TECHNICAL REPORT

LOWER SOUTH EAST WATER BALANCE PROJECT PHASE 1 – REVIEW OF THE CONCEPTUAL MODEL AND RECOMMENDATIONS FOR A MODELLING APPROACH

2011/12

Government of South Australia
Department for Water

REPORT LOWER SOUTH EAST WATER BALANCE PROJECT PHASE 1 – REVIEW OF THE CONCEPTUAL MODEL AND RECOMMENDATIONS FOR A MODELLING APPROACH

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FOREWORD

South Australia's Department for Water leads the management of our most valuable resource—water.

Water is fundamental to our health, our way of life and our environment. It underpins growth in population and our economy—and these are critical to South Australia's future prosperity.

High quality science and monitoring of our State's natural water resources is central to the work that we do. This will ensure we have a better understanding of our surface and groundwater resources so that there is sustainable allocation of water between communities, industry and the environment.

Department for Water scientific and technical staff continue to expand their knowledge of our water resources through undertaking investigations, technical reviews and resource modelling.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT FOR WATER

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- Attendees of the Technical Workshop, who made the event a great success, provided valuable feedback on the project approach and highlighted the volume of work that has been done and is underway on water resources in the South East.

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Overview and Objectives

The Establishing Total Water Balance for Water Planning in the (Lower) South East Project was initiated under the New Knowledge for the Future sub-program of the Department For Water's (DFW) Groundwater Program. The objectives of the project are to:

- provide an improved technical base, in the form of a water balance model, for water resources management in the Lower South East
- provide recommendations for how the water balance modelling approach may evolve in response to new knowledge gained over the next 5-10 yrs
- provide recommendations for future studies, data collection and data management to improve the conceptual model and ensure availability and quality of key data in the future
- promote collaboration between organisations working on water-related projects in the Lower South East (e.g. DFW, CSIRO, SARDI, state agencies, universities, industry and private consultants).

Phase 1 of the project has involved:

- consultation with key stakeholders to understand the policy issues, policy context and framework into which the water balance model should provide input and determine the model objectives (see Section 3 of this report)
- review of available data and knowledge of the hydrologic system in the Lower South East for input to numerical models
- consultation with technical experts on a short and long-term modelling approach that addresses the management needs of the region.

This summary provides an overview of the main outcomes from Phase 1, including objectives for future models developed to support the development Lower Limestone Coast Water Allocation Plan (LLC WAP), and recommendations for a long term modelling approach. The details of the conceptual model review are included in the main body of the report but not summarised here, with the exception of the knowledge gaps that were identified through this exercise.

Terminology

This project involves the development of a range of types of models and hence the term "model' is used throughout this report in a few different contexts. The types of models to be discussed are:
Conceptual model – Conceptual models are simplified representations of the essential features of a physical hydrogeological system, and its hydrological behaviour, to an adequate degree of detail (Middlemis et al., 2000)

Numerical model –Numerical models use numerical methods within a computer program to solve a series of equations. Numerical models use an iterative process to reach an approximate solution to the set of equations and are powerful tools in that they can solve large numbers of equations quickly, hence being able to represent large or complex systems. The results from numerical models are often approximations, as opposed to analytic models, which produce exact solutions. Numerical models are developed based on conceptual models of real systems. The numerical models referred to in this report are predominantly three dimensional numerical groundwater flow models, unless otherwise specified, i.e. there may also be reference to two dimensional numerical groundwater flow models or numerical surface water flow models.

Regional scale numerical model –A numerical model developed to represent a system at a regional scale, i.e. representing regional flow systems, regional water balances and larger scale features. The model grid is comprised of cells with dimensions of the order of kilometres to tens of kilometres. This is required to represent large areas, where using smaller cells would result in an excessive number of cells, requiring prohibitively large computer run-times and memory. Regional models are also useful to represent large scale processes where knowledge of smaller scale details and processes is sparse. Smaller scale local processes that operate at scales of the order of hundreds of metres or less are not well represented by these models.

Local scale numerical model - A numerical model developed to represent smaller scale local flow systems where sufficiently detailed data and knowledge of processes is available. Local scale numerical models are developed for areas where knowledge of local impacts of something is required and where small scale features are expected to have an influence. For example the local impacts (within tens of kilometres or less) on water tables and salinities of a groundwater extraction or forestry development, and representation of small scale process such as surface water-groundwater interactions. The model grid is comprised of cells with dimensions of the order of metres to kilometres. Regional scale processes need to be carefully represented as boundary conditions for these models and hence processes operating outside the boundaries of the model may not be well represented.

Numerical modelling framework – the modelling framework proposed here includes a suite of different numerical (groundwater flow) models at both regional and local scales, as well as the conceptual model, an agreed set of modelling objectives and a methodology for translating the conceptual model into the numerical models.

Coupled surface water – groundwater flow model – A numerical surface water model and a numerical groundwater model are set up in a computer model framework so that the outputs from one provides input to the other and vice versa, hence fully representing a connected surface water and groundwater system.

IDENTIFICATION OF SCOPE AND OBJECTIVES FOR WATER BALANCE MODELLING IN THE LOWER SOUTH EAST

Based on the Phase 1 consultation and review process, the following general issues / needs for a future modelling strategy for the Lower South East have been highlighted.

- Three-dimensional numerical groundwater flow models are essential to underpin the management of groundwater resources in the Lower South East through testing of our understanding of the resource and simulation of outcomes of proposed management scenarios.

- Previous approaches to groundwater modelling have focused on specific issues and have not been coordinated in any way. As a result, a number of models exist in various stages of development, with varied objectives and hence varied input data and conceptual models. The outputs of such models are not necessarily comparable or relevant for addressing the management questions that have been identified through this project.

- A suite of numerical models is required, with consistent conceptual models and input data, designed to address at both regional and local scales specific management questions / issues important to the WAP process. Such a product should be able to identify emerging and likely risks through simulation of specific climate and management scenarios.

- There is a preference amongst a number of stakeholders to move towards a fully-coupled surface water – groundwater modelling approach. However, the specific objectives of such an exercise, the data / knowledge requirements and hence feasibility (cost/benefit) of such an exercise have not been explored.

- There is an urgent need for a tool to assist with identifying and prioritising the research / data needs that are critical to water resources management in the (Lower) South East and to provide a link between current and proposed management scenarios and observed / modelled ecosystem responses.

PROPOSED THREE-STEP MODELLING APPROACH

In consultation with the Technical Reference Group, the following three-step modelling approach has been developed to address the objectives identified through the stakeholder consultation.

1. Construct a regional three-dimensional numerical model (current project), with a domain targeting the Lower Limestone Coast Prescribed Wells Area but otherwise governed by aquifer extents where possible, with the following objectives:

    - identify and prioritise critical knowledge / data gaps at a regional scale

    - assess / improve our knowledge of the regional water balance, including recharge, groundwater extraction, groundwater inflows from Victoria and outflows at the coast

    - quantify available water (surface water and groundwater) at a regional scale

    - provide first-pass assessments of current allocation approach – e.g. what are the implications at a regional scale of allocating 90% of recharge?

    - provide broad-scale information on likely locations and types of surface water - groundwater interactions and identify those groundwater-dependent ecosystems (GDEs) likely to be impacted by up-stream activities

    - identify areas of interaction between the confined/unconfined aquifers or areas where this is likely, but requires further investigation

    - assist stakeholders with visualising the system and provide an educational tool

    - provide a basis / boundary conditions for more detailed localised models and recommendations for a consistent modelling approach for these models (i.e. recommendations for step 2).

The broad details of the proposed regional water balance model, based on the detailed review of the conceptual model and the outcomes of consultation with the Technical Reference Group, have been provided in Section 8 of this report.

2. Develop a consistent framework for numerical groundwater flow modelling in the (Lower) South East, including:

   - the regional numerical model to provide boundary conditions and regional conceptual framework for smaller scale models (step 1)
   - documentation of the possible approaches for translating the conceptual model into numerical models, i.e. approaches for representing key processes, e.g. historical recharge, groundwater extraction, evapotranspiration (ET), forestry impacts, surface water – groundwater interactions, etc, including their benefits and limitations to different modelling applications
   - a clear set of objectives for a suite of local-scale "hotspot" numerical models to be developed specifically to support the WAP. It is important to consider here (and to emphasise to stakeholders) that one size does not necessarily fit all in modelling, and that not all potential objectives may be able to be addressed by one model (see below)
   - a consistent methodology for constructing local-scale numerical models to meet the above objectives
   - a mechanism for reviewing the framework and the numerical models to incorporate new knowledge.

3. Develop a suite of local-scale "hotspot" numerical models to address known and emerging risks that should be considered in any WAP review, using the framework proposed in step 2. Possible objectives of these models include:

   - identify and prioritise critical knowledge / data gaps at local scales
   - assess validity of current resource condition triggers
   - quantify water balances of individual management areas (current and proposed)
   - provide a better understanding of localised processes, e.g. confined-unconfined aquifer interactions, surface water-groundwater interactions (including GDEs) and the role of preferential recharge
   - detailed (quantitative) assessment of impacts of potential future climate scenarios and proposed management scenarios or developments (e.g. irrigation, forestry and industry)
   - contaminant transport modelling or investigation of groundwater salinity issues.

The different methodologies for allowing feedback to occur between the regional numerical model developed during the current project (Step 1) and the smaller scale models developed during Step 3 have been investigated.

Numerical models are emerging as critical tools in water resources management and hence the quality of the conceptual models upon which these are based should be considered of high importance to water resource managers. It is usually the numerical models themselves that provide the best indication of the areas of the conceptual model that require improvement. Therefore, modelling is an iterative process and requires a long-term commitment if the best outcomes are to be achieved.

ADDRESSING SURFACE WATER – GROUNDWATER INTERACTIONS

The following issues regarding a "fully-coupled" surface water – groundwater model for the (Lower) South East have been identified in consultation with the Technical Reference Group.

- The objectives of such a modelling exercise must be clearly identified in order to determine whether a fully coupled model is likely to or necessary to address these objectives.
- MODFLOW (the proposed groundwater modelling platform for this project) incorporates surface water interactions through the drain, river and stream-routing packages in a way that is probably adequate for most needs based on likely objectives and available data.
- In order to provide more accuracy than the above approach, a fully coupled model would require much more detailed data than is currently available.

For these reasons, a "fully-coupled" surface water – groundwater model has not been proposed for the long-term modelling approach. However, if the desire for such a model remains amongst the stakeholders, it is recommended that a cost-benefit and feasibility analysis be carried out as soon as the groundwater flow modelling has clarified what the key knowledge and data gaps are.

LIMITATIONS AND KNOWLEDGE GAPS IN THE CONCEPTUAL MODEL

A number of gaps in knowledge of the water balance of the Lower South East have been identified through the Technical Workshop (Section 5) and the detailed review of the conceptual model (Section 6). These are presented in Table 4 of Section 9 and prioritised as areas of future work based on (a) the current level of understanding and (b) the likely impacts of the knowledge gap on regional and local scale groundwater models for the region. Based on this method of prioritisation, the following areas were identified as priority areas for improvement of the conceptual model:

- groundwater flow around numerous faults in the region (i.e. impacts of faults on aquifer geometry, properties and preferential vertical flow)
- occurrence and magnitude of vertical leakage between unconfined and confined aquifers
- spatial and temporal variability of SW-GW interactions around drains
- evapotranspiration from shallow water tables
- spatial and temporal variability in recharge interception and direct extraction of groundwater by forest plantations
- coastal and offshore groundwater discharge (includes understanding of seawater intrusion).

This list will be revised based on outcomes of the regional water balance model (Phase 2 of this project) and it is also anticipated that Phase 2 will allow us to be more specific about the work required in these general areas.

