South East Regional Water Balance Project – Phase 2
Project Summary Report

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1 Introduction

1.1 Background

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), and the extensive scheme of natural and man-made drainage channels that moves water around the landscape, draining agricultural land and feeding the ecologically and culturally significant lakes and wetlands, is also 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) (Figure 1.). 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.

Compared with many regions of Australia, a large body of data exists for the South East, numerous research projects have been carried out and there are quite a few numerical groundwater flow models already in existence (Harrington and Lamontagne, 2013). However, this information has been limited in its applicability to addressing resource management questions because:

- The existing groundwater flow models are variable in their original objectives, system conceptualisations and input datasets, and hence are not applicable for addressing large-scale management issues.
- Most of the datasets required for the development of groundwater flow models of the study area have not been readily accessible, nor have they been in formats that could be used directly as model inputs, e.g. hydrostratigraphy data, groundwater extraction data and details of the man-made drains.
- Regional-scale recharge and evapotranspiration dataset did not exist.
- Therefore, the incorporation of recharge into groundwater models to date has consisted of implementation of recharge zones with constant rates based on long-term averages, or at best, rolling averages based on trends in rainfall. This is a common methodology employed in groundwater model development. However, this method has a limited ability for making predictions under future land use, climate or water management scenarios. It also does not incorporate the influence of depth to watertable on recharge, which is likely to be an important factor in the South East.
- Although there are point measurements of inter-aquifer leakage and evidence for its occurrence based upon groundwater environmental tracer signatures, the magnitude of this on a regional scale has been largely unknown, causing large uncertainty in how water resources should be managed.
• The most recently available information and data had not been consolidated into a conceptual model of the groundwater flow system, nor tested in a groundwater model framework to assess its quality or worth in addressing management questions.

• The most recent estimate of the water balance for the Lower Limestone Coast PWA was based on the data available at the time, but still contained a large number of limitations, including the use of long-term average flux data, uncertainties associated with groundwater extraction estimates, and limited characterisation of surface water–groundwater interactions (Wood, 2010). It included neither estimates of rates of lateral groundwater inflow to, nor submarine groundwater discharge from, the PWA, nor estimates of inter-aquifer leakage, due to a lack of available information on these water balance components.

• Knowledge of wetland-groundwater interactions has been very limited, consisting mainly of broad regional-scale assessments, and little field data.

The South East Regional Water Balance project is a collaboration between Flinders University (The National Centre for Groundwater Research and Training), 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.

This report is intended to provide a summary of the activities and major outcomes. A suite of Goyder Institute technical reports and research papers has been produced, each providing details of specific project tasks and outcomes. These are listed in Section 4.
1.2 Project Overview and Objectives

Through the partnership between Flinders University, CSIRO and DEWNR, the South East Regional Water Balance project has brought together a range of experts in groundwater modelling, recharge modelling and assessment, and surface water–groundwater interaction, as well as team members with site-specific knowledge of the hydrogeology of the South East. The project has been strengthened by the high level of
engagement with the SA Department of Environment, Water and Natural Resources (DEWNR), who are both the custodians of the data that were critical to the project outcomes and the end-users of the project outputs. This engagement was facilitated through direct contributions within the project team, involvement in the project’s Technical Working Group, and through formal stakeholder liaison meetings.

In recognition of the likely iterative approach required to build the knowledge and modelling tools required to support water management in the Lower Limestone Coast PWA, a particular focus of the project has been that the outcomes should form part of a long-term approach. As such, it was considered imperative that the outputs should be amenable to further development, be integrated with other modelling activities, and provide clear direction for further work.

1.2.1 PHASE 1

The project was undertaken in two Phases. Phase 1 (2012-2013) consisted of three tasks, which aimed to characterise key aspects of the hydrogeological conceptual model, thereby laying the foundation for the development of the regional water balance model:

- Task 1 – Development of a regional water balance framework, including a detailed assessment of recharge processes.
- Task 2 – Preliminary assessment of the spatial variability and indicative fluxes of groundwater discharge to the marine environment.

Task 1 of Phase 1 included compilation of all relevant data and knowledge, and development of a methodology for incorporation of this into a numerical groundwater flow model. Tasks 2 and 3 were preliminary research projects addressing two of the major knowledge gaps for the region identified by Harrington et al. (2011). The outcomes of Phase 1 are described in Harrington and Lamontagne (2013).

1.2.2 OBJECTIVES OF PHASE 2

Phase 2 of the project was carried out between 2013 and 2015 and consisted of three tasks with the following objectives:

**Task 1: Regional Water Balance Modelling**

The aim of Task 1 was to develop a regional groundwater flow model of the LLC PWA, including both major aquifers: the unconfined Tertiary Limestone Aquifer (TLA) and the Tertiary Confined Sand Aquifer (TCSA), 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 PWA, 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 sections 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.
Task 2: Recharge Modelling

A relatively large amount of point-scale field data exists for the South East to support recharge estimation, although these data have various limitations in the spatial and temporal scales of recharge that they represent. A major effort is required to utilise the existing data to understand the dynamics of rainfall recharge in the South East and to develop a methodology for including this knowledge in groundwater models designed to assess future groundwater management scenarios. In Phase 1 of the project, all available recharge data was assessed at a regional scale to better understand the processes driving recharge in the South East and how these might be incorporated into a regional groundwater flow model. Climate, soil type, vegetation type and depth to watertable are important factors controlling rainfall recharge in the South East. However, the current recharge and evapotranspiration packages in MODFLOW are unable to effectively represent the relationships between recharge and depth to watertable observed in the South East. Although coupling of regional groundwater flow models with Richard’s Equation-based unsaturated zone models has been achieved in several studies (e.g. Stisen et al. (2008) and Maxwell et al. (2014)), such a framework involves large model run-times and is likely to be too cumbersome to be a useful management tool for the South East. Therefore, a new MODFLOW net recharge package was proposed that incorporates the results of an unsaturated zone model through a simpler lookup-table approach. As rainfall recharge is a major input to the water balance for the South East (Wood, 2010), this activity was designated as a separate task in Phase 2 of the project, with the following objectives:

- Complete one-dimensional numerical recharge modelling, conditioned to the recharge rates estimated in Phase 1.
- Develop look-up tables that are based on: monthly rainfall, month of year, vegetation type, soil type, and depth to watertable.
- Develop a new MODFLOW package capable of interpreting the look-up tables, and trial the implementation of this within the regional groundwater flow model.

