GL/y. As both of the modelled aquifers are known to extend offshore, it is likely that some discharge of groundwater occurs further out to sea than the near-shore zone sampled during the Phase 1 investigation, and therefore the modelled value appears reasonable.

The steady-state model predicts a flow from layer 1 to layer 3 (through layer 2) of 317 GL/y. This value is higher than the rough estimate of 20 – 80 GL/y which is based on the point-scale isotopic analyses of Harrington et al. (1999). However, given the uncertainty associated with both estimates, it is considered reassuring that values of a similar order of magnitude were obtained. The velocity vectors through the base of layer 1 predicted by the steady-state model suggest a pattern of inter-aquifer leakage that is more complex than previously thought based upon observed head differences and trends in groundwater hydrochemistry and isotopes, particularly in the north of the model domain. However, in general, the locations of downward flow and upward flow agree with measured head differences between layer 1 and layer 3.

The model allows an estimate of fluxes across the South Australia - Victoria border and into the LLC PWA (i.e., across the eastern boundary) and across the northern border of the LLC PWA. Modelled net inflows from Victoria and net outflows across the northern boundary are reasonably constant over the period of the transient simulation. In 2013 net inflows from Victoria are 310 GL/y and net outflows across the northern boundary are 31 GL/y.

The transient hydrographs show a reasonably good match between short-term (i.e., seasonal) head changes in the majority of cases. This indicates that seasonality of recharge, groundwater evapotranspiration and extraction are being represented with reasonable accuracy in the model. Long-term trends in head also match reasonably well, indicating that long-term climate, extraction, irrigation and land use change impacts are generally well represented including, for example, the rise in water levels following the 1983 Ash Wednesday bushfires, which destroyed extensive areas of plantation forestry and native vegetation, with the resulting increase in recharge being obvious in hydrographs around that area. However, differences in long-term modelled and measured head trends do occur in hydrographs close to the Kimberley Clark pulp and paper mills and South Australian highlands. Also, a number of hydrographs have a steeper decline in modelled heads than measured heads for the period since 1990, especially in forested areas.

The sensitivity analysis indicates that the water balance and goodness-of-fit statistics are most sensitive to changes in (gross) recharge and hydraulic conductivity in layer 1. Therefore, future work to improve the accuracy of these data sets will have a significant benefit in terms of increasing confidence in model outputs. Changing drain conductance had a large impact on drainage fluxes but minimal impact on the model goodness-of-fit. Therefore, the calibration process is not able to inform drain conductance on the basis of the current observation dataset. Monitoring of flows and water levels in the drains would reduce uncertainties associated with drainage fluxes.

A number of improvements to the regional water balance model are required to improve its suitability for use as a quantitative management model. For example, the calibration approach and uncertainty analysis should be upgraded to better capture the complex nature of the aquifer characteristics. Nonetheless, the model is considered to have the majority of the characteristics of a Class 2 model, as described by the Australian Groundwater Modelling Guidelines (Barnett et al., 2012). As such, it is able to provide: (a) valuable information on intermediate and regional groundwater flow paths, particularly in relation to the influence of these on wetlands (see Taylor et al. (2015)), (b) areas of the model that require improved conceptualisation and the attainment of additional field measurements, (c) semi-quantitative information about the likely impacts of future climate or management scenarios, and (d) improved estimates of the regional water balance and how it varies over time.

8.1 Improved Knowledge of the Regional Water Balance for the LLC PWA

An objective of the regional groundwater flow model was to provide more information about the regional water balance for the LLC PWA. The model forms a tool that can be used to estimate the regional water balance and observe how it changes over time or under different scenarios. Table E.1 shows a decadal average water balance for the LLC PWA obtained from the groundwater model that was developed in this project, compared with that developed as part of the South East Science Review by Wood (2010). The LLC PWA is a sub-area of the model domain and therefore these values differ to those presented above.