RECOMMENDATIONS FROM PHASE 1

The recommendations from Phase 1 of the Lower South East Water Balance Modelling Project can be summarised as follows:

- to address the needs of the Water Allocation Process, identified through consultation with stakeholders, and through consultation with the Technical Reference Group, a three-stage process should be carried out, involving:
    - development of a regional scale numerical groundwater flow model to address regional scale objectives (Phase 2 of this project)
    - development of a numerical modelling framework, which would include the regional numerical model itself, guidelines for the development of consistent and relevant local scale models, a methodology for allowing feedback between the two scales of model and a mechanism for reviewing the framework and the numerical models to incorporate new knowledge
    - development of the local scale models described above to address local scale objectives
- a groundwater flow model is the appropriate platform for the numerical modelling, given that the system is groundwater dominated and that groundwater models have facilities for including surface water-groundwater interactions at the level that is required and justified by the data available
- feasibility of fully coupled surface water – groundwater modelling should be investigated as soon as possible if this is still considered to be a desirable option
- outcomes from the regional numerical model should be used to guide future research and work plans for the Lower South East.

1. INTRODUCTION

1.1. BACKGROUND

The South East of South Australia, particularly the region south of Naracoorte (the Lower South East), has been identified as a priority region for improvement of the technical base for groundwater management because:

- the conceptual model for the water balance of the aquifer system is complex and unresolved. However, there have been a large number of technical investigations and groundwater modelling projects carried out across the region over the past 30 years, many of which had independent objectives and scopes, and whose outcomes could be incorporated into a regional conceptual model or used to refine management policies and identify critical gaps.
- the recent National Water Commission (NWC) funded projects on hydrogeology and inter-aquifer leakage in the Lower South East, for example, are expected to dramatically improve the understanding of the groundwater system in the region and then to be incorporated into a regional conceptual model
- the region is an important economic zone that is highly dependent on groundwater as its water resource and, in some areas, groundwater levels are declining and salinities are increasing beyond what could be expected from climatic influences alone
- there are growing demands for development of the water resource in the South East due to many factors, including its perceived robustness
- in some areas, groundwater is currently allocated based on a percentage of total available recharge. The understanding of rainfall recharge is fairly good for the Lower South East and has been improved by the results of the South East National Water Initiative (NWI) project. However, further refinement of this major component of the water balance is still required, particularly how it may vary in response to climate.
- there is a growing demand for a whole water balance approach to managing groundwater in the Lower South East. The application of this approach has partly been investigated by the South East Water Science Review (see Section 2.1). However, the current project recognises that it is not just knowledge of the global water balance that can provide a sound basis for effective groundwater management but how the different components of the water budget interact with each other and respond to external stresses at a range of scales. An example is the establishment of a new forest plantation, which would have an impact on the regional balance through evapotranspiration and groundwater extraction (interception of throughflow). However, the significance of this impact may not be as great as the local impacts on water tables and throughflow to local groundwater dependent assets, the magnitude of which could be governed by local scale variations in topography and aquifer geometry / properties. Taking a whole water balance approach alone could underestimate such risks.

Although the South East (and particularly the Lower South East) is a region for which there is a great deal of data and technical knowledge relating to water resources, the current situation is that:

- this information is not integrated into a whole system water balance model, and

- there has been a lack of co-ordination of projects across disciplines, regions and between scientific organisations.

As a result of this lack of integration and co-ordination, the outcomes of individual projects are not optimised and the water allocation planning process is not able to take full advantage of the extensive work that has been carried out.

Appendix A shows the current administrative boundaries for the South East, including confined and unconfined aquifer management zones.

1.2. TERMINOLOGY

This project involves the development of a range of types of models and hence the term "model' is used throughout this report in a few different contexts. The types of models to be discussed are:

Conceptual model – Conceptual models are simplified representations of the essential features of a physical hydrogeological system, and its hydrological behaviour, to an adequate degree of detail (Middlemis et al., 2000)

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Numerical modelling framework – the modelling framework proposed here includes a suite of different numerical (groundwater flow) models at both regional and local scales, as well as the conceptual model, an agreed set of modelling objectives and a methodology for translating the conceptual model into the numerical models.

Coupled surface water – groundwater flow model – A numerical surface water model and a numerical groundwater model are set up in a computer model framework so that the outputs from one provides input to the other and vice versa, hence fully representing a connected surface water and groundwater system.

1.3. OBJECTIVES

The Establishing Total Water Balance for Water Planning in the (Lower) South East project was developed with the following objectives:

- provide an improved technical base, in the form of a water balance model, for water resources management in the Lower South East
- provide recommendations for how the water balance modelling approach may evolve in response to new knowledge gained over the next 5-10 yrs
- provide recommendations for future studies, data collection and data management to improve the conceptual model and ensure availability and quality of key data in the future
- promote collaboration between organisations working on water-related projects in the Lower South East (e.g. DFW, CSIRO, SARDI, universities and private consultants).

1.4. METHODOLOGY

The project is being carried out in two phases:

- Phase 1: Review and consultation (i.e. assessment of capability vs need), followed by development of scope and approach for Phase 2.
- Phase 2: A proposed modelling phase.

Phase 1 has been carried out in the following stages:

- review all existing numerical groundwater models for the Lower South East
- organise and hold a technical workshop to review projects and data related to the water balance in the Lower South East and facilitate collaboration between projects within the region
- review the availability and quality of water balance data (both measured and modelled / calculated) for use in a numerical model
- organise and hold a workshop with key stakeholders to identify and prioritize objectives for any future numerical models in the Lower South East region
- In consultation with the Project Reference Group, (i) develop the modelling approach for Phase 2 of the project and (ii) make recommendations for work over the next 5-10 yrs to achieve the wider objectives of the stakeholders.

It is proposed that Phase 2 will be carried out in the following four broad stages:

- development of a detailed conceptual model

- development of the groundwater flow model
- calibration and assessment of the groundwater flow model
- Reporting.

This report provides details of the outcomes of Phase 1.

2. PREVIOUS REVIEWS OF THE WATER BALANCE

2.1. SOUTH EAST WATER SCIENCE REVIEW (BROOKES (ED.), 2010)

The South East Water Science Review (Brookes (ed.), 2010) was commissioned by the Lower Limestone Coast Taskforce to examine the science behind the Water Allocation Planning process in the South East region of South Australia (South East). The Review was conducted by the Environment Institute at Adelaide University, and focused on the hydrological science, hydrogeological science, ecological science, and aspects of the geographic information systems behind decision-making in the South East. It also commissioned hydrogeological and economic modelling, and conducted a land capability assessment and a review of water availability in the drainage system.

The objectives of the Review were to:

- develop a global water budget for the region
- assess the assumptions in current science and policy pertaining to forestry water use
- predict future water availability
- determine the implications of falling groundwater levels on groundwater-dependent ecosystems.

The review revealed several areas of limited understanding, including:

- The water balance in the South East and the water balance hundred by hundred
- The relationship between groundwater and surface water
- Determination of losses in the stream and drain system so that sub-catchment flows can be properly accounted for
- The impacts of irrigation and forestry development in Victoria on groundwater flows in South Australia
- Lack of a method for allocation that considers ecological requirements
- How landholders value their water allocations
- How the identified high value wetlands can be maintained if groundwater quality and quantity decline. This includes a more detailed understanding of how priority wetlands will respond to changes to groundwater depth, and a systematic approach to the protection of adequately connected remnant habitat.
- Appropriate approaches to modelling the South East short of a full 3-D groundwater and surface water model.
- The most appropriate governance, public participation and trust-building, knowledge sharing and capacity-building, and social and economic impact assessment of water management processes.

The current project builds on the outcomes of the Science Review by focusing on the need for an appropriate approach to modelling in the Lower South East. Here, we review the conceptual model for the water balance of the Lower South East and identify the knowledge gaps that are relevant to such a modelling exercise.

2.2. A REVIEW OF SCIENTIFIC ASSESSMENTS UNDERPINNING THE WORK-IN-PROGRESS WATER ALLOCATION PLAN FOR THE LOWER LIMESTONE COAST PRESCRIBED WELLS AREA (SMERDON, 2009).

Smerdon (2009) carried out a review of (i) the methods used to quantify fundamental hydrogeological processes underpinning the WAP, i.e. the water balance components and associated data, (ii) the potential impacts of climate change, (iii) evidence of stress to groundwater resources caused by use, climate variability and long-term climate change. The review led to the following recommendations:

- Take a precautionary approach to water allocation due to the lack of knowledge of environmental water requirements and individual components of the water budget.
- Determine environmental water requirements.
- Re-assessment and estimation of recharge values in the context of the most recent decade of climate data. If the water-table fluctuation method continues to be applicable for the majority of the region, acquisition of actual specific yield values was recommended.
- Field assessment of groundwater discharge. Using recently installed instrumentation at case study GDE sites, develop complete wetland water budgets and gain a better understanding of groundwater discharge processes.
- Develop a three-dimensional regional-scale groundwater model to (i) represent whole-of-system groundwater flow, (ii) determine realistic water budget components at management area scales, (iii) understand the connection between potential causes of resource decline and impact to water dependent assets and (iv) assist in determining environmental water requirements. The recommendation was for a transient three-dimensional flow model, similar to the Coles-Short model (WR2010) but with the extent of the Tertiary Confined Sands Aquifer model

2.3. CURRENT UNDERSTANDING OF THE WATER CYCLE IN THE LIMESTONE COAST REGION (PAYDAR ET AL., 2009)

This study was conducted under the CRC for Irrigation Futures System Harmonisation program, which aims to provide a framework to improve regional production and environmental outcomes through improved understanding and management of a region's water resources. The study presented a literature review, a simple conceptual model and water balance calculations for the Limestone Coast region. Recommendations that arose from the study were:

- Future hydrological studies should consider spatial variability in the water balance and water quality issues as these affect the placement of agricultural development.
- More accurate estimates of regional evapotranspiration. Remote sensing was suggested for capturing spatial variability in ET.
- A fully dynamic model of the surface and groundwater system in the Limestone Coast.

3. OBJECTIVES FOR SHORT- AND LONG-TERM GROUNDWATER MODELLING IN THE LOWER SOUTH EAST

3.1. CONSULTATION APPROACH

In order to clarify what the main objectives of numerical models in the Lower South East should be and hence to assist with developing the modelling approach for this project, two consultation meetings were held with the key stakeholders for the project, the Policy Division of the Department for Water and the South East Natural Resources Management Board. Although there are many stakeholders for the project, these two groups were considered to have the greatest understanding of the science needed to inform policy development in the Lower South East and to have a general understanding of the positions of other stakeholder groups. These focused meetings were considered to be the best way to develop a series of short- and long-term objectives for numerical modelling projects in the Lower South East. The main points from these meetings are summarised below.

3.2. KEY REGIONAL ISSUES

- validation of resource condition triggers.
- the risk of double accounting of surface water and groundwater and unconfined and confined groundwater
- accurately accounting for forestry impacts
- quantifying available water and identifying location of available water
- quantifying groundwater inflows from Victoria and outflows at the coast
- water balances for current individual management areas and also for possible hydrogeology-based management areas
- appropriateness of management area boundaries with respect to hydrogeological boundaries and how future unconfined, confined and surface water management area boundaries could line up
- areas of high recharge / interaction between the confined/unconfined possibly to assist with revising management area boundaries.
- validating estimates of recharge under different land uses and different soil types and methods used to scale up these estimates.
- having a regional tool that can be used to assess issues in non-hotspot areas in the future.

- future management of sub-units of the confined and unconfined aquifers.

3.3. CONSIDERATIONS FOR INTERFACING THE (SHORT- AND LONG-TERM) MODEL APPROACH WITH THE WATER ALLOCATION PLANNING PROCESS

The following considerations for interfacing the short- and long-term model approach with the Water Allocation Planning process were highlighted by the South East Natural Resources Management Board:

- The timing of this project will not allow it to influence the development of the current WAP (to be finalised July 2011) with the exception that some of the outputs from the Conceptual Modelling (pictures / diagrams, etc) may be useful as educational tools.
- The lifetime of the WAP is five years, with provisions for revisions to management settings to be made after three years or more frequently if the science supports it.