This activity was carried out in parallel and in close collaboration with the regional model construction (Task 1) so that the understanding gained could be fed, where possible, into the first iteration of the groundwater flow model. Additional methodologies for incorporating the watertable depth dependence of recharge were also investigated, taking advantage of an existing but un-calibrated LEACHM recharge model for the South East. The use of multiple approaches provides an opportunity to test the influence of the use of different (but equally acceptable) recharge modelling methods on the overall modelled regional water balance, recognising that rainfall recharge is one of the largest components of the water balance. It also provides the basis for determining how to best simulate rainfall recharge in the different landscapes of the South East.

Task 3: Wetland Connectivity Modelling

Future water allocation policy exercises in the LLC PWA will need to evaluate potential impacts on wetlands and other groundwater-dependent ecosystems. However, by necessity, the regional model was developed at a coarse spatial scale (1 km by 1 km cells) relative to the size of most wetlands in the region (a few km² or less). Thus, the aim for Task 3 was to develop a complementary approach to the regional model to help evaluate potential impacts of future changes in climate, land-use and water allocation policy on wetland water level regimes. To achieve this, Task 3 had three objectives:

1) Development of a conceptual framework for wetland – groundwater interactions in the LLC PWA;
2) Inform the development of this framework by evaluating groundwater – surface water interactions for three wetlands in the region (Deadmans Swamp, Bool Lagoon and Lake Robe) using historical data and an environmental tracer field study;
3) Develop a MODFLOW-based wetland – groundwater modelling framework representative of deflation basins and other shallow wetlands in the region.
The three wetlands selected for the field study were hypothesised to represent a regional recharge (Deadmans Swamp), flow-through (Bool Lagoon) and discharge wetland (Lake Robe) along a regional hydrogeological system.
2 Outcomes

2.1 Rainfall Recharge Assessment

2.1.1 A SPATIALLY CONTINUOUS RECHARGE DATASET

Phase 1 of this study built upon half a century of recharge estimation in the South East to provide the first spatially continuous estimation of recharge in the region (Crosbie et al., 2015). This estimation was achieved through ground-truthing net recharge estimates derived from the CSIRO MODIS reflectance based scaling evapotranspiration (CMRSET) algorithm (Guerschman et al. 2009). The advantage of the new net recharge estimates is that they are spatially continuous on a ~250 m grid and because the CMRSET evapotranspiration data is on an 8 day time step there is also a temporal resolution that we have not had access to before. These net recharge estimates were ground-truthed against hundreds of point scale water table fluctuation estimates of recharge over the period 2001-2010. A further comparison against the hundreds of previous point scale estimates of recharge demonstrated that the new net recharge estimates were not biased overall, but there were considerable differences in individual points. For the 10 year period 2001-2010 the areal average net recharge was found to be 40 mm/yr.

2.1.2 FACTORS CONTROLLING NET AND GROSS RECHARGE

The availability of this spatially continuous recharge dataset allowed for an assessment of the variability of net recharge under different vegetation type, soil type and depth to water table conditions. It was found that, as well as the expected dependence of recharge upon climate, soil type and vegetation type, recharge under forestry plantation was strongly dependent upon depth to water table for groundwater depths up to 6 m. For all vegetation types, the watertable fluctuation estimates of gross recharge showed a low recharge when the watertable was close to the surface climbing to a maximum recharge when the watertable was 1-2 m below land surface and then reaching a point beyond about 6 m where the depth to watertable no longer had an impact on the magnitude of recharge. The low recharge when the depth to watertable was near the surface was due to a lack of storage space in the unsaturated zone and this led to little infiltration and additional runoff. The maximum recharge at 1-2 m depth is because the rainfall could rapidly infiltrate to the watertable without being evaporated or transpired while moving through the unsaturated zone. The volume of gross recharge increases, but at the same time, evapotranspiration from the groundwater will also increase. The reduction in recharge with greater depth to watertable was due to the infiltrating rainfall replenishing diminished unsaturated zone storage and being available for evaporation or transpiration.

The net recharge estimates had a different relationship with depth to watertable as this also incorporates evaporation and transpiration processes that are known to exhibit a dependence upon depth to watertable. For the forestry land use, when the watertable was shallow, there was a negative net recharge with a peak reached at around 2-3 m depth, from this point the net recharge increased, became positive, and at a depth of around 8 to 20 metres, it was no longer dependent upon the depth to watertable. The depth to watertable where the net recharge under the forestry land use was no longer dependent occurred at around 6 m under sandy soils and may be greater than 20 m under clayey soils. This difference is due to higher capillary fluxes for the finer textured soil rather than differences in rooting depths. The pasture land use had almost no relationship between net recharge and the depth to watertable from the remote sensing based water balance estimates, presumably because of the difference in rooting depth of the vegetation types.
In Phase 2 of the project, the validity of the observations of the depth dependence of recharge was tested using the WAVES unsaturated zone model (Zhang and Dawes, 1998). Using the same soil, vegetation and climate inputs the model was run for various depths to watertable to investigate these relationships. The relationships seen between soil evaporation and transpiration and depth to watertable were as had previously been described in the literature and the relationships between both gross and net recharge were replicated as seen in this study in the SE (Figure 2).