Net recharge and extraction fluxes are very similar for the two water balances. Flows to drains are larger in the groundwater model, but this value was checked against measured drainage flows at the coast and evaporation from drains and is thought to be reasonable. Additionally, Wood (2010) only considered outflows at the coast (and not inflows to the drains), which in 2010 were relatively low. The groundwater model allows for the estimation of lateral flows into and out of the LLC PWA and these lateral flows are a large component of the water balance. There is a net outflow of 952 GL/y across the coastal boundary, a net inflow of 309 GL/y across the eastern boundary (from Victoria) and a net outflow of 31 GL/y across the northern boundary. The negative change in net storage of -116 GL/yr estimated by the groundwater model is consistent with declining groundwater heads over the 2004 to 2013 period. If the majority of this storage change occurs in the unconfined aquifer, and assuming a specific yield of 0.1, this represents an average drop in the water table of approximately 0.68 m across the LLC PWA between 2004 and 2013. This compares well with observation well hydrographs for the unconfined aquifer, which show an average drop in water level of 0.65 m across the LLC PWA between March 2004 and March/April 2013.

The regional groundwater flow model includes all available data and system understanding to date and the comparisons presented above are encouraging that it provides a reasonable representation of the regional water balance. However, in considering these water balance outputs, it is important to recognise that the model is a simplified representation of a complex natural system. As such, there are still large amounts of uncertainty around each of the water balance components. It is likely that these estimates will change as improvements are made to the regional model over time following the recommendations provided in Section 2.2.4. A formal uncertainty analysis of the influence of model parameters on the magnitudes of the different water balance components should be carried out before these or any other water balance outputs are used to influence management decisions.

As an example, rainfall recharge is a process that is notoriously difficult to quantify, because of the number of factors that influence it and the fact that it is difficult to measure. However, it is often a large component of regional water balances. The use of various different but equally valid recharge modelling techniques can result in vastly different recharge estimates. This project has included a large effort to improve the capability to model rainfall recharge in the South East, using a combination of new and different modelling approaches and all available field data including remote sensing data. Despite this, there remains a difference of 20% between the modelled and measured (remote sensing) average areal recharge rate.

Table 8.1 Comparison of the LLC PWA water balance from the South East Science Review (Wood, 2010) and the results of the current groundwater and recharge modelling. The water balance by Wood (2010) is a first-order approximation for 2010, whereas the water balance from this project is a decadal average (2004-2013). Please note that there is a high degree of uncertainty in the magnitudes of the water balance components presented in this table and an appropriate assessment of this uncertainty should be carried out before they are used for management purposes.

	Water balance component	Wood (2010) (GL/y)	Groundwater model (GL/y)
Inflows	Net recharge*	682	930
	Coastal boundary	**ND	10
	Eastern boundary	ND	310
	Northern boundary	ND	50
	Surface water inflows	15	ND
Outflows	Extraction	285	220
	Drains	99	220
	Coastal boundary	ND	960
	Eastern boundary	ND	5
	Northern boundary	ND	15
	Discharge from gw springs	97	ND
	Net storage change	216	-120

*Net recharge estimates for Wood (2010) are comprised of 1,256 GL/y (recharge) +23 GL/y (drainage from flood irrigation) + 309 GL/y (rainfall on surface water bodies) -601 GL/y (evaporation from surface water bodies) -199 GL/y (interception of recharge by plantation forestry) -106 GL/y (direct extraction from plantation forestry). Net recharge from the groundwater model is comprised of 1,890 GL/y gross recharge and -969 GL/y groundwater evapotranspiration.

8.2 Limitations of the Current Model and Recommendations for Further Work

The large spatial scale of the study area requires the regional-scale model to have relatively coarse levels of spatial discretisation (i.e. large model cells). For this reason, regardless of its level of calibration or the amount of input data included, the regional groundwater model will be able to represent intermediate and regional groundwater flow systems, but not local-scale processes. With this in mind, it is intended that the regional groundwater flow model will provide a basis for future local-scale groundwater models to answer local-scale hydrogeological questions.

It is important to remember that the regional groundwater flow model is a simplified model of a complex natural system. As such, it includes a large number of standard assumptions about the system it represents and its outputs are limited by the degree of initial system understanding and amount of input data available. For example, there is limited field data within the large model domain on hydraulic parameters and fluxes. This restricts the ability to constrain many of the parameters used within the model and hence there is currently a high degree of uncertainty in model outputs. Future work is needed to improve the calibration when additional information becomes available. The model has been developed as a regional-scale water balance model and hence the focus has been on incorporating large scale water balance processes rather than calibration to measured heads. Additional work is needed for the model to be able to simulate localised changes in water levels in response to stresses such as pumping. A detailed uncertainty analysis is required to improve understanding of the models suitability for use as a management tool.