3.4. OTHER RECOMMENDATIONS FROM THE STAKEHOLDERS

Other recommendations from the stakeholders were:

- Ensure that people have realistic expectations about what the current (and future) modelling is expected to achieve (i.e. understand its limitations).
- That this model be set in a consistent framework so that it becomes a tool for the whole Department and results are consistent with other models and other products (e.g. water accounting, BoM).
- A highly desirable outcome from this project would not just be a model, but a modelling infrastructure for the region that guides how future models are set up – i.e. what input data is used, how the data is quality controlled, and how it is manipulated for use as input parameters in models.
- An example of this is: How do we obtain /estimate historical recharge data for use in groundwater models? This would probably involve deciding on accepted average recharge estimates for different regions and manipulating these using a combination of land-use and rainfall data to obtain a spatial and temporal (historical) dataset. There should be a standard methodology for this so that results from different models can be assessed equally.
- A regional model can also be a part of this outcome, providing boundary inputs for smaller scale models.

3.5. GUIDING FUTURE RESEARCH AND DATA COLLECTION EFFORTS

A common theme throughout the consultation process for this project, as well as a number of separate meetings and workshops attended by the project team, was an urgent need for a tool to help identify and prioritise future knowledge and data collection projects. The list of proposed research projects is long and, despite a great deal of consultation, how these projects should be prioritised is still unclear.

4. PREVIOUS MODELLING STUDIES IN THE LLC REGION

4.1. OVERVIEW

Several numerical groundwater flow models already exist for various regions of the Lower South East. These are summarised in Table 1 below, along with some of the major features of their input datasets, and their model domains are shown in Figure 1. All numerical groundwater models for South Australia are being archived and catalogued as part of the Groundwater Model Warehouse Project, another sub-project of the Groundwater Program. Some of the following general descriptions are based on information presented in the June 2010 Milestone Report for that project.

Table 1. Summary of existing numerical groundwater flow models for the Lower South East (after Groundwater Model Warehouse project, June 2010 Milestone Report).

Model Name	Sub-zones/ Project area	Package and Version	Model Status	Purpose	Reports	Model Availability	GIS Domain
Gambier Basin Compartmental Mixing Cell Model	East-West transect through Gambier Basin	MODFLOW (flow model), Analytical CMC Model (solute transport)	Completed	Estimate leakage between confined / unconfined aquifers. Investigate advantages of using integrated MODFLOW and CMC approach to improve model calibration and confidence in estimates of aquifer parameters.	Harrington, G.A., Walker, G.R., Love, A.J and Narayan, K.A., 1999, A compartmental Mixing-cell approach for the quantitative assessment of groundwater dynamics in the Otway Basin, South Australia., J. Hydrol., 214: 49-63.	No	No

Model Name	Sub-zones/ Project area	Package and Version	Model Status	Purpose	Reports	Model Availability	GIS Domain
Tertiary Confined Sand Aquifer Model	South East of South Australia	Visual MODFLOW (Flow Model)	Completed in 2000	Impact assessment and to assist with Water Allocation Planning	PIRSA Report Book 2000/16	No	Yes (to be updated)
Wattle Range (Coles - Short)		GW Vistas (Flow Model)	Completed in 2010	Forestry impact assessment/policy and potentially for assisting Water Allocation Planning	Final Report (Aquaterra, 2010)	Yes	Yes
Coonawarra	Zone 3A and 3B of Border Designated Area, parts of Zones 2A, 2B, 4A, 4B.	Visual MODFLOW (Flow Model)	Preliminary model. Calibration questionable. May be updated in the future	1. Proposed to assist with Water Allocation Planning (WAP). 2. Constructed to model nitrate (etc) pathways for Diffuse Impacts Project. Calibration not good enough.	Conceptual model report (REM, 2007). Draft model report in progress.	Yes	Yes

Model Name	Sub-zones/ Project area	Package and Version	Model Status	Purpose	Reports	Model Availability	GIS Domain
Zone 1A	Zone 1A of the Border Designated Area. Includes Mount Gambier and surrounds, south to the coast.	Visual MODFLOW (Flow Model)	Preliminary model May be updated in the future	Constructed to model nitrate (etc) pathways for Diffuse Impacts Project.	Conceptual model report (DWLBC Report 2008/12) Draft model report in progress	Yes	Yes
South of Mount Gambier	South of Mount Gambier.	Visual MODFLOW (Flow Model)	Model completed in 2000	Impact assessment and to assist with Water Allocation Planning	DWR Report 2000/40	Yes	Yes
Border Zone Inter-aquifer leakage model(s)	Border Zone		Proposed (not included in summary below)	Model inter-aquifer leakage in the Border Zone	NA	NA	NA

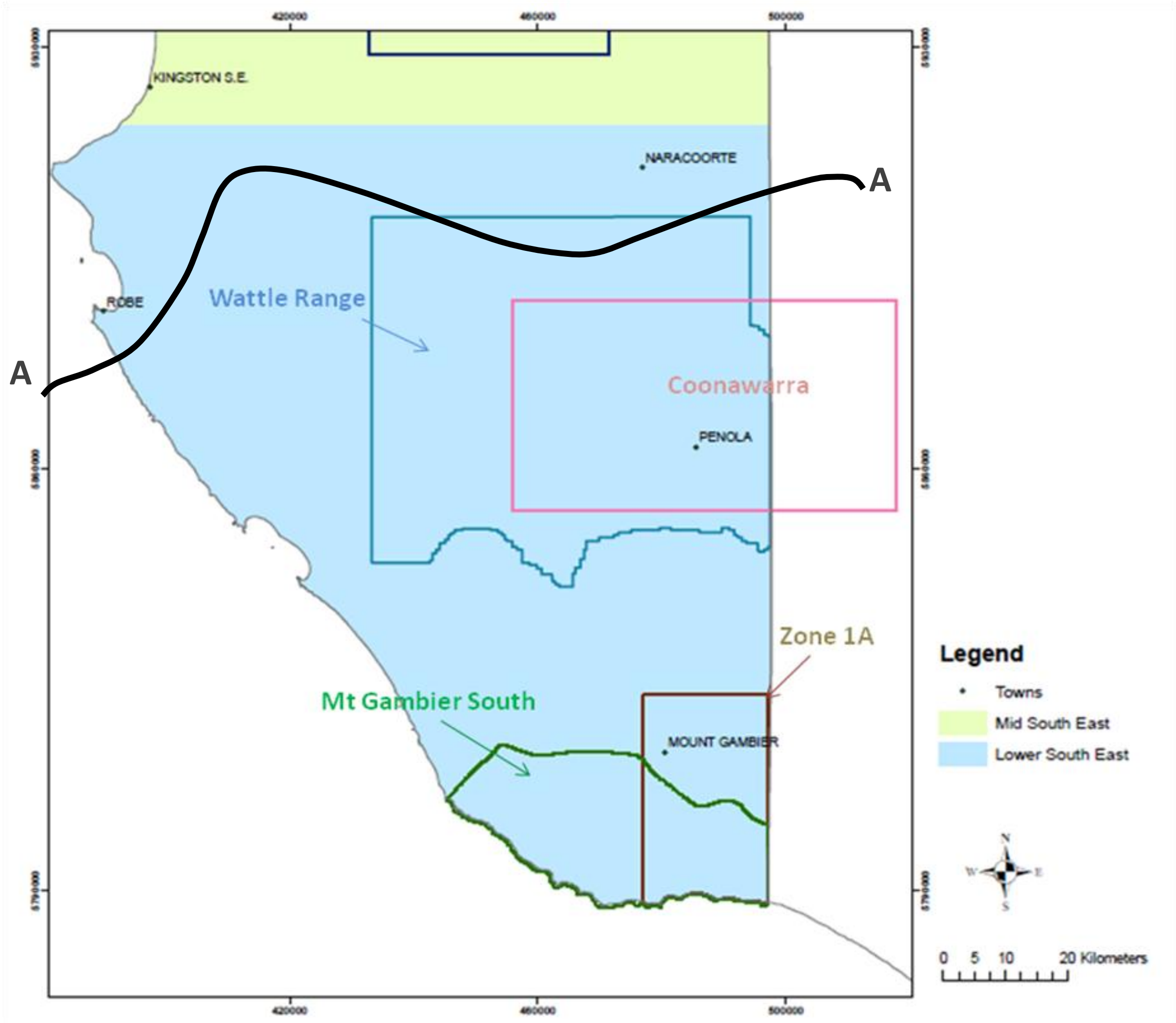

Figure 1. Model domains for existing Lower South East numerical groundwater flow models (where available; after Groundwater Model Warehouse project, June 2010 Milestone Report). Cross section AA represents approximate location of cross section for Compartmental Mixing Cell Model (Harrington et al., 1999)

4.2. MODEL SUMMARIES

4.2.1. COMPARTMENTAL MIXING CELL MODEL

4.2.1.1. Purpose

The objective of the Compartmental Mixing Cell study was to investigate the advantages and disadvantages of using an integrated transient groundwater flow and solute transport modelling approach to improve confidence in estimating aquifer parameters.

4.2.1.2. Background

A number of regional hydrogeological investigations had recently been carried out in the Gambier Basin, including the use of environmental isotopes and hydrochemical techniques to determine recharge and groundwater flow patterns within the aquifers (Love, 1991; Love et al., 1993), the palaeohydrology of the basin (Love et al., 1994) and to investigate diffuse leakage between the unconfined and confined aquifers (Love et al., 1996). The latter study concluded that diffuse leakage between the aquifers was minimal throughout the basin and hence that water and solutes must be transported between the aquifers via preferential pathways. The process of inter-aquifer leakage to the Dilwyn Confined aquifer was still yet to be quantified.

The compartmental mixing cell (CMC) approach is a modelling methodology that has been used extensively over the past 25 yrs to interpret environmental tracer data inversely through estimating hydraulic fluxes. An iterative procedure between obtaining a calibrated MODFLOW model and using this as input to the CMC model to attempt to accurately simulate observed isotope distributions was carried out.

4.2.1.3. Location

The model was set along an east-west transect in the northern portion of the Gambier Basin (transect AA'; Figure 1). This transect was perpendicular to the potentiometric contours for both the unconfined and confined aquifers.

4.2.1.4. Model Structure

The 2-D vertical slice model included both the confined Dilwyn and the unconfined Gambier aquifer systems. The slice was divided into 30 columns and model simulations were carried out for the period between 27 000 yrs before present (BP) until present. The long simulation period was required due to the long residence times of the tracers being investigated.

4.2.1.5. Model Outcomes and Limitations

It was considered to be questionable that any model could be expected to accurately simulate a groundwater system over such long time scales due to the unknown input functions for most tracers and the unknown details of the groundwater flow system. However, with a good understanding of the model limitations and assumptions, the recharge to the confined aquifer, via leakage from the unconfined aquifer, was estimated to be 2 – 9 mm/yr with greater confidence than previous estimates. This was considered to be a worthwhile improvement to the understanding of the aquifer system.

4.2.1.6. Report

Harrington, G.A., Walker, G.R., Love, A.J., and Narayan, K.A., 1999, A compartmental mixing-cell approach for the quantitative assessment of groundwater dynamics in the Otway Basin, South Australia., J. Hydrol., 214: 49-63.

4.2.2. TERTIARY CONFINED SAND AQUIFER (TCSA) MODEL

4.2.2.1. Purpose

To assist in the understanding of the mechanisms that control flow into, and through the TCSA, and to assess the long term impact of various extraction scenarios. Determine appropriate Permissible Annual Volumes (PAVs) for extraction from the TCSA.

4.2.2.2. Background

The large contrasts in groundwater use from the Tertiary Confined Sand Aquifer between the Border Designated Area (low use) and the main artesian area, approximately 15 km east of Robe (high use), coupled with the sensitivity of water levels in confined aquifers to groundwater extraction, meant that it was considered important to manage the Tertiary Confined Sand Aquifer in the South East of SA as a whole. A groundwater flow model was constructed to be used as a predictive tool to provide both seasonal and long-term changes in the potentiometric head of the aquifer under different extraction scenarios and determine the appropriate volume of extraction from the Tertiary Sand Confined Aquifer (Brown, 2000).