The relationships observed here between depth to watertable and both gross and net recharge are not generally seen in the literature and, consequently, little thought has been put into how to model them in a regional groundwater model to date. Two new and different methodologies for this have been developed as part of the South East Regional Water Balance project, and are described in the following sections.
Figure 2. Example of groundwater depth vs. net recharge curves generated from WAVES modelling for (a) Mount Gambier softwoods on soil type 2, (b) Bordertown crops on soil type 5, (c) Lucindale perennial grazing on soil type 5 and (d) Lucindale native vegetation on soil type 2. Net recharge is indicated by the black line. Other unsaturated zone fluxes used to calculate net recharge are also shown: transpiration (OS\_T, red), canopy interception (OS\_i, orange), soil evaporation (Soil\_E, yellow), runoff (Q, green), gross recharge (Gross\_R, light blue) and ET from groundwater (ETGW, purple).
2.2 Regional Groundwater Flow Model

2.2.1 MODEL DEVELOPMENT

The regional groundwater flow 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. New data sets were developed as part of the project and these have been implemented in the groundwater model and the recharge model that supports it, 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. The model domain covers the area shown in Figure 1 and is discretised into model cells that are 1 km x 1 km in area. Three model layers are implemented, as shown in Figure 3. The model domain covers part of the Gambier Basin of the Otway Basin and part of the Murray Basin, and the geological units of the Murray Basin are identified in italics in Figure 3.

![Figure 3. A typical cross section through the regional groundwater flow model showing model layers.](image)

The regional groundwater flow model includes all available information on the conceptual model, including hydrostratigraphy, current and historical groundwater extraction and man-made drains. 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.

2.2.2 RAINFALL RECHARGE

A particular focus of the Regional Water Balance project was on the quantification of rainfall recharge, particularly in shallow watertable areas. Despite being a very large component of the regional water balance, there was no suitable spatial and temporal rainfall recharge dataset that had been validated against real measured recharge data for the study area prior to this project. As part of the Regional Water Balance project, a new methodology, including the development of a new MODFLOW net recharge package has been developed in parallel with the regional model construction. This has resulted in a preliminary tool that will support future recharge modelling but requires further development and testing within the framework of the regional model as the latter evolves (see Section 2.3 below). If successful, this tool will provide a user-friendly means of incorporating watertable dependent recharge into groundwater models and predicting recharge under future scenarios.

In the meantime, previous work in the South East by Fleming and Hutson (2014) provides a spatially and temporally variable rainfall recharge input dataset for the majority of the study area. This dataset was developed using the Richard’s Equation-based LEACHM unsaturated zone model (Hutson, 2003) implemented in a GIS framework. This dataset does not include the effect of depth to watertable on net recharge and previously had not been compared to real field data. However, the outcomes of the Phase 1 recharge study provided an opportunity to condition the LEACHM recharge model to real data, providing: (a) a valid recharge input dataset to facilitate construction of the preliminary regional groundwater flow model, (b) an opportunity to closely evaluate the model parameters that influence the recharge model outputs, and (c) a second valid methodology against which to test the outcomes of the new MODFLOW net recharge approach.

The recharge and evapotranspiration outputs of the LEACHM unsaturated zone model were compared against the CSIRO MODIS-derived net recharge datasets that had been developed and evaluated as part of Phase 1 (Section 2.1.1) (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).

Along with the outputs of gross recharge from the LEACHM 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, 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. 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. The approach was validated through comparison with the CSIRO MODIS datasets described above.

Using this approach, combining gross recharge from the LEACHM model with watertable depth dependent evapotranspiration in MODFLOW, the estimated areal average net recharge for the study area for the 10 year period 2001-2010 was 48 mm/y, compared with 40 mm/y estimated as net recharge by Crosbie et al. (2015).
2.2.3 CALIBRATION

The steady state model takes less than a minute to run and calibration was carried out using the PEST model calibration code (Doherty, 2005), with hydraulic conductivities allowed to vary within acceptable ranges for the geology in the region, as outlined in Morgan et al., (2015a). 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. A small number of zones have been employed during calibration because of the limited spatial hydraulic property data currently available for the area. Recalibration of the model using additional zones or 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%). The plot of measured versus modelled heads for the steady-state and transient models are shown in Figure 4 and Figure 5. Maps of measured versus modelled heads contours for the steady state model are shown in Figure 6 and Figure 7, respectively.
Figure 4 Steady-state calibration scatter plot

Figure 5 Transient model comparison between observed and modelled heads.
Figure 6 Comparison of modelled and observed head contours for layer 1.
Figure 7 Comparison of modelled and observed head contours for layer 3.
The transient hydrographs (see Appendix A) show a good match between short-term (i.e., seasonal) head changes in the majority of cases. This indicates that seasonality of recharge, groundwater ET 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 this suggests that extraction values used in the model are too low. Measured hydrographs in the South Australian highlands indicate a rise in water levels from the start of the model period in 1970 to the 1990s. This is due to a lag in recharge reaching the water table after forest clearing. The current LEACHM recharge model has attempted to incorporate this effect in a preliminary way but further work is needed. Also, a number of hydrographs have a steeper decline in modelled heads than measured heads for the period since 1990, especially in highland areas. The match between measured and modelled heads in layer 3 of the model (i.e., the confined aquifer) is variable across hydrographs. The difference is 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 confined aquifer. For the hydrographs near to extraction wells the seasonal change in measured heads is not matched by the model. This is likely due to both model averaging effects over a 1 km x 1km cell size as well as the use of only a small number of hydraulic conductivity and storage zones. 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 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. A number of rehabilitated wells were not included within the model because data was not available at the time of model development. Please refer to Morgan et al., (2015) for further details of the model calibration.