A number of activities are recommended to improve the knowledge pertaining to the water balance of the South East, and to characterise and reduce the uncertainty that is inherent in the recharge and groundwater models that were developed as the central focal points of this project.

- The sensitivity analysis indicated that the model water balance and goodness-of-fit are highly sensitive to hydraulic conductivity values in layer 1 (the unconfined aquifer). There is a surprisingly small amount of measured hydraulic parameter data available for the South East of South Australia, which has impacted calibration activities within this project. Improving the dataset of measured aquifer hydraulic parameters will enhance future calibration activities. Additional pump test data is available for the Naracoorte Ranges, Tatiara, Upper South East, Bordertown and Padthaway regions (George Mackenzie, DEWNR, pers. comm., April 2015). Obtaining this information will require searching for the relevant reports, which are only available in hard copy in the majority of cases, if available at all. It is recommended that all pump test data for the South East be entered into SAGeodata.
- Improved understanding of the flow across the Tartwaup Fault is required to improve the modelling of this feature. A zone of lower hydraulic conductivity was used to represent the fault. Future work should consider the use of the MODFLOW Horizontal Flow Barrier package to represent the fault.
- Additional data is needed for the Victorian portion of the model domain, if available, including measured heads and hydraulic parameters.
- The sensitivity analysis indicated that the model water balance and goodness-of-fit are highly sensitive to changes in recharge. Rainfall recharge is a process that is notoriously difficult to quantify, because of the number of factors that influence it and the fact that it is difficult to measure. However, it is often a large component of a regional water balance. This project has included a large effort to improve the capability to model rainfall recharge in the South East, using a combination of new and different modelling approaches and all available field data including remote sensing data. Even following this, there remains a difference of 20% between the modelled and measured (remote sensing) average areal recharge rate suggesting that further work, to refine these methodologies and draw comparisons between them would be beneficial.
- The recharge model needs further refinement to improve representation of lag times in recharge reaching the water table after clearing of native vegetation in the 1960s, if we wish to represent the effects of this process accurately in the model. One approach to doing this would be to use a spatially variable soil column depth for the model domain.
- Seasonal trends in modelled heads show a good match to measured heads in the unconfined aquifer. This provides evidence that the ratio of net recharge to storage (in particular in the upper model layer) in the model is reasonable. However, long-term trends in modelled groundwater heads show a steeper decline than measured heads after 1990 in some areas. This requires further investigation to ascertain aquifer parameters and/or LEACHM crop factors that require adjustment in these areas.
- Modelling of the confined aquifer requires further attention to be able to better simulate seasonal and long-term trends, particularly in the areas of highest groundwater use.
- The sensitivity analysis indicated that while drainage flows are highly sensitive to drain conductance, changes in drain conductance had minimal impact on the model goodness-of-fit. Therefore, the calibration process is not able to inform drain conductance on the basis of the current observation dataset. Incorporating flux estimates (i.e., for drain discharge and discharge to wetlands, if these can be obtained) into the calibration process will assist in reducing the non-uniqueness of calibrated parameters. Further, regularisation applied to parameters estimated during calibration will further alleviate non-uniqueness and thereby provide more reliable model parameters.
- A spatially variable extinction depth has been used, following the modified extinction depth function described in Section 4.8. It is recommended that a time-varying extinction depth approach be employed to incorporate changes in the spatial extent of forestry.