The objectives of the model were to:

- organise and evaluate hydrogeological information in order to construct a conceptual model of the Tertiary Confined Sand Aquifer within the study area
- develop a transient, numerical three dimensional regional groundwater flow model for the Tertiary Confined Sand Aquifer
- assess the likely impacts of extracting the volumes of groundwater from the Tertiary Confined Sand Aquifer as determined by the Department of Natural Resources and Environment in Victoria (1998).
- examine the possible impacts of the long term extraction in the main artesian area in the South East of Australia.

4.2.2.3. Location

The location of the model domain is shown in Figures 1 and 2.

4.2.2.4. Model structure

Model domain and grid size

The model domain covers an area of approximately 45,000 km^2 (Figure 2). The entire groundwater flow path was modelled. The model grid is divided into 57 rows and 49 columns. The grid has a uniform cell size of 4,000 m × 4,000 m. The model grid is applied to three layers, resulting in 8,379 finite difference cells.

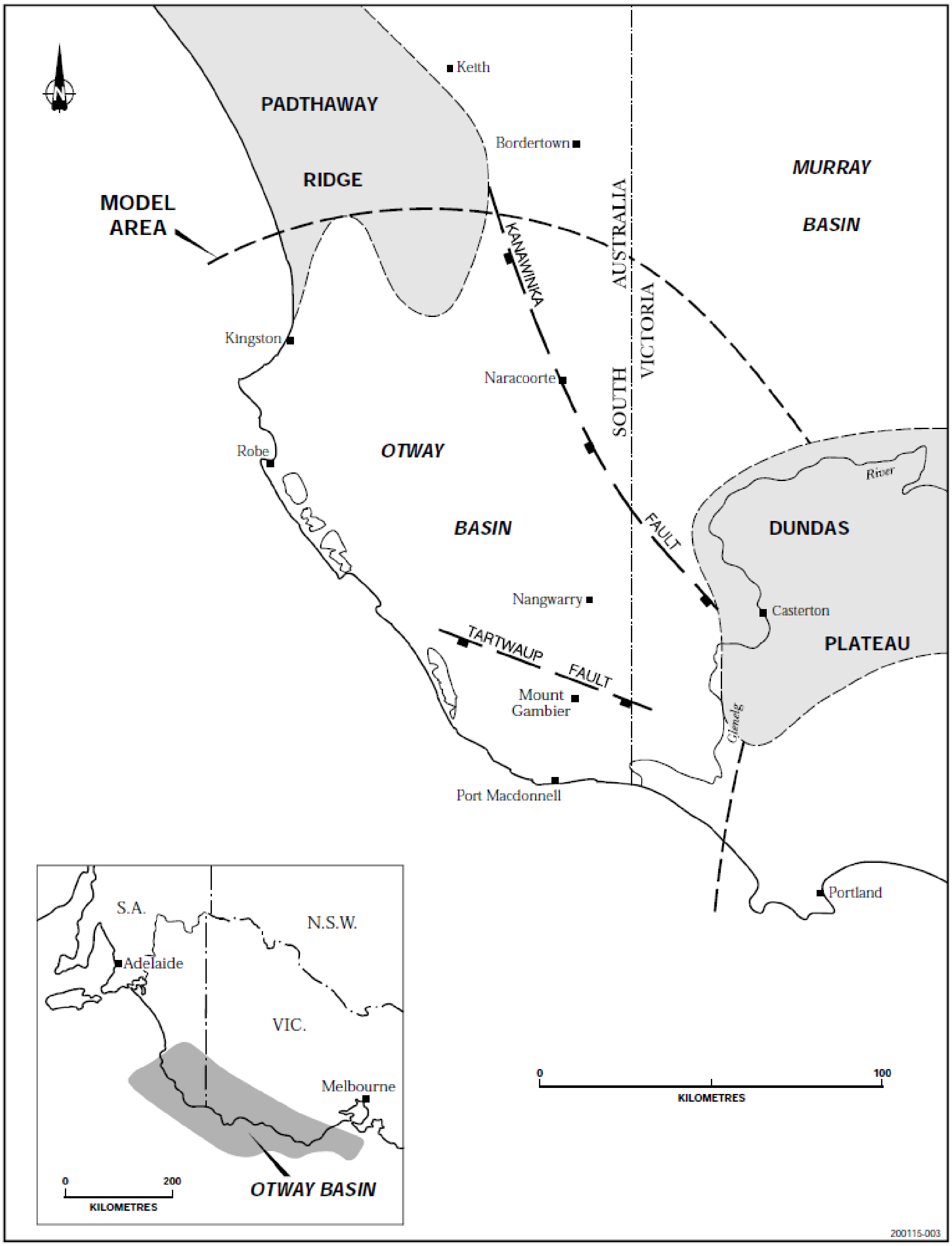

Figure 2. Tertiary Confined Sand Aquifer model domain, showing major geological features (Brown, 2000)

Model layers

The regional aquifer system is conceptualised as three layers, including two aquifer layers and one aquitard layer (**Error! Reference source not found.**3). Topography was computer generated based on easured values at observation wells.

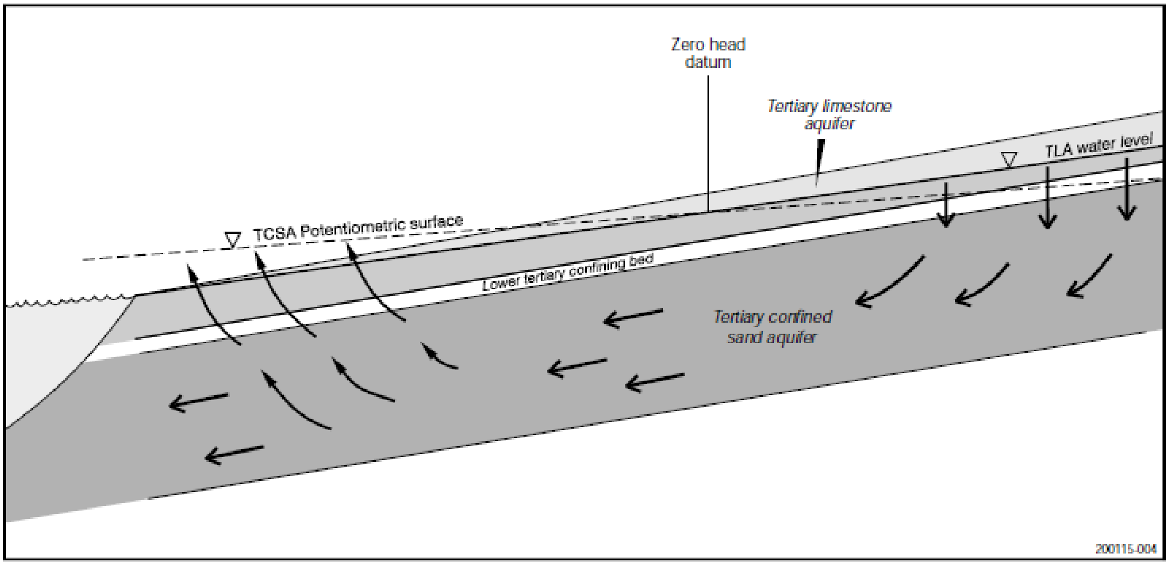

Figure 3. Representative conceptual cross-section for the TCSA model (Brown, 2000)

Groundwater extraction

When the model was constructed, extraction data was only available for the 1996-97 irrigation season. The extraction data was based on estimates of irrigated crop requirements, rather than metered volumes. Extraction from each well in the model was applied based on the date the well was drilled (i.e. for a well drilled in 1990, extraction from that well was implemented from 1990 onwards, and extraction volumes based on the 1996-97 data). Extraction was also only applied from October to March in each year, representing a summer irrigation season. The application of extraction in this way assumed there was little change in irrigation practices over the model period, which was recognised as a model limitation.

In addition to this, extraction for town water supply was included in the model, with extraction volumes based on data provided by SA Water. Leakage from poorly constructed wells in areas where the confined aquifer is artesian was also modelled, by applying a further 10% of extraction volumes in artesian areas.

4.2.2.5. Model Outcomes and Limitations

Model calibration was achieved by matching the observed head distribution for September 1997 and from observed long term hydrographic information for more than 30 observation wells. Despite the simplification of the conceptual model, good matches were achieved between modelled and observed potentiometric head contours for September 1997, as well as seasonal and long term trends in observation well hydrographs.

There were a few areas, particularly adjacent the Tartwaup and Kanawinka Faults, where good calibration could not be achieved due to the regional scale of the model and the coarse grid size applied. The seasonal drawdown in the cone of depression was reasonably well simulated. The model was considered to be reasonably well calibrated against the available hydraulic head data for the TCSA.

The major limitations of the model were:

- The assumptions made in the application of groundwater extraction data.
- The unconfined aquifer was not modelled accurately.
- The model does not take into account structural complexities.

- The discharge process from the TCSA along the western model boundary is not well understood
- The magnitude of losses from leaking wells in the main artesian irrigation area is unknown and was therefore estimated.

Results from the modelling showed a long-term decline in the potentiometric head of the TCSA of between 2m and 6m under the scenario of the recommended PAVs. Scenario modelling also suggested that an increase in extraction from the TCSA would result in an increase in vertical leakage to the TCSA from the overlying unconfined aquifer.

The model was updated in 2005 to reflect current licensed allocations, provide improved treatment of leaky wells and allow possible recalculation of PAVs (Harrington and Brown, 2007). The updated model provided reasonable agreement between observed and modelled groundwater levels, including the recovery of water levels around recently rehabilitated wells. Modelled drawdown was generally underestimated in all areas of high density irrigation, possibly due to averaging of groundwater extraction values across grid cells or using allocations rather than actual use.

4.2.2.6. Report

Brown K, 2000, *A groundwater flow model of the Tertiary confined sand aquifer in south east South Australia and south west Victoria*, Report PIRSA 2000/00016, Primary Industries and Resources South Australia, Adelaide.

Harrington, G. And Brown, K., 2007, South East Confined Aquifer Groundwater Resource Assessment: A review of the condition of the resource and estimates of Permissible Annual Volume., DWLBC Draft Report.

4.2.3. WATTLE RANGE (COLES-SHORT) MODEL

4.2.3.1. Purpose

The Wattle Range (WR2010) model was developed to estimate the effects of forestry plantations on the water balance and groundwater levels of the Wattle Range region (including the groundwater management areas of Coles, Joyce, Killanoola, Monbulla, Short and Spence) and to undertake selected scenario modelling to inform future management of the forestry areas in the South East. It also provided input to the South East Science Review (Brookes (ed.), 2010).

4.2.3.2. Background

The modelling work supported work by DWLBC (now DFW) to quantify the effects of existing forestry plantations in the groundwater management areas of Coles, Joyce, Killanoola, Monbulla, Short and Spence in the South East of South Australia. DWLBC (now DFW), in collaboration with other organisations, had undertaken several studies and monitoring initiatives to investigate the effects of plantations on groundwater systems (Mustafa et al., 2006). In 2006, DWLBC developed a groundwater numerical model covering the area of interest to simulate the groundwater system responses to hydrological processes (Osei-Bonsu, 2009). That model, referred to as the Bakers Range model, was considered inadequate in its existing form for the objectives of the modelling study. It was upgraded, mainly by expanding boundaries to reduce potential boundary effects, and including revised information on groundwater abstraction, revised layer elevations and other improvements to the conceptual model (Aquaterra, 2010).

4.2.3.3. Location

The location of the model domain is shown on Figure 1.

4.2.3.4. Model Structure

The model was constructed as a one layer model.