The transient model produces reasonable water balance results (Figure 8), 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 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 evaporation from the drains (estimated), 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. The discharge along the near shore for the rest of the coastline in the study area is unknown. However, near shore discharge is possibly small elsewhere because of the presence of several coastal lakes located below mean sea level (Lake Bonney, etc). These could intercept shallow groundwater before it can reach the coastline. Modelled total groundwater discharge at the coastal boundary for the whole study area is evaluated as 1368 GL/y in 2013. It is likely that much of this discharge is occurring offshore. It is not possible to independently evaluate modelled offshore discharge fluxes at present, but it may represent a substantial component of the water balance. Whilst technically challenging, further independent evaluation of coastal flux would help to constrain the water balance model.
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 (Figure 9). However, in general, the locations of downward flow and upward flow agree with measured head differences between layer 1 and layer 3.
Figure 9 Flows from layer 1 to layer 3 (positive values indicate downward flow).
Because the model domain extends beyond the boundary of the LLC PWA and incorporates the whole regional groundwater flow system, estimates can be provided 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 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 refinements 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.

### 2.2.4 KEY LIMITATIONS OF THE REGIONAL GROUNDWATER FLOW MODEL

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. There is limited field data within the large model domain on hydraulic parameters and key water balance 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. A detailed uncertainty analysis is required to improve understanding of the models suitability for use as a management tool.

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.

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, the regional groundwater model will not be able to represent local-scale processes (such as those associated with interdunal systems, etc.). The purpose of the model is to represent intermediate and regional groundwater flow systems in the study area. With this in mind, the regional groundwater flow model can provide a basis for future local-scale groundwater models aiming to answer local-scale hydrogeological questions (such as defining environmental water requirements for specific wetlands, etc.). Detailed recommendations to further improve the regional model can be found in Morgan et al. (2015) and are also summarised in Chapter 3.
2.3 A new MODFLOW net recharge package (NETR)

2.3.1 METHODOLOGY

The results described in Section 2.1.2 above clearly demonstrate the need to incorporate the depth to watertable dependence of recharge into groundwater models of the South East. This has been achieved in the current preliminary version of the regional groundwater flow model through the development of gross recharge datasets in an unsaturated zone model (LEACHM) and application of a new modified extinction depth ET approach in MODFLOW. However, a simplified approach to implementing net recharge in MODFLOW in shallow watertable areas has also been developed, to make regional models more user-friendly and amenable to scenario modelling for management purposes. Conventionally in MODFLOW, recharge is an input that is independent of the depth to watertable (RCH package). This serves regions well where the watertable is well below the land surface. Evapotranspiration (EVT or ETS packages) has always been modelled in MODFLOW as a linear relationship with depth to watertable, with the evapotranspiration being at a maximum when the watertable is at the land surface and then decreasing to 0 at the extinction depth. These existing packages do not simulate what we have observed in the South East, with gross recharge being dependent upon depth to watertable and the evapotranspiration not being at a maximum when the watertable is at the surface.

To enable these processes as observed to be replicated in groundwater models of the South East, a more complex coupled unsaturated-saturated zone model would normally be required. Coupled unsaturated-saturated models generally need a much finer numerical discretisation leading to run times that can be orders of magnitude greater than an equivalent MODFLOW model. Consequently these complex model codes are generally only used in a small-scale research models rather than regional-scale management models. The approach currently implemented in the regional groundwater model also requires spatial and temporal gross recharge datasets to be developed for each scenario outside the MODFLOW framework, which is labour intensive. One of the aims of this regional-scale model of the South East is to investigate the predictive uncertainty in elements of the water balance. This requires running the model hundreds of times at a minimum, making these methods impractical. The solution pursued here was to create a new MODFLOW package that can incorporate the depth dependent net recharge that has been observed.

The existing segmented evapotranspiration (ETS) package returns an ET rate that is dependent on the depth to watertable from a piecewise linear function that is limited to having the maximum when the watertable is at the surface, decreasing to 0 when the watertable reaches the extinction depth. The new MODFLOW net recharge package (NETR) developed as part of this project relaxes these restrictions to enable the piecewise linear function to be both positive and negative. This allows the maximum to occur at any depth and not be restricted to having a flux of 0 at the maximum depth. The package reads a landscape key that is assigned to each grid cell and then reads the values of the piecewise linear function from a look-up table that has a row for each landscape key value (Figure 10) The NETR package can use a new look-up table and landscape key for each stress period or continue to use the same inputs as the previous time step. This enables both transient land use and transient net recharge relationships to be incorporated into the model.
The new net recharge MODFLOW package (NETR) was tested on a small tutorial model of 17 x 17 cells and five layers to mimic the conventional RCH and EVT package behaviour. When the test model had recharge (RCH) only, the new package returned identical outputs for both water balance and heads. When it had evapotranspiration (EVT) only, the new package returned identical outputs for both water balance and heads. When both recharge (RCH) and evapotranspiration (EVT) were implemented, the new model returned net recharge outputs that were fractionally (but insignificantly) higher than the combined output of the RCH and EVT packages, the difference is believed to be due to the sequencing of packages in MODFLOW. This confirmed that the functions were implemented into MODFLOW successfully.

As a proof of concept, the test model demonstrated that the new net recharge package (NETR) works for both steady-state and transient model instances, however, a more complex test within a regional model was required.
2.3.2 ESTIMATING RECHARGE FOR THE REGIONAL MODEL

To test the new net recharge package more extensively, it was incorporated into a steady-state version of the regional groundwater model. The inputs needed were the landscape key and the look-up table.