- The representation of topography was found to have a significant influence on modelled groundwater evapotranspiration, and hence the water balance. At a regional-scale, topographic variation is downscaled significantly within regional-scale models. For the groundwater model developed as part of this project, each of the 1 km square groundwater model cells has 10,000 DEM cells (of 10 m square) and hence there is a significant loss of information relating to topographic variation and evapotranspiration fluxes. To overcome this, a modified extinction depth approach was applied within the MODFLOW EVT package which better represents which scales evapotranspiration using topographic variation information from the DEM. Preliminary analysis indicated an improved fit between modelled and observed evapotranspiration (i.e., the CMRSET estimates of evapotranspiration) using this approach compared to traditional approaches. A more detailed assessment of the value of this new approach would benefit future modelling activities for the South East, and regional scale modelling of other shallow water table environments.
- Density corrected heads are applied at the coast (which is better than using values of 0 m AHD), but there remains areas where the assigned coastal boundary head differs to measured values. Future work should extend the model domain offshore and use a general head boundary to better represent heads at the coast. More work is needed to account for the impact of the continuation of aquifers offshore on the choice of head values at the coast.
- Additional sensitivity and uncertainty analyses will provide an indication of the uncertainty around flux predictions and more importantly, which parameters are most influential to individual flux predictions. The sensitivity of the model to initial conditions should also be assessed.
- Scenario modelling to evaluate possible future hydrogeological conditions in the South East, including under the impacts of climate and land-use change, are recommended.
- Further refinement of extraction rates for the Kimberley Clark extraction wells is needed.
- A significant amount of carbon-14 data exists (Love et al., 1993) and was used to guide model development but could be used as a formal calibration parameter in future to constrain groundwater flow paths and inter-aquifer leakage.
- Further work to include the new MODFLOW net recharge and recharge lookup-table approach in the regional model and an assessment of the results against the results using the LEACHM and modified extinction depth ET approach. As described below, the module has been tested within the steady-state groundwater model but requires further evaluation under transient model conditions, and the results of the new module are yet to be assessed.

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Appendix A Rehabilitated leaky confined aquifer wells

Unit No	Easting	Northing	Rehab Status at 2007	Rehab Date	Leak rate (m3/d)	Leak rate (ML/y)	Management Area	Alloc Purpose
692301956	420481	5887867	Rep	2005	86.4	31.536	Kingston	Irrigation
682300411	409389	5902229	Rep	2003	1.44	0.5256	Kingston	Irrigation
682300722	407217	5900119	NYC	2009	34.6	12.629	Kingston	Irrigation
682300733	402460	5896745	Rep	2005	80	29.2	Kingston	Irrigation
682300956	407084	5896704	Abd	2003	2160	788.4	Kingston	Irrigation
682301454	413195	5903554	Relined	1977	1.44	0.5256	Kingston	Irrigation
682301455	413079	5903440	Rep	2005	1.44	0.5256	Kingston	Irrigation
682301462	413030	5902710	Rep	2005	1.44	0.5256	Kingston	Irrigation
682301469	414671	5901325	BF	2005	1.44	0.5256	Kingston	Irrigation
682301488	416624	5904486	Abd	2003	1175	428.875	Kingston	Irrigation
682400056	403170	5927335	Rep	2002	1.44	0.5256	Kingston	Irrigation
682400429	405493	5907329	Rep	2001	23.3	8.5045	Kingston	Irrigation
692301501	417742	5897452	Rep	2002	1.44	0.5256	Kingston	Irrigation
692301510	413921	5896005	Rep	2002	1.44	0.5256	Kingston	Irrigation
692301527	413228	5890631	Rep	2003	1.44	0.5256	Kingston	Irrigation
692301529	414343	5891314	Rep	2003	544	198.56	Kingston	Irrigation
692301533	416647	5893407	Rep	2003	1.44	0.5256	Kingston	Irrigation
692301901	419792	5894148	Rep	2002	1.44	0.5256	Kingston	Irrigation
692301908	418591	5892494	Rep	2003	1.44	0.5256	Kingston	Irrigation
692301918	420950	5892783	Rep	2003	1.44	0.5256	Kingston	Irrigation
692301935	418722	5890199	Rep	2004	1.44	0.5256	Kingston	Irrigation
692301936	421424	5891372	Abd	2003	2940	1073.1	Kingston	Irrigation
692301968	419689	5886764	Rep	2005	1.44	0.5256	Kingston	Irrigation
692301983	422274	5885705	Rep	2005	1.44	0.5256	Kingston	Irrigation
692302067	420956	5876009	Rep/NYBF	2004	1.44	0.5256	Kingston	Irrigation
692302120	423110	5871201	NYC	2009	432	157.68	Kingston	Irrigation
692302667	420383	5883546	BF/NYR	2005	1.44	0.5256	Kingston	Irrigation
692302705	423203	5879098	Rep/NYBF	2005	1.44	0.5256	Kingston	Irrigation
692302709	424797	5879293	BF/NYR	2002	1.44	0.5256	Kingston	Irrigation