Recharge

The initial model for this project used a uniform annual recharge rate of 200 mm/y, however these were reduced and set to the rates reported in Brown et al. (2006) for individual groundwater management areas in the model domain. For areas under plantation forestry, different annual recharge rates were used. Areas under blue gum plantations had recharge reduced incrementally to 0 mm/y four years after modelled planting date (representing canopy closure). Under pine plantations, recharge was reduced incrementally to 0 mm/y seven years after plantation date (canopy closure). Areas under pine plantation received 50% of mean annual recharge (MAR) in the eleventh year after planting to simulate crop thinning, before recharge rates returned to 0 mm/y. Crop thinning was then modelled every five years after the eleventh year of plantation establishment (i.e. 50% MAR under pine plantations every 5th year after the 11th year, 0 mm/y recharge for all other years).

Groundwater Extraction

The Aquaterra model for the Wattle Range area (referred to as WR2010) is an updated version of a model previously constructed by DWLBC (Mustafa et al, 2006). The initial model (Osei-Bonsu, 2009) was based on information available at the time, and groundwater extraction was set at 81% of estimated recharge. Locations of extraction were set as the centre of licensed irrigation land parcels. The model was updated by Aquaterra in 2010. This included updating extraction well pumping rates to reflect metered data collected in 2009. Also, the location of extraction was updated by assigning extraction points either to the same locations as meters, or to the specific location of a known irrigation well (where the data was available). The model domain was extended to include part of Zone 3A, however no extraction in this area was modelled.

Impacts of Plantation Forestry

In the original model, water use by plantation forestry was set as 435 mm/y in areas where the depth to groundwater was <6m. Groundwater use was assumed to start 3 years after plantation, and increase to 435 mm/y after five years. Use was varied seasonally, with more plantation extraction in summer months (see Figure 4).

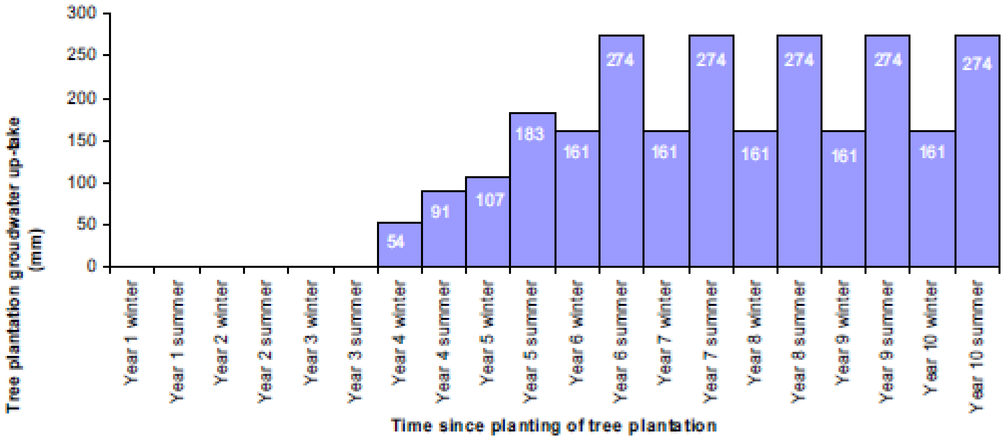

Figure 4. Modelled plantation forestry groundwater uptake

In the updated version, direct extraction by plantation forestry was modelled as 'negative recharge', and hence independent of depth. Extraction rates ranged from 0 ML/ha (directly after plantation) to 3.64 ML/ha (seven years after plantation) for both blue gums and pine plantations, with extraction rates varying as a result of plantation management (coppicing and rotation) to give an annualised extraction rate of 1.82 ML/ha/y under blue gums and 1.663 ML/ha/y under pine plantations.

4.2.3.5. Model Outcomes and Limitations

A good match between measured and modelled groundwater levels was obtained for the forestry development period (1999-2009).
The model had a number of key findings in the areas of:

- The maximum drawdown induced by the current forest plantations and the extent of this drawdown.
- The relative effects of recharge interception and direct extraction by the forests.
- The importance of the forestry management scenario selected.
- Potential impacts of forestry on Bool Lagoon and the application of the model to determine relative impacts of different groundwater affecting practices on Bool Lagoon.
- Potential impacts on other groundwater dependent ecosystems.

The main limitations of the model are:

- Average annual recharge rates are applied to areas outside the forestry developments. The effects of varying recharge in these areas have not been investigated.

4.2.3.6. Report

Aquaterra, 2010, Modelling forestry effects on groundwater resources in the Southeast of SA.
Osei Bonsu, K., 2009, Bakers Range 2006 Groundwater Flow Model, DWLBC Report 2009/28 (in prep.)

4.2.4. COONAWARRA (ZONE 3A) MODEL

4.2.4.1. Purpose

The Coonawarra (Zone 3A) model was developed to:

- adequately represent groundwater flow in the unconfined aquifer in the Coonawarra (Zone 3A) region,
- be used to assess the effects on groundwater levels of activities such as plantation forestry and groundwater abstraction for irrigation and other purposes.
- assist future land-use planning and water resource management.
- form a base for a salt transport model.

The model was also intended to be used as a base for modelling the movement of diffuse source contaminants, such as nitrate, through the aquifer system as part of the Diffuse Impacts Project.

4.2.4.2. Background

Groundwater resource condition has been observed to be declining in various parts of the South East over the past two decades, mainly due to a high incidence of below average rainfall and increased groundwater abstraction. However, there are several areas in the region where plantation forestry is also believed to be impacting on shallow groundwater levels. In the Zone 3A Management Area of the Border Designated area, intensive viticultural development competes with relatively large areas of plantation forestry for groundwater resources. To investigate the relative impacts of the two types of development, the project titled "Estimating Regional Impacts of Plantation Forestry and Intensive Irrigation Development on Groundwater Resources in the Lower South East" commenced in 2006. The project was carried out in two phases, both of which were funded by the Natural Heritage Trust through the South East Natural Resources Management Board's Regional Investment Strategy. Phase 1 received funding in 2006/2007 and involved the development of a conceptual model for groundwater flow and solute transport in Zone 3A of the Border Designated Area. This was done through (i) collation of existing data, (ii) preliminary field sampling of existing observation wells and (iii) a drilling program in February 2007 resulting in the establishment of 10 new research sites, some of which were cored and instrumented with piezometers. Details of the Phase 1 work and conceptual model were provided in a separate consultants' report (Resource and Environmental Management (REM), 2007). Phase 2 of the project involved the construction of the numerical groundwater flow and solute transport model for the region including and surrounding Zone 3A in the lower South East.

As well as being a valuable management tool, the numerical model was intended to be used as a framework to model the groundwater impacts of diffuse source pollutants in the Zone 3A area through the "Primary Production to Mitigate Water Quality Threats" project, also known as the "Diffuse Impacts Project". The "Primary Production to Mitigate Water Quality Threats" project was a collaborative study between the South Australian Research and Development Institute (SARDI), the Flinders University of South Australia (FUSA) and the Department of Water, Land and Biodiversity Conservation (DWLBC). The specific objectives of that project were to:

- Assess the risk of contamination of water resources in the South East from primary production.
- Quantify the sources of diffuse pollution from primary production.
- Decrease the risk of contamination of water resources from primary production within the South East.

The Zone 3A area represented one of the selected key regions to be studied intensively through the "Primary Production to Mitigate Water Quality Threats" project. The other regions included the Zone 1A area surrounding and to the south of Mount Gambier and the Padthaway Prescribed Wells Area.

4.2.4.3. Location

The location of the model domain is shown in Figure 1.

4.2.4.4. Model Structure

Model Domain and Grid

Due to the presence of significant plantation forestry developments upgradient (east) of Zone 3A, and the need to minimise boundary effects on the model results in the area of interest, the model domain was extended beyond the boundaries of Zone 3A, to include Zone 3B, parts of Zone 2A and 4A and a 10 km buffer zone to the west of the Zone 3A boundary. The model domain therefore encompassed a 50 km x 61 km area (Figure 1). The model domain was discretised using a grid with cells of dimensions 250 m x 250 m.

Model Layers

Three model layers were used to represent the following components of the unconfined aquifer:

- Bridgewater Formation
- Green Point Member, Units 1-5 (Gambier Limestone)
- Camelback Member (Gambier Limestone)

The top of Layer 1 (ground surface) was contoured from the Digital Elevation Model (DEM) for the South East. The bottom of Layer 3 (base of unconfined aquifer) was contoured using all available drillhole data, including that from a recent drilling program. The base of the model, which is a no-flow boundary, represents the top of the aquitard that separates the confined Dilwyn Sand aquifer from the overlying unconfined Gambier Limestone. The aquitard comprises the low permeability Greenways member of the Gambier Limestone, the Narrawaturk Clay, Mepunga Formation and Dilwyn Clay.

Three model layers were used to allow some vertical flow to be simulated within the unconfined aquifer. Some data exists for the elevations of the boundaries between the various units of the unconfined aquifer, including data from the recent drilling program. However, the boundaries between the three model layers were assigned to divide the model domain into three layers of equal thickness rather than being based on real data. The reasons for this were:

1) Despite the recent work, the relevant dataset is sparse in a geologically complicated area, where there are sharp changes in layer elevations due to faulting and some units are missing in some areas. Creating layers based on this is misleading in its accuracy and introduces instability and grid complications that may be unnecessary and impossible to rectify due to a lack of data.
2) There is very little data available on the hydraulic properties of the individual units in the unconfined aquifer, meaning that defining them accurately is meaningless to the model outcomes.

Recharge

The steady state model used recharge rates based on the recharge zones reported in Bradley et al. (1995), with areas under pine plantation having recharge rates reduced by 83%. For the transient numerical model, recharge rates were varied annually based on rainfall records.

The majority of recharge is considered to occur in winter, and hence the annual recharge to the aquifer depends on winter rainfall rather than annual rainfall. Based on this, an annual correction was applied to the average recharge rates using the following approach:

1) "Winter" rainfall was calculated for each year by summing daily rainfall between 1 May and 31 October.
2) An average winter rainfall for the time period 1889 to 2008 was calculated from this data.

3) For each recharge zone, the difference between the average winter rainfall and the average recharge was calculated. This was deemed to be the “wetting amount” for each recharge zone (i.e. the amount of winter rainfall required to wet up the soil before recharge occurs):

$W_x = WRain_{av} – Rav_x$

Where W_x is the wetting amount for recharge zone x, $WRain_{av}$ is the average winter rainfall (1889-2008) and Rav_x is the average annual recharge rate for recharge zone x.

4) Annual recharge amounts for each zone were calculated according to the following formula:

$R_{x,i} = WRain_i – W_x$

Where $R_{x,I}$ is the recharge rate for recharge zone x in year i and $WRain_i$ is the winter rainfall in year i.”

The transient model also used a reduced recharge rate under plantation forestry areas. The influence of the Ash Wednesday bushfires was modelled by having forestry recharge zones returning to pasture recharge zones (i.e. zones receiving 100% winter rainfall recharge) after 1983, to simulate the destruction of plantations and higher recharge following the change in land use. These areas were replanted following the bushfires, and so modelled recharge was reduced again by 83% in 1993 in the bushfire affected areas. The same method of applying temporal changes in recharge was used in a numerical model of the Zone 1A region (Harrington, in prep.). In both cases, recharge was applied over the entire year (a 365 day stress period) but trends in groundwater levels were reasonably well simulated compared with observation well hydrographs. It was considered that dividing the year into one recharge and one non-recharge stress period, with these being opposite to groundwater extraction stress periods, would provide a better representation of groundwater level fluctuations.

Groundwater extraction

Metered groundwater extraction data from 2007-08 was available for many of the licenses in the area of the model. For licenses without metered data, groundwater extraction was based on estimates of use. All extraction wells present in the 2007-08 data set were implemented in the model in 1980. Between 1960 and 1980, only a selection of the 2007-08 set of extraction wells were present, based on locations of irrigation determined from aerial photography. No extraction was modelled prior to 1960.