The landscape key was developed based upon the factors found to be important determinants for net recharge. These were climate, soil type and vegetation type. The climate within the model domain was attributed based upon Theissen polygons around 12 representative climate stations. The soil type was attributed according to the average clay content of the top 2 m of the soil profile estimated using the ASRIS database, and was split into 7 classes. The vegetation type was a simplification of ACLUMP (Australian Collaborative Land Use and Management Program) mapping (ABARES, 2010) down to 8 functional classes that behave differently for recharge. This gave a potential for 672 individual classes in the landscape key of which currently 502 physically exist in the region.

The look-up table was populated using the WAVES model. Despite the fact that only 502 currently exist, all 672 landscape classes were modelled using WAVES to support possible future scenario modelling. For each of the 672 landscape classes, WAVES was run for 26 depths to watertable ranging from 0.01 m to 20 m. The net recharge was then averaged over 100 years to give a long-term steady-state net recharge for populating the look-up table.

The approach was algorithmically tested using R with a static watertable derived from averaged spring and autumn water levels and also a 2008 watertable. This algorithmic test returned a net recharge value for every grid cell in the raster using the static watertable, landscape key and look-up table. This test provided a raster of net recharge that should be able to be compared with the net recharge raster derived from the remotely-sensed (CMRSET) ET. This test demonstrated that the logic of the look-up table approach worked successfully but the values in the look-up table were not correct. The resulting net recharge raster was too extreme, the inter-dunal flats had a negative net recharge (groundwater discharge) that was much greater in magnitude than that estimated through the water balance and also the dunes had much greater positive net recharge than that estimated through the CMRSET-based water balance. The model did represent the bluegum forestry areas south of Lucindale and the pine plantations around Penola well compared with the CMRSET data. Irrigated areas were shown to be recharging in the WAVES outputs due to the additional irrigation volume applied, while the CMRSET-based water balance indicated that these areas were evaporating, as applied irrigation was not included in the water balance. Overall the look-up table approach had an areal average net recharge rate of 15 mm/yr whereas the remote-sensing derived water balance had an areal average net recharge rate of 40 mm/yr (Figure 11).

The final test of the new net recharge MODFLOW package (NETR) was incorporating it into the regional groundwater model. The steady-state model converged successfully demonstrating that the new package works, however the water balance was substantially different from that calibrated using a different recharge input approach in Task 1, suggesting that further work is needed. Forested areas were better represented than other vegetation types, while higher elevations were better represented than those with extremely shallow groundwater (DTWT <1m). Areas for improvement include better calibrated vegetation parameters in the WAVES model and improvements in the representation of the evaporation surface in the large cells of the MODFLOW model, perhaps using probabilistic methods.
2.4 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 and in Section 2.2.3 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 E1 Comparison of the LLC PWA water balance from the South East Science Review (Wood, 2010) and a preliminary one obtained through the regional model. 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). The uncertainty of these modelled fluxes needs to be evaluated before they can be used for management purposes. Modelled fluxes are presented here to demonstrate that the regional model does capture the correct magnitude for key water balance components.

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<td>Inflows</td>
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<td>Coastal boundary</td>
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<td>310</td>
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<td>Northern boundary</td>
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<td>Northern boundary</td>
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<tr>
<td>Discharge from gw springs</td>
<td>97</td>
<td>ND</td>
</tr>
<tr>
<td>Net storage change</td>
<td>216</td>
<td>-120</td>
</tr>
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</table>

*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.

** Not determined.
2.5 Wetlands

2.5.1 CONCEPTUAL MODEL FOR WETLAND-GROUNDWATER INTERACTIONS

Interactions between wetlands and shallow groundwater are complex because they can be influenced by both regional and local factors. For LLC PWA wetlands, six regional and local-scale factors are proposed to control groundwater – surface water interactions. These are:

1) Landscape position – whether wetlands are located in recharge (Figure 12 top), flow-through (Figure 12 middle) or discharge zones (Figure 12 bottom);
2) Topography – the development of local flow systems in hummocky terrain, etc;
3) Subsurface control – whether the presence of geological basement intrusions or faults promote upward regional groundwater flow or the development of local flow systems;
4) The presence or absence of clogging layers at the base of wetlands;
5) Whether a wetland receives surface runoff or is only rain- and groundwater-fed;
6) The morphometry of wetlands (including depth, surface area, and degree of incision in the landscape).

In the LLC PWA, wetlands in regional recharge areas tend to be fresher but with a more variable watertable regime; wetlands in regional discharge areas tend to have a less variable watertable regime but are more saline (see examples in the next section).

The key here is that some factors (landscape position and subsurface control in particular) are regional or subregional in nature whereas others are more wetland-specific. Thus, evaluating the impact of changes in land-use, climate or water allocation policy on wetland water level regimes in the LLC PWA will be a two-step process. Regional trends should be evaluated first (using the regional water balance model or similar tools) to evaluate, for example, how wetlands in regional groundwater recharge and discharge areas could respond to change. The second step (using the wetland-groundwater model proposed below) would evaluate how local scale features of wetlands (presence or absence of a clogging layer, etc) modulate their response to change in the watertable regime at the regional scale.

Figure 12 Conceptual cross-section of a regional hydrogeological system illustrating how regional-scale factors can influence wetland-groundwater connectivity. The flow system represented is influenced by subsurface control in the form a shallow bedrock intrusion (grey) and the coastal salt wedge (green), which in both cases promote upward regional groundwater flow.
2.5.2 DATA REVIEW AND FIELD STUDIES

To help the development of the conceptual model presented above and the wetland-groundwater numerical model presented below, groundwater – surface water interactions were evaluated for three wetlands along a landscape gradient in the LLC PWA (Figure 13). This evaluation was made in part using a review of historical monitoring data and in part by sampling surface and groundwater at the wetlands for various environmental tracers in March 2014.