692302712	424895	5878489	Relined	2002	1.44	0.5256	Kingston	Irrigation
692302714	423779	5878175	Rep/NYBF	2004	1.44	0.5256	Kingston	Irrigation
692302717	422543	5877538	Rep/NYBF	2003	1.44	0.5256	Kingston	Irrigation
692302782	426298	5877930	Bkf	2002	1.44	0.5256	Kingston	Irrigation
692401045	411733	5912462	Rep	2001	1.44	0.5256	Kingston	Irrigation
692401066	413289	5908777	Rep	2005	1.44	0.5256	Kingston	Irrigation
692401070	411464	5906527	Rep	2004	1.44	0.5256	Kingston	Irrigation
692401075	412210	5905218	Abd	2000	1.44	0.5256	Kingston	Irrigation
692401103	416043	5906158	Abd	2003	1.44	0.5256	Kingston	Irrigation
682401131	408600	5937374	Bkf	2002	1.44	0.5256	Taratap	Irrigation
682300406	405347	59901240	REP	2004	1.44	0.5256		Stock
682300727	406123	5897763	Abd	2002	1.44	0.5256		Stock
682301501	417742	5897452	REP	2002	1.44	0.5256		Stock
682400015	408786	5921274	REP	2002	1.44	0.5256		Stock
682400040	401306	5930281	REP	2005	1.44	0.5256		Stock
682400052	402093	5927825	REP	2001	1.44	0.5256		Stock
682400089	406169	5930627	REP	2001	1.44	0.5256		Stock
682400092	408255	5930582	REP	2005	1.44	0.5256		Stock
682400096	405958	5929414	REP	2001	1.44	0.5256		Stock
682400107	405414	5924329	Bkf	2000	1.44	0.5256		Stock
682400138	408468	5919400	REP	2005	1.44	0.5256		Stock
682400395	400482	5906410	Abd	2003	1.44	0.5256		Stock
682400403	402760	5915043	Abd	2002	1.44	0.5256		Stock
682400429	405493	5907329	REP	2001	1.44	0.5256		Stock
682400740	408939	5934016	REP	2001	1.44	0.5256		Stock
682400834	407011	5935050	REP	2001	1.44	0.5256		Stock
682400836	407707	5935258	Abd	2002	1.44	0.5256		Stock
682400914	403506	5912611	REP	2002	1.44	0.5256		Stock
692301574	412739	5883524	REP	2001	1.44	0.5256		Stock
692301629	422808	5903638	Abd	2000	1.44	0.5256		Stock
692301758	428005	5899872	Abd	2003	1.44	0.5256		Stock
692302145	422602	5870076	REP	2002	1.44	0.5256		Stock
692302146	422916	5869619	Abd	2002	1.44	0.5256		Stock
692302319	425332	5868399	Abd	2002	1.44	0.5256		Stock
692302557	426137	5890369	Abd	2000	1.44	0.5256		Stock
692302596	426554	5885758	Abd	2002	1.44	0.5256		Stock
692302694	424097	5881349	Abd	2000	1.44	0.5256		Stock