4.2.4.5. Model Outcomes and Limitations

The model area is complex in terms of its structural geology, and this project was carried out in parallel with a separate project being undertaken by DWLBC, that aimed to better characterise the structural geology and related hydrogeology for the region (Lawson et al., 2009). Information from the comprehensive drilling and coring program associated with this project was used in the construction of the model grid. The model also included the most recently available groundwater abstraction information collected through meters recently installed as part of the Volumetric Conversion Project, and a representation of the temporal variation in plantation forestry coverage and groundwater use, interpreted from a series of aerial photos. Consequently the numerical model represented the most up-to-date conceptual model available at the time. Despite this, model calibration statistics were poorer than those recommended by the Murray Darling Basin Groundwater Modelling Guidelines, with model RMS values around 15-20%. Trends in groundwater levels, particularly groundwater level rises in response to removal of plantation forestry by the Ash Wednesday bushfires, were largely well simulated, suggesting that the conceptual model may be a reasonable representation of the system. However, due to this poor calibration and project resourcing issues, the model has not yet been finalized.

4.2.4.6. Report

The preliminary conceptual model was developed in the following report:

Resource and Environmental Management Pty Ltd (REM), 2007, Estimating Regional Impacts of Plantation Forestry and Intensive Irrigation Development on Groundwater Resources in the Lower South East. Phase 1 (2006/2007) Final Research Report.

The draft model report is in preparation (Harrington et al., in prep.).

4.2.5. ZONE 1A MODEL

4.2.5.1. Purpose

The Zone 1A Model was constructed to assess the current understanding of the conceptual model of groundwater flow in the Zone 1A region and model nitrate (etc) pathways for the “Primary Production to Mitigate Water Quality Threats” or “Diffuse Impacts” project.

4.2.5.2. Background

The “Primary Production to Mitigate Water Quality Threats” Project commenced in March 2006 as a collaborative study between the South Australian Research and Development Institute (SARDI), the Flinders University of South Australia (FUSA) and the Department of Water, Land and Biodiversity Conservation (DWLBC). The project aimed to mitigate the impacts of primary production on water quality throughout the South East of South Australia. The specific objectives of the project were to:

- Assess the risk of contamination of water resources in the South East from primary production.
- Quantify the sources of diffuse pollution from primary production.
- Decrease the risk of contamination of water resources from primary production within the South East.

The methodology was to include a combination of unsaturated zone and saturated zone modelling of contaminant movement through the landscape. This methodology could then be used to investigate the likely outcomes of a range of scenarios, for example:

- Climate change.
- Changing groundwater extraction regime.
- Changes in land use.

For the purpose of the study, the South East was divided into a number of regions to be modelled separately. The first region to be used as a trial for the methodology was Zone 1A of the Border Designated Area, located in the south eastern corner of the study area, around and to the south of Mount Gambier (Figure1).

4.2.5.3. Location

The location of the model domain is shown in Figure 1.

4.2.5.4. Model Structure

Model Domain

The entire Zone 1A model domain covers an area of 50 km x 50 km, with an active domain of 20 km x 35 km (Figure 1). The boundaries of the current active domain are defined by the Zone 1A Management

Area boundaries. Whilst it was recognised that having the model boundary at the edge of the area of interest may introduce undesirable boundary effects, this approach was taken to keep the model sufficiently simple (i.e. extending the model domain would involve incorporating a number of complex geological features that are currently not well understood). A surrounding area of inactive cells was included to allow the model domain to be easily extended in the future if a) the influence of boundary effects was considered to be unsatisfactory in relation to the objectives of the current project, b) additional knowledge of the surrounding hydrogeology was obtained, improving the confidence in a model with a larger domain, and/or c) expansion of the objectives of the project, or requirements of some other project required that the model domain be expanded.

Model Grid

The model domain is discretised using a grid with cells ranging from 62.5 m to 125 m in the x- and y-directions. This relatively fine grid was required due to the large slopes in layer boundary elevations and resulting problems with cells not overlapping when a coarser grid was used. This was particularly important in the north-west of the model domain where the finest grid cells were required.

Model Layers

Three layers were used to represent the following hydrogeologic units of the unconfined aquifer:

- Layer 1: Bridgewater Formation and Unit 1 of Green Point Member (Gambier Limestone)
- Layer 2: Units 2-5 of Green Point Member (Gambier Limestone)
- Layer 3: Camelback Member (Gambier Limestone)

The tops and thicknesses of the layers were derived from selected bore logs. The database used for this was more extensive than that used by Harrington et al. (2007) to create the stratigraphy model of Zone 1A. The base of the model, which is a no-flow boundary, represents the top of the aquitard that separates the confined Dilwyn Sand aquifer and the unconfined Gambier Limestone. Due to the complex nature of the geology, some manual modifications to the grid were required following importation of the layer boundary elevations.

4.2.5.5. Model Outcomes and Limitations

Although the model was considered to be the best possible representation of the conceptual model at the time, calibration results suggest that it does not currently represent the complexities in the system adequately to allow it to be used for either quantitative or qualitative analysis. The steady state calibration results were relatively good, with an overall RMS error of 8%. Removing one particularly problematic well from the calibration results reduced the RMS error to 6%. However, the model did not adequately simulate transient groundwater level trends. This may be due either to (a) error(s) or oversimplication of the conceptual model, or (b) misrepresentation of the impacts of recharge and groundwater extraction in annual time steps. It is hoped that this can be explored further in the future.

4.2.5.6. Report

The conceptual model report is:

Harrington, N, Chambers, K & Lawson, J 2007, *Primary Production to Mitigate Water Quality Threats Project. Zone 1A Numerical Modelling Study: Conceptual Model Development*, DWLBC Report 2008/12, Government of South Australia, through Department of Water, Land and Biodiversity Conservation, GPO Box 2834, Adelaide SA 5001.

The draft model report is in progress.

4.2.6. SOUTH OF MT GAMBIER MODEL

4.2.6.1. Purpose

To assess the potential use of the groundwater resources from the unconfined aquifer in the area south of Mount Gambier.

4.2.6.2. Background

The South East of South Australia is almost totally reliant on its extensive groundwater resources which predominantly occur in two regional aquifer systems – an upper unconfined aquifer and a deeper confined aquifer. Over the previous few years, particularly following the prescription of the Lacepede-Kongorong Prescribed Wells Area in 1997, the potential to use some of the lateral throughflow of groundwater in the unconfined aquifer in addition to the vertical recharge had been raised as a management issue for areas south of Mount Gambier. Partially funded by the South East Catchment Water management Board, a groundwater flow model was developed to provide technical input for the water allocation plans being developed for the Comaum – Caroline and Lacepede – Kongorong Prescribed Wells Areas.

4.2.6.3. Location

The location of the model domain is shown in Figure 1.

4.2.6.4. Model structure

The MODFLOW model domain simulates an area 52 km (east to west) by 28 km (north to south) (Figure 1). The rectangular model grid is divided into 100 rows and 200 columns. The grid has a uniform cell size of 260 m × 280 m. The regional aquifer system was conceptualised as three layers, including two aquifer layers (the Gambier Limestone and Dilwyn Sand (Tertiary Confined Sand Aquifer) and one aquitard layer separating them (**Error! Reference source not found.**5). The model covered the period between 1970 nd 2030, with modelling of predictive scenarios beginning in 2000.

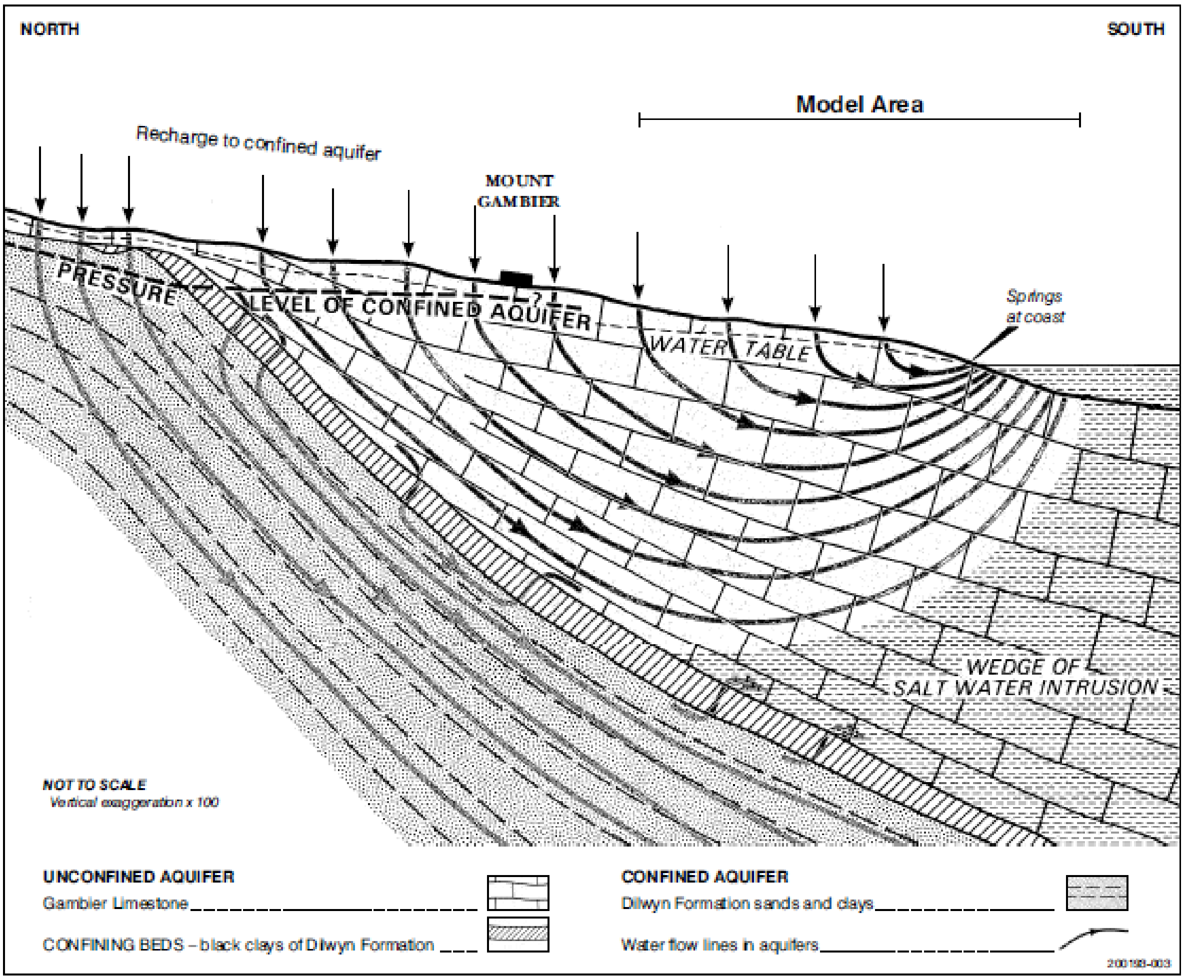

Figure 5. Geological cross-section showing the area south of Mount Gambier

Recharge

Recharge rates for this model were applied based on soil type and land use (using recharge rates reported by Bradley et al., 1995) for Zone 1A, and based on the recharge rates used to determine Permissible Annual Volumes (PAVs) of groundwater extraction at that point in time. Recharge rates varied between 0 – 90 mm/y, and were applied over a 185 day period between April and September, simulating the influence of winter rainfall. Recharge rates were held constant from year to year (i.e. there was no temporal variation in recharge). The remainder of the simulation period (October to March), no recharge was applied and groundwater extraction was implemented.

Groundwater extraction

Data on allocation and use from 1999, combined with local knowledge about irrigation activity and well location, was used to model groundwater extraction. Estimated extraction volumes (based on crop water requirement estimates) were applied to irrigation wells based on their construction date, with the extraction volume from each well remaining constant thereafter. Extraction was applied over a 180 day summer irrigation season.

The lack of detailed extraction data was an acknowledged limitation, however the method for applying irrigation did allow for the expansion in irrigation over time to be captured in the model, with a large increase in irrigation activity following prescription of the Lacepede-Kongorong area in 1997 (extraction volumes are show in Table 1).