![Figure 13 Elevation profile along a transect intersecting the three study wetlands (see Taylor et al. 2015 for details of the transect location).](image)

Position in the landscape was clearly an important factor determining groundwater – surface water interactions in this environment. In a regional recharge area (Deadmans Swamp) the piezometric surface was seasonally variable, the wetland was ephemeral, but salinities were low (Figure 14). Conversely, in a regional discharge area (Lake Robe), seasonal variations in the piezometric surface were smaller, the wetland was perennial, but it was also hypersaline (Figure 14). The piezometric surface was most variable in space and in time at Bool Lagoon, in part because it is the only of the three wetlands receiving significant surface runoff (usually at the end of winter). The evaluation of gaining and losing conditions using potentiometric surfaces was difficult in all wetlands because of their limited surface water level record (Taylor et al., 2015). However, potentiometric surfaces suggested that Bool Lagoon is a groundwater recharge area during wet periods and a groundwater discharge area during dry periods. Much of the groundwater discharge probably occurs by evaporation from shallow watertables from areas of the wetland with exposed sediments.
Figure 14 Examples of temporal piezometric surface variations at Deadmans Swamp (left), Bool Lagoon (middle) and Lake Robe (right). Also shown is a typical range in surface water salinity in each wetland. At Deadmans Swamp (JOA027) and Lake Robe (WAT034) the piezometers are at the edge of the wetland. At Bool Lagoon, one piezometer is upgradient (ROB006; green) and the other downgradient (ROB022; red) from the wetland (see Taylor et al. 2015 for more details).

Environmental tracers (major ions, stable isotopes of water, tritium, and noble gases) were sampled in surface water and groundwater in March 2014 at Bool Lagoon and Lake Robe only. Deadmans Swamp was dry during this period and currently only has one piezometer near the wetland, so could not be investigated with environmental tracers. At Bool Lagoon, surface water was relatively fresh in March 2014 (<1000 mg Cl/L or ~4 dS/m) and groundwater located 6 to 12 m below the wetland was fresh to saline (300 – 8000 mg Cl/L or ~1.6 – 23 dS/m; Figure 15). However, surface water salinity at Bool Lagoon is known to vary over time between fresh and saline (1.4 – 17.5 dS/m; Taylor et al. 2015). There may be a vertical stratification in groundwater salinity in Bool Lagoon, with brackish to saline groundwater (6 – 20 dS/m) found across the wetland in shallow pits (1 – 2 m below the surface) dug in late March 2014, when the wetland was drying. Bool Lagoon surface water samples had a strong evaporation signal in the stable isotopes of water, and this signal was found in groundwater as well, especially in groundwater along its western margin (Smith et al., 2015; Figure 15). Tritium activity in Bool Lagoon surface water was ~2.5 TU, or 85% of the value expected for precipitation in the region, whereas activities in groundwater ranged from ~0 to 1.1 TU (Smith et al., 2015). Thus, some of the groundwater below and near the lagoon was recharged prior to 1960. Some of the groundwater samples had terrigenic He, especially upgradient from the wetland, indicating a much older source of groundwater is also present. An intriguing feature at Bool Lagoon was low bromide/chloride ratios in groundwater suggesting halite dissolution as a source of salinity in groundwater. However, it is not clear if halite formation and dissolution is ongoing between current wetting and drying cycles or if this represents remnant groundwater recharged under a past climate, when Bool Lagoon could have been a salt lake.
Lake Robe had hypersaline conditions in surface water and fresh to brackish conditions in neighbouring groundwater (Smith et al., 2015). This is consistent with a discharge environment, where fresher groundwater discharging to the wetland evaporates. However, there was limited evidence for regional groundwater discharging to Lake Robe, but the lake receives discharge from springs associated with neighboring coastal sand dunes. Despite being located below sea level, Lake Robe is still slightly higher than the neighbouring Lake Eliza. Thus, the latter may be the focus for regional groundwater discharge.

Based on the data review and the field study, a better picture of groundwater – surface water connectivity at the three wetlands was gained. Based on its location in the landscape (Naracoorte Ranges), Deadmans Swamp is in a regional recharge area. However, as it is surrounded by a network of eolian sand dunes, its local connectivity is unclear and will require a more comprehensive piezometer network to be investigated. Lake Robe appears to be a local discharge wetland set in a regional discharge area. Bool Lagoon has the most complex groundwater – surface water connectivity of the three, and could be characterised as an ephemeral recharge wetland located in a discharge zone for an intermediate flow system (Figure 16). The Bool Lagoon complex (which also includes a number of other smaller wetlands) is probably an example of a ‘Boinka’ – a landform complex of groundwater discharge, which occupies shallow depressions in semi-arid regions of low relief (Macumber, 1991). Location at the toe of the Naracoorte Scarp and some form of bedrock control may explain why a major discharge zone occurs there. In particular, a major regional fault (the Kanawinka Fault) occurs near Bool Lagoon and may induce upward groundwater flow.