692302782	426176	5877752	Abd	2002	1.44	0.5256	Stock
692400279	447579	5917808	REP	2005	1.44	0.5256	Stock
692400647	417849	59355785	REP	2003	1.44	0.5256	Stock
692400806	423240	5944253	Abd	2001	1.44	0.5256	Stock
692400857	421906	5933744	REP	2002	1.44	0.5256	Stock
692400875	424557	5934606	Abd	2005	1.44	0.5256	Stock
692400879	425991	5934731	REP	2005	1.44	0.5256	Stock
692400905	429302	5935699	REP	2001	1.44	0.5256	Stock
692400910	412562	5930900	Abd	2003	1.44	0.5256	Stock
692400923	413150	5931139	Abd	2003	1.44	0.5256	Stock
692401037	417738	5915180	REP	2002	1.44	0.5256	Stock
692401126	423259	5927630	REP	2005	1.44	0.5256	Stock
692401133	425257	5930228	Abd	2001	1.44	0.5256	Stock
692401152	428779	5932270	REP	2002	1.44	0.5256	Stock
692401157	430672	5929804	rep	2001	1.44	0.5256	Stock
692401163	420548	5917923	Abd	2005	1.44	0.5256	Stock
692401165	419372	5923700	Abd	2005	1.44	0.5256	Stock
692401205	431338	5925627	Bkf	2001	1.44	0.5256	Stock
692401226	429659	5922232	REP	2002	1.44	0.5256	Stock
692401257	430883	5917201	Abd	2001	1.44	0.5256	Stock
692401609	443629	5948979	REP	2001	1.44	0.5256	Stock

Appendix B Land use classes for LEACHM modelling

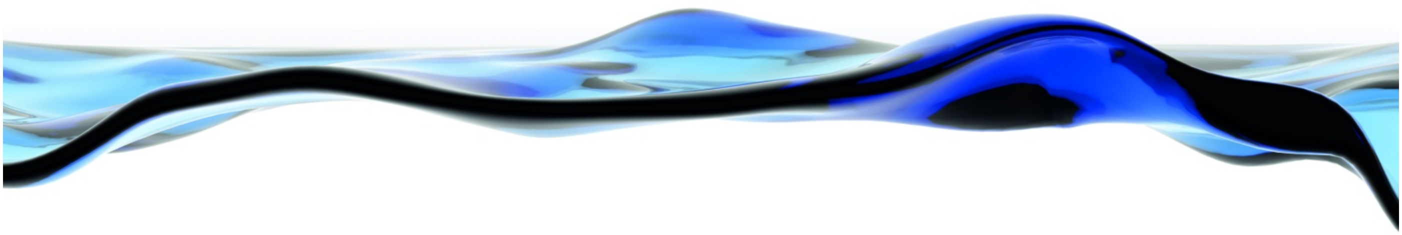
Use: start		**Jan-70**		**Feb-83**		**1990**		**Jul-01**		**Reduced LU classes**		**Reduced LU classes**
until: End		**to 1/01/1983**		**to 1990**		**to 1/06/2001**		**to 2013**		**for temporal change**		**for temporal change**
										2.4 m profile		**5.0 m profile**
Derivation:		**1969 maps developed in-house**				**1998 State land use map**		**2008 State land use map**				
	67	Rural residential	67	Rural residential	67	Rural residential	67	Rural residential	1	Built	9	Built
	78	Roads	78	Roads	78	Roads	78	Roads				
	68	Water	68	Water	68	Water	68	Water	2	Water	10	Water
	5	Other conserved area	5	Other conserved area	5	Other conserved area	5	Other conserved area	3	Grazing	1	Natural veg
	14	Grazing modified pastures	14	Grazing modified pastures	14	Grazing modified pastures	14	Grazing modified pastures			2	Grazing
			91	Burnt out							8	Cleared
	92	Cleared for forestry	92	Cleared for forestry								
	93	Recently cleared	93	Recently cleared								
					17	Pasture legumes	17	Pasture legumes	4	Crops	3	Crops
					18	Pasture legume/grass mixtures	18	Pasture legume/grass mixtures				
					22	Hay & silage	19	Sown grasses				
							22	Hay & silage				
					24	Legumes	24	Legumes				
	21	Cereals	21	Cereals	21	Cereals	21	Cereals				
					20	Cropping	20	Cropping				
					23	Oil seeds	23	Oil seeds				