4.2.6.5. Report

Stadter F and Yan W, 2000, *Assessment of the potential use of the groundwater resources in the area south of Mount Gambier*, Report PIRSA 2000/00040, Primary Industries and Resources South Australia, Adelaide

4.2.7. PADTHAWAY MODEL (PADMOD1 AND PADMOD2)

4.2.7.1. Purpose

Predicting historical and future groundwater levels and salinities in the Padthaway Prescribed Wells Area (Padthaway PWA) in response to changes in land use and pumping scenarios, and for determining the benefits of alternative groundwater management options.

4.2.7.2. Background

The groundwater flow and solute transport model, PADMOD1 (Aquaterra, 2008), represents the final output of the Department of Water Land and Biodiversity Conservation's (now DFW's) Padthaway Salt Accession Project (Harrington et al., 2004; Van den Akker, 2005; Wohling et al., 2005; Van den Akker et al., 2006; Harrington et al., 2006). The Padthaway Salt Accession Project was an intensive field-based investigation into salt accumulation in groundwater under the main irrigation area of the Padthaway PWA, providing information on (a) the flushing of the unsaturated zone salt store following clearing in the Naracoorte Ranges and (b) the recycling of irrigation water salinity in the main irrigation area. The main conclusion was that the predominant cause of rising groundwater salinities in the main irrigation area was the former process (a). The initial project was funded through the National Action Plan for Salinity and Water Quality, the South East NRM Board and the Padthaway Grape Growers' Association and was carried out to inform the Water Allocation Plan for the Padthaway PWA. The numerical model, being required as a tool to engage the community and assess management options for the PWA, was funded through the National Water Commission's National Water Initiative (NWI). PADMOD1 was updated to PADMOD2 with a revised recharge dataset to address some model limitations and investigate some additional pumping scenarios (Wohling, 2008).

4.2.7.3. Location

The location of the model is the Padthaway Prescribed Wells Area (Figure 1).

4.2.7.4. Model Structure

The model covers an area of 38 x 33 km, discretised using a 100 m square grid and consists of three layers, representing the layers of the unconfined aquifer, the Padthaway / Bridgewater Formations, the underlying clay aquitard and the Coomandook / Gambier Limestone formations.

Recharge

Recharge for this model was applied differently in three areas – the Naracoorte Ranges, irrigated areas, and non-irrigated areas of the Padthaway Flats. In all cases, recharge rates were applied annually (i.e. the modelled recharge period was 365 days for each year).

Recharge to the Naracoorte Ranges was based on previous studies by Wohling et al. (2005) and Wohling (2006), which simulated an increase in recharge following clearance of native vegetation in the 1960s. Recharge rates initially ranged from 0 – 110 mm/y, and varied spatially according to land use and soil type. However during calibration, recharge in the Naracoorte Ranges was capped at 50 mm/y. Recharge rates also varied temporally, with increases occurring over ten year periods following the change in land use.

Recharge under irrigation was based on measurements of drainage reported by DWLBC (Harrington et al., 2006). Under drip irrigation, modelled recharge rates ranged from 91 mm/y to 118 mm/y. Under pivot irrigated areas, modelled recharge of 100mm/y was applied. Recharge under flood irrigated areas was initially applied at 1400 mm/y, but reduced to 840 mm/y during calibration because of poor model performance.

Recharge to non-irrigated areas in the Padthaway Flats was based on rainfall data recorded at Padthaway, and hydrograph analysis in the Flats, given the correlation between trends in rainfall and groundwater level in the flats. Recharge was applied as 30% of the eight year moving average of rainfall, and varied between 55 mm/y and 110 mm/y. Using this method, the long term mean recharge rate was 75 mm/y, which is the recharge rate for Padthaway reported by Brown et al. (2006).

Groundwater extraction

When the Padthaway model was constructed, metered groundwater extraction data was available for the 2004-05 irrigation season for a significant proportion of licences, and estimated use for the remainder of licences. Given the accuracy of the 2004-05 data set, it was used as a basis for extraction in the model. Extraction was set at 110% of the 2004-05 rate from 1992 until 2006 (the increase in volume related to uncertainty in the estimated use figures in the 2004-05 data set, which were thought to be underestimates). From 1970 to 1992, extraction was set at 75% of the estimated 2004-05 rate, based on local knowledge of groundwater use. No extraction was implemented in the model prior to 1970 (transient model simulation commenced in 1950). All groundwater extraction wells present in 2004-05 were included in the model simulation for all irrigation periods. Extraction was applied throughout the year, not limited to a summer irrigation season (as in other models of the South East).

Evapotranspiration

Evapotranspiration (ET) from the shallow water table on the Padthaway Flats (below the main irrigation area) was measured on a weekly basis at several CSIRO flux stations during the Padthaway Salt Accession Project. The total actual ET for 2004 was measured at 499 mm/y (i.e. similar to rainfall), with the highest rates in summer (up to 20 mm/month) and lowest in winter (about 5 mm/month). ET was implemented in the model by specifying an extinction depth of 3 m.

4.2.7.5. Report

Aquaterra, 2008, Padthaway Groundwater Flow and Solute Transport Model (PADMOD1), Prepared for DWLBC, October 2008.

Wohling, D., 2008, Padthaway Groundwater Flow and Solute Transport Model (PADMOD2): New Abstraction Scenarios Requested by the SENRM Board., Department of Water, Land and Biodiversity Conservation. DWLBC Technical Note 2008/22. June 2008.

4.3. CONCLUSIONS AND RECOMMENDATIONS

Based on the review of existing numerical groundwater models for the Lower South East, the following conclusions and recommendations can be made:

- A wide variety of numerical groundwater models exist for the Lower South East.
- These models represent our best understanding of the groundwater system in the areas that they cover, and are a collation of all of the relevant information, providing a large knowledge base for a regional-scale model.
- The complexity and variety of the models that already exist show that the Lower South East is an area rich in data.
- The models have been developed to fulfil a range of objectives, including investigating the applicability of modelling methodologies, testing conceptual model of groundwater flow systems, modelling pathways of diffuse source contaminants, assessing the impacts of plantation forestry and determining PAVs and impacts of proposed management scenarios.
- For this reason, the various components of the water balance, e.g. recharge, evapotranspiration, forestry impacts and groundwater extraction have been represented in the models in a variety of different ways, with an array of different input datasets, with the result that the outputs of the models are not necessarily comparable from region to region, nor are all of the models applicable to addressing all potential modelling objectives.

5. OUTCOMES FROM A TECHNICAL WORKSHOP REVIEWING THE STATUS OF THE CONCEPTUAL MODEL

5.1. BACKGROUND

A full-day technical workshop was held as part of the Lower South East Water Balance Project on Tues 25th May 2010, with the following objectives:

- Review the scope, outcomes and challenges faced by previous, current and planned technical projects across the following water balance topics for the Lower South East:
  - Existing Groundwater Models
  - Groundwater Recharge Processes
  - Groundwater Flow
  - Irrigation and Forestry Impacts (groundwater extraction, recharge interception, irrigation return flows)
  - Groundwater Dependent Ecosystems (including the Blue Lake)
  - Surface Water Flows
  - Inter-aquifer Leakage
  - Rainfall and Climate Change.
- Review water balance data availability and quality and identify the key knowledge / data gaps from the perspective of developing a numerical groundwater model of the Lower South East.
- Discuss opportunities for future collaboration and co-ordination of projects towards improving the overall conceptual model.

There were 33 attendees from DFW, CSIRO, universities and private consulting firms. A series of presentations on previous and current technical projects in the Lower South East was followed by workshop-style discussions. A summary of the main points that were taken away from the workshop by the project team is presented below.

5.2. SUMMARY

There were some clear themes that came out throughout the workshop. The following data / knowledge gaps were identified as the key priorities:

- Good representations of spatial and temporal variations in:
  - Land use
  - Recharge
  - ET
  - Groundwater interaction with drains
  - Forestry impacts

- An understanding of, and monitoring data to inform the feasibility of modelling Surface Water – Groundwater interactions.
- A quantitative knowledge of the salt balance.

The general consensus was that there needs to be a major effort to identify our future priorities in knowledge acquisition for the region (i.e. what are the objectives and what data do we really need) and to optimise our monitoring efforts towards those priorities. This requires a co-ordinated and inclusive approach and someone or some organisation designated to co-ordinate this.

It was also clear that a co-ordinated approach to the collation of the historical data described above would be of great benefit to everybody. This would essentially build a chronological history of the South East and may involve a combination of desktop studies of historical reports, digitising aerial photos and modelling. Having this available as a central resource would be of great benefit to the region.

The general opinion was that a regional three dimensional model would be required to bring the community on board for groundwater management in the Lower South East. However, it was also emphasised that conceptual models can be an extremely powerful tool in helping to understand systems and educate the wider community. Conceptual models are under-used in this respect and this should be an important output from the Lower South East Water Balance Project. A three dimensional numerical model may have large limitations but ultimately needs to be seen by the community to maintain their confidence in management decisions.

6. DETAILED REVIEW OF CONCEPTUAL MODEL AND INPUT DATA AVAILABILITY

6.1. PHYSICAL CHARACTERISTICS OF THE LLC REGION

6.1.1. TOPOGRAPHY

The Gambier Basin of the Otway Basin, in which the study area is located, is an undulating coastal plain with a general slope to the west and southwest towards the sea. It is bound by topographic highs in the east and north, the Dundas Plateau and the Padthaway Ridge respectively, and by the Southern Ocean to the south and west. The topographic relief in the study area is generally low, rising to a maximum of 50 m along a series of northwest to southeast trending stranded coastal ridges (Fig. 6 shows the South Australian portion of the study area). Topographic lows (< 30 m AHD) occur in the inter-dunal regions. The highest points in the landscape are the Mount Gambier and Mount Schank volcanic cones, rising to 190 m and 120 m AHD respectively (Fig. 6).

Topographic data is available for both South Australia and Victoria through Geoscience Australia, with an accuracy of 0.5m and a point spacing of <2m.