Figure 15 Variations in chloride concentration (left) and deuterium (right) in Bool Lagoon surface water and groundwater along a west to east transect in March 2014. Regional groundwater flow is approximately from right to left on each diagram (see Smith et al., 2015 for details of sample location).
2.5.3 WETLAND – GROUNDWATER MODEL

A generic, local scale wetland–groundwater interaction numerical model was developed for LLC PWA wetlands (Turnadge and Lamontagne, 2015). As most wetlands in the region are small relative to the grid of the regional groundwater flow model, the purpose for the wetland-groundwater model was to translate regional patterns in watertable variations into wetland water level regimes. In particular, the wetland-groundwater model was designed to evaluate how local wetland features (presence of a clogging layer, surface runoff, morphometry) influence a wetland’s response to a change in the regional watertable regime. Some of the requirements considered in the development of the wetland–groundwater modelling approach included that:

- Long-term variations in the regional watertable (whether obtained from the regional scale groundwater model or from other sources) could be incorporated;
- The approach is not too computationally demanding, thereby enabling the evaluation of a wide range of management scenarios over long time periods (i.e. decades to centuries);
- The tool is generic and applicable to deflation basins and other shallow (< 3 m) wetland types in the LLC PWA, rather than applicable to a specific wetland within the region;
- The output should be provided in the form of simple surface water level metrics that can be used by water managers and wetland ecologists to evaluate potential environmental impacts.

The industry standard groundwater flow simulation code MODFLOW (Hanson et al., 2014) was used as the basis for this approach. For the wetland, the components of the water mass balance included precipitation, evaporative losses from inundated areas, and evapotranspiration losses from non-inundated areas (Figure 17). For the groundwater domain, significant water mass balance components included in- and outflows at the lateral and lower domain boundaries, leakage from the wetland, and evapotranspiration from shallow watertables. Each of these components was characterised as a time-varying flux. Of particular novelty was the combined approach used to represent recharge and evapotranspiration, which can be represented as a net flux from groundwater rather than by following the traditional approach of compartmentalising the two fluxes. For the cases of wetlands receiving surface runoff, a time-varying boundary condition can be introduced for wetland surface water level – essentially ‘topping-up’ the wetland on a seasonal basis.

Figure 16 Conceptual representation of recharge and discharge processes at Bool Lagoon.
Figure 17 Water mass balance components for the 2D wetland–groundwater interaction model for the South East wetlands. Also shown are the groundwater level (blue dashes) and wetland water level (green dashes). In order to improve clarity, topographic and hydraulic gradients are neither consistent nor to scale. Parameter definition are described in Turnadge et al. (2015).

The type of information provided by the model was demonstrated using a synthetic dataset in lieu of outputs from the regional groundwater flow model, which was still under development at the time of writing. The synthetic dataset represented a scenario for a 5 m drop in a regional watertable and was applied for a 2 m deep flow-through wetland, without a clogging layer, for different levels of annual surface water level inputs (+0 m, +0.5 m, +1.0 m and +1.5 m). For these conditions, the synthetic demonstration showed that the water level regime would switch from permanent to either ephemeral or permanently dry under a lower regional watertable (Figure 18). However, surface water addition may partially offset the watertable drawdown. For example, for the case with no surface water addition, the wetland would switch from ephemeral to permanently dry, whereas with +1 m annual surface runoff input, the wetland would switch from permanent to ephemeral (Figure 18).
Figure 18 Box and whisker plots of minimum and maximum fraction of wetland inundated on an annual basis for (a) pre-watertable decline period and (b) post-watertable decline period for a regional flow-through wetland type with annual surface water additions equivalent to water level increases of 0.0, 0.5, 1.0 and 1.5 m. Boxes indicate the interquartile range (IQR) of each data series, whiskers indicate the extent 1.5 times beyond the IQR, and red lines indicate median values.

The wetland-groundwater model is generic and is not meant to represent specific wetlands in the region. Its purpose is to understand wetland behaviour at a regional to subregional scale under different management scenarios. For example, in the example provided above, further simulations could be made for wetlands with different shapes, different positions in the landscape (recharge areas, discharge areas, etc) or with a clogging layer to evaluate what are the wetland properties that make them most resilient or most vulnerable to change. As for the regional model, the wetland-groundwater model does not include solute transport so it cannot evaluate changes in wetland salinity over time (a key ecological driver in this environment). However, a simple salinisation risk index was defined and can be used to evaluate whether salinity could increase or decrease under different conditions. Turnadge and Lamontagne (2015) proposed a strategy to couple the regional and wetland models. Briefly, the strategy would involve determining ‘hydrogeological subregions’ in the LLC PWA. For example, the LLC PWA could be divided into recharge and discharge zones for a northern area (drier climate, shallower bedrock) and southern area (wetter, deeper bedrock). The regional model could then be interrogated to determine ‘representative’ watertable variation regimes in each subregion. This strategy will need to be further tested and developed in future studies.
3 Conclusion and Recommendations

A regional-scale water balance model has been developed for the unconfined Tertiary Limestone Aquifer and the confined Tertiary Confined Sands Aquifer in the south east of South Australia, with a model domain that covers the entire regional groundwater flow system, including part of Victoria. The model incorporates all currently available information on the various components of the regional water balance, including new or consolidated datasets that have been developed for the purpose of this project. The model adopts monthly stress periods and simulates the period between January 1970 and December 2013.

The groundwater model is complemented by an unsaturated zone recharge model that has undergone significant validation and testing. The recharge model simulates the period between January 1955 and December 2013 and has been used for recharge inputs to the current version of the groundwater model. Despite the simplifications involved in developing a regional groundwater flow model, and the limitations of the available data, the model represents reasonably well the observed long-term fluctuations in groundwater levels and the elements of the regional water balance of which there is some knowledge. However, further work is required to improve the model calibration before it is suitable for use in predictive scenario modelling.

The groundwater model produces reasonable water balance results, based upon comparison with measured estimates of net recharge, drainage fluxes, coastal discharge fluxes and inter-aquifer leakage. Additionally, changes in modelled storage compare well to changes in storage that were estimated using measured water level changes. It can be concluded that the model currently provides a useful tool to investigate changes in the regional water balance. However, before any results are used in management, an appropriate uncertainty analysis should be carried out, and it should be recognised that these water balance results are likely to be refined as the model is refined and re-calibrated in the future.