						26	Seasonal horticulture				
25	Fruit/nuts	25	Fruit/nuts			25	Fruit/nuts				
36	Irrigated sown grasses	36	Irrigated sown grasses	36	Irrigated sown grasses	36	Irrigated sown grasses	5	Irrig. Pastures	4	Irrig. Pastures
				32	Irrigated modified pastures	32	Irrigated modified pastures				
						33	Irrigated woody fodder plants				
				34	Irrigated pasture legumes	34	Irrigated pasture legumes				
				35	Irrigated legume/grass mixtures	35	Irrigated legume/grass mixtures				
				39	Irrigated hay and silage	39	Irrigated hay and silage				
38	Irrigated Cereals	38	Irrigated Cereals			38	Irrigated Cereals	6	Irrig. Crops	5	Irrig. Crops
						37	Irrigated cropping				
50	Irrigated vegetables and herbs	50	Irrigated vegetables and herbs	50	Irrigated vegetables and herbs	50	Irrigated vegetables and herbs				
46	Irrigated perennial vine fruits	46	Irrigated perennial vine fruits	46	Irrigated perennial vine fruits	46	Irrigated perennial vine fruits	7	Irrig. Vines	6	Irrig. Vines
10	Hardwood plantation	10	Hardwood plantation	10	Hardwood plantation	10	Hardwood plantation	8	Hardwood	7	Forest
11	Softwood plantation	11	Softwood plantation	11	Softwood plantation	11	Softwood plantation	9	Softwood		
94	Young forestry (seedling)	94	Young forestry (seedling)								
95	Young forestry (almost closed canopy)	95	Young forestry (almost closed canopy)								

A 'cleared poygon' was overlaid on part
of the land use raster from 1950 to 1962;
after 1962 the original ratsers were used.

Appendix C Vegetation parameters used in the LEACHM model

Raster ID	Land use	Duration	Root depth (mm)	Crop cover Max (fraction)	Crop cover Harvest (fraction)	Mulch effect % of Ep	Irrigation
5	Other conserved area	Continuous	600	0.4	0.4	20	No
7	Residual native cover	Continuous	600	0.4	0.4	20	No
10	Hardwood production	Continuous	1800	0.8	0.8	50	No
11	Softwood production	Continuous	1800	0.8	0.8	50	No
14	Grazing modified pastures	02/05 31/10	720	0.7	0.3	15	No
17	Pasture legumes	02/05 31/10	720	0.7	0.3	15	No
18	Pasture legume/grass mixtures	02/05 31/10	720	0.7	0.3	15	No
19	Sown grasses	02/05 31/10	600	0.7	0.3	15	No
20	Cropping	07/06 20/12	720	0.8	0.2	0	No
21	Cereals	07/06 20/12	720	0.8	0.2	0	No
22	Hay & silage	02/05 31/10	720	0.7	0.3	15	No
23	Oil seeds	07/06 20/12	720	0.8	0.2	0	No
24	Legumes	07/06 20/12	720	0.8	0.2	0	No
25	Fruit/nuts	02/09 30/04	720	0.3	0.2	10	No
26	Seasonal horticulture	02/09 31/05	480	0.5	0.5	0	No
32	Irrigated modified pastures	07/06 30/05	720	0.8	0.8	30	Yes
33	Irrigated woody fodder plants	02/05 31/10	720	0.7	0.3	15	Yes
34	Irrigated pasture legumes	07/06 30/05	720	0.8	0.8	30	Yes
35	Irrigated legume/grass mixtures	07/06 30/05	720	0.8	0.8	30	Yes
36	Irrigated sown grasses	07/06 30/05	600	0.8	0.8	30	Yes
37	Irrigated cropping	01/01 31/12	720	0.8	0.2	0	Yes
38	Irrigated Cereals	07/06 20/12	720	0.8	0.2	0	Yes
39	Irrigated hay and silage	07/06 30/05	720	0.8	0.8	30	Yes
41	Irrigated legumes	01/01 31/12	720	0.8	0.2	0	Yes
46	Irrigated perennial vine fruits	02/09 30/04	720	0.3	0.2	60	Yes
50	Irrigated vegetables and herbs	02/09 31/05	480	0.5	0.5	0	Yes
66	Urban residential	Continuous	600	0.2	0.2	50	Yes
67	Rural residential	Continuous	600	0.2	0.2	50	Yes
68	Water	Continuous	0	0.0	0.0	100	No
69	Roads, paved surface	Continuous	0	0.0	0.0	100	No
72	Recreation and culture	Continuous	720	0.6	0.6	20	Yes



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