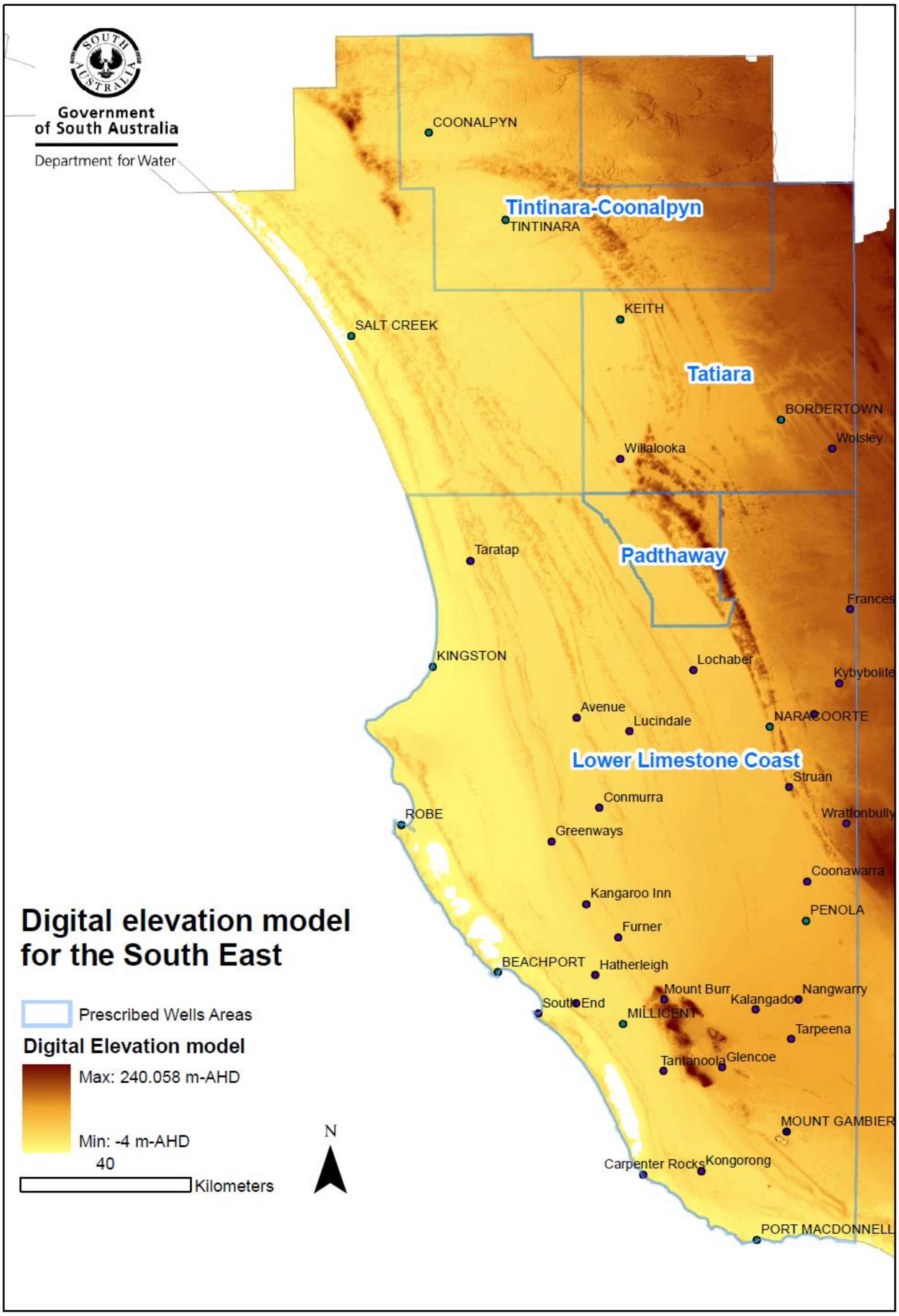

Figure 6. Digital elevation model for the South East

6.1.2. CLIMATE

The South East maintains a Mediterranean climate of hot dry summers and cool wet winters. Daily maxima can be as high as 40°C in the summer months and as low as 10–12 °C during the winter months. A rainfall gradient exists in the South East, with generally higher rainfall in the southern part of the region, and lower rainfall further north. Figure 7 displays mean annual rainfall for the South Australian portion of the study area, which ranges from 835 mm/y in the elevated Mt Burr Ranges (north east of Millicent), to 460mm/y in Keith (Fawcett et al., 2006). Approximately 75% of annual rainfall falls between the months of April – October, and this is typically when recharge occurs (when monthly rainfall exceeds monthly evapotranspiration). Evapotranspiration also follows an approximate north-south gradient, with potential evapotranspiration ranging from ~ 1400 mm/y in Mount Gambier to ~1700 mm/y in Keith. Rainfall and evapotranspiration are discussed in more detail in the Recharge and Evapotranspiration sections below.

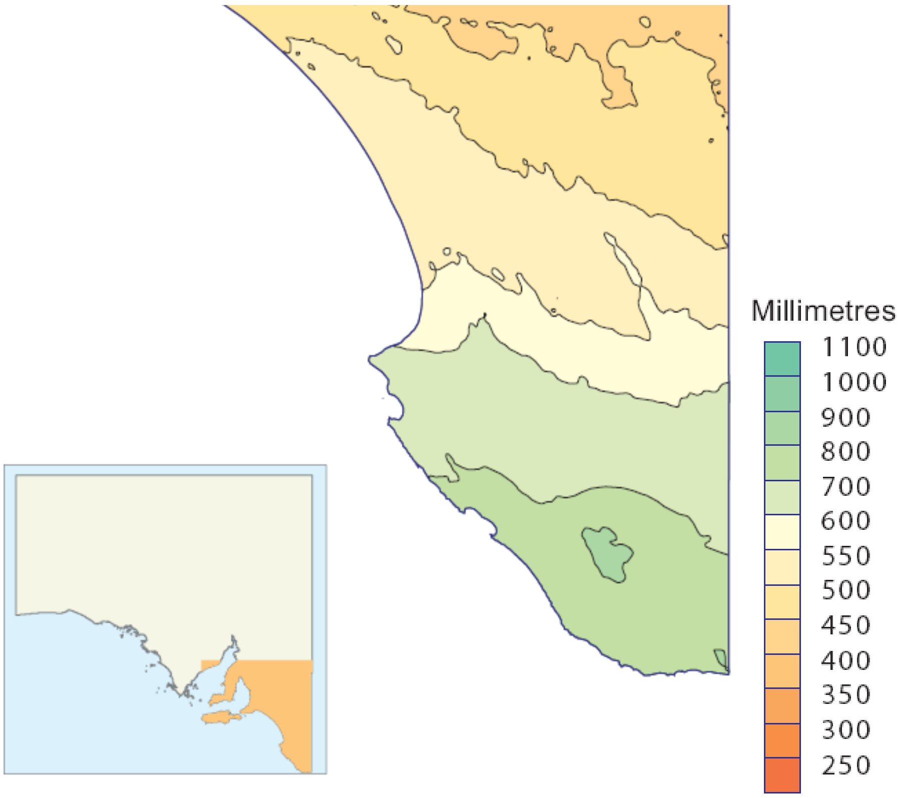

Figure 7. Long term average (1971 – 2000) annual rainfall for the South East of South Australia (taken from Fawcett et al., 2006)

6.1.3. LAND USE

Knowledge of changes in land use over time is important for understanding temporal changes to rainfall recharge, evapotranspiration and plantation forestry impacts. It can also be useful, in the absence of more accurate data, as a surrogate for estimating changes to groundwater extraction over time. GIS-based land use maps for both the Victorian and the South Australian portions of the study area are available for approximately 2002 - 2005 from the ABARES (Australian Bureau of Agricultural and Resource Economics and Sciences) website. The Victorian data has also been obtained separately from the Victorian Dept. Of Sustainability and Environment (DSE). Figure 8 shows the 2008 Land Use classification map for the South East.

Digital land use maps are not available prior to 2000. However, temporal land use information can be gained by digitising and interpreting historical aerial photos, a time consuming process that would nonetheless have benefits for numerous applications. This has been done for the domain of the Coonawarra (Zone 3A) Model, for the years 1969 and 1987. A map of the forestry footprint for the South East in 1995-96 is also available.

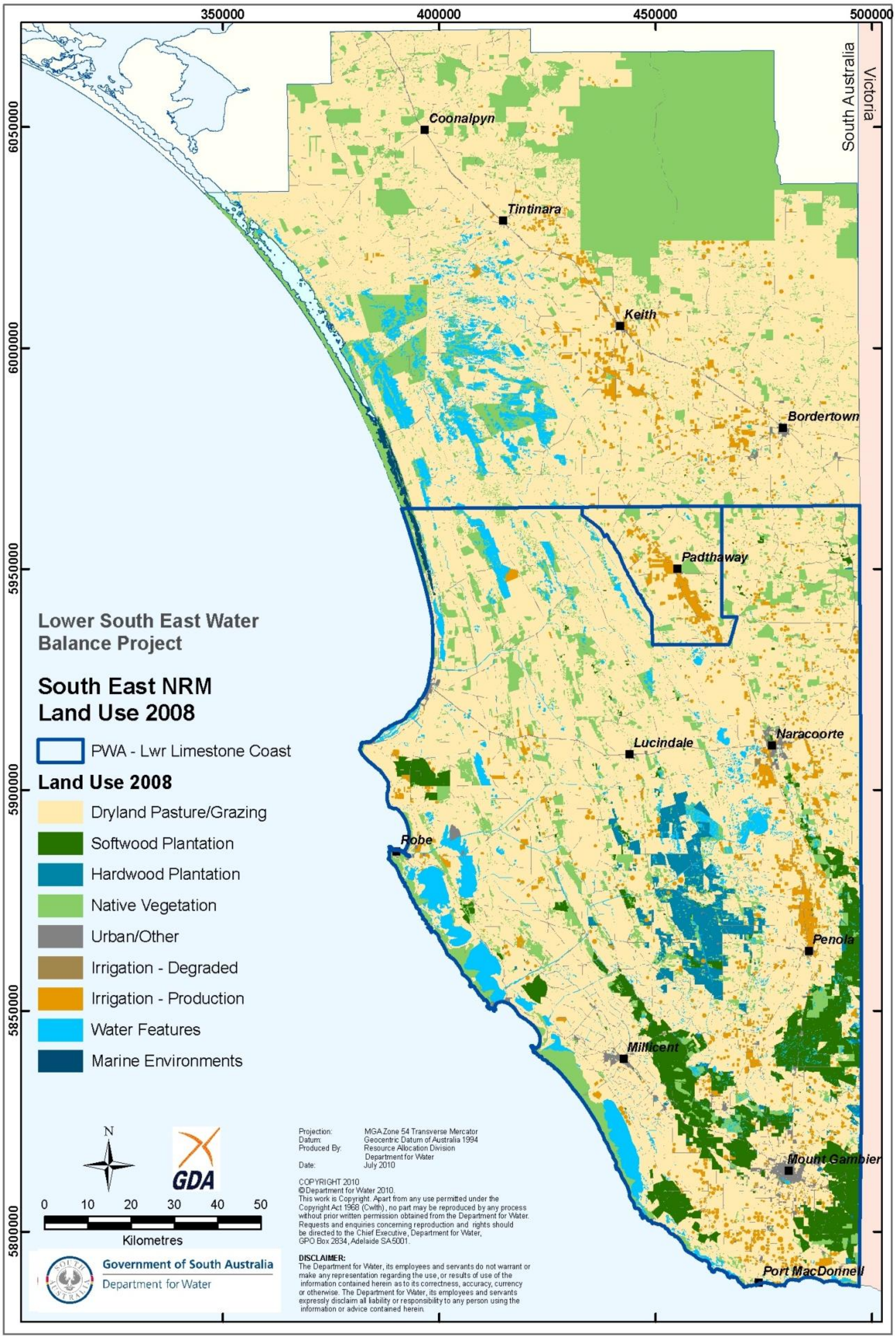

Figure 8. Land use in the South East (based on 2008 land use mapping)

6.1.4. SURFACE WATER

Natural watercourses in the Lower South East are generally impeded by the low slope of the topography and the transverse dune system, resulting in the occurrence of numerous swamps and wetlands, lakes and sinkholes in inter-dunal corridors. Swamps and wetlands usually occur over shallow water tables and clay horizons during the wet winter months, as a result of clay soils holding surface water in low lying depressions. These are typically found to the north of Mount Gambier. Since the 1860s, approximately 2000 km of drains have been constructed throughout the South East. Historically they were constructed to drain land and make it more agriculturally viable. More recently, drains have been constructed to mitigate flooding in high rainfall years, and (in the Upper South East) manage dryland salinity. The introduction of drainage to the South East, and subsequent changes in land use, is thought to have reduced the original extent of wetlands by 93% (Harding, 2009).

The South East drainage network consists of a combination of shallow drains (less than 2m deep), and deeper drains (greater than 2m deep) designed to intercept groundwater. The main groundwater drains are the Didicoolum Drain, the Fairview Drain and Ballater Main Drain. Long term flow records are not available for these drains, however recordings from Fairview Drain showed flow to be approximately 6.7GL in 2009 and 2010. The majority of the surface water – groundwater interactions occurring around drains are of the gaining type (groundwater discharge to drains), however, the spatial and temporal variability of this discharge is not well understood. Groundwater outflows via drains will be discussed in more detail in Section 6.4.6.

A number of creeks flow into the South East, with catchments that extend into western Victoria, such as Morambro Creek, Mosquito Creek and Naracoorte Creek (Figure 9). Mosquito Creek discharges into Bool Lagoon, a RAMSAR listed wetland complex south-west of Naracoorte. Morambro Creek discharges into Cockatoo Lake north-west of Naracoorte, and is the only prescribed surface watercourse in the South East. Flow in all of these creeks is ephemeral, and highly dependent upon winter rainfall.