In parallel with the regional groundwater flow model construction, a major focus of the project has been the development of methodologies to accurately quantify spatial and temporal variations in rainfall recharge for the study area. In particular, the depth to watertable has been shown in many previous studies to be a key determinant of evaporation and transpiration from shallow watertable environments. This study has shown that the depth to watertable is a key determinant for both gross and net recharge for shallow watertable regions such as the south east of South Australia. This link between recharge and depth to watertable has been poorly studied in the past and means that this important process has not been incorporated into commercial groundwater modelling software (including MODFLOW).

To overcome the limitations of existing software for use in areas of shallow groundwater, this study has led to the development of a net recharge package (NETR) for MODFLOW. This new package is based upon a piecewise linear relationship between net recharge and depth to watertable that is read into MODFLOW as a look-up table. The package overcomes the limitation of the existing recharge package (RCH) whereby recharge is independent of the depth to watertable, and also the limitations of the existing ET packages (EVT, ETS) whereby the maximum ET rate occurs when the watertable is at the surface and decreases to 0 at some critical extinction depth. This new MODFLOW package has been run in a steady-state version of the regional groundwater model as a proof-of-concept, although it is not yet ready for operational use.

Finally, a conceptual model for wetland-groundwater interactions that combines regional- and local-scale processes has been developed. This framework was used to develop a two-dimensional MODFLOW-based model of wetland – groundwater interactions in the LLC PWA. The wetland-groundwater model should be suitable to evaluate how the surface water level regime of generic wetlands could be impacted when evaluating regional scenarios of change in climate, land-use or water allocation policy.

The field studies on wetland-groundwater interactions were useful in unravelling the complexity of groundwater-surface water interactions in this landscape, in particular how wetlands can have intricate local and regional scales of interactions. For example, identifying the Bool Lagoon Complex as a part of a
major regional discharge zone has important management implications for these wetlands. Wetlands that are part of a regional system could take a much longer-time to achieve a new state when conditions change relative to neighbouring wetlands that are part of local hydrogeological systems only.

In summary, the South East Regional Water Balance project has provided (1) an advanced understanding of the regional water balance for the Lower Limestone Coast PWA, (2) a regional-scale groundwater model that incorporates all of the existing knowledge of the groundwater system, (3) in this, a tool that can be used to further investigate the conceptual model of the South East groundwater system, (4) a better understanding of the spatial and temporal dynamics of rainfall recharge in the South East, (5) some preliminary tools for incorporating the watertable dependence of recharge into groundwater models, (5) a new understanding of the regional- and local-scale drivers of wetland-groundwater interactions, and (6) a conceptual wetland-groundwater numerical model for translating outputs from the regional groundwater model into wetland water regimes.

**Recommendations**

The regional model and its associated recharge and wetland modelling tools are fairly advanced but still require some additional work before they could be applied to guide policy decisions relative to climate change, land use and water allocation in the LLC PWA. Key recommendations arising from this study are:

1. Further update key hydraulic parameters in the model by searching for additional data in the ‘grey’ literature for the region or through targeted field programs. In particular, additional hydraulic conductivity data evaluated by pump tests should be available in particular subregions (Naracoorte Ranges, Tatiara, Upper South East, Bordertown and Padthaway regions).
2. Independently evaluate groundwater discharge to drains to help constrain the regional model.
3. Further work is needed to explore the effects of representing the coastal boundary condition as a truncated version of what is otherwise an extensive offshore aquifer system.
4. Continue to evaluate the use of a modified extinction depth approach within the MODFLOW EVT package to scale evapotranspiration using topographic variation information from the DEM.
5. Refine the look-up table strategy to evaluate recharge rates, in particular through additional calibration of the model used (WAVES) to populate the tables. Establish and maintain a robust surface water monitoring program for a representative range of wetlands in the region. Future development of both the regional and wetland groundwater models would be greatly helped by establishing a more robust surface water level monitoring network for wetlands in the region. Groundwater monitoring near wetlands would also be improved by installing piezometers in nests (to measure vertical hydraulic gradient) and to combine piezometer nests with shallow watertable monitoring wells (to more accurately determine the position of the watertable).
6. Use remote sensing data to evaluate historical water level variations in LLC PWA wetlands. Recent work on remote sensing of South East wetland inundation regimes (Deane et al., 2015) could form the basis for such an analysis.
7. Evaluate downscaling strategies for developing local flow models, such as iMOD (Vermeulen and Minnema, 2015) or MODFLOW-USG (Panday et al., 2013).
8. Further constrain recharge fluxes in the model by considering groundwater salinity. This would be especially useful in the northern section of the LLC PWA, where saline water tables are more common.
4 Associated Technical Reports and Research Papers

Technical Reports:


Research Papers:


Appendix A Transient Calibration Hydrographs for the Preliminary Regional Model

Figure A1 Hydrograph comparison between modelled and measured heads in layer 1, interdunal flats.
Figure A2 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain.
Figure A3 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain near extractions.

Figure A4 Hydrograph comparison between modelled and measured heads in layer 1, coastal plain near forestry.
Figure A5 Hydrograph comparison between modelled and measured heads in layer 1, highlands.
Figure A6 Hydrograph comparison between modelled and measured heads in layer 1, near coastal lakes (BRA023, WAT012, LKG013) and near Blue Lake (BLA082, BLA005, GAM008).
Figure A7 Hydrograph comparison between modelled and measured heads in layer 3, regional observation wells.

Figure A8 Hydrograph comparison between modelled and measured heads in layer 3, near extraction wells.
References


Fleming N and Hutson J (2014) Primary production to mitigate water quality threats. Final report for Project 54116. South Australian Research and Development Institute, Primary Industries and Regions SA.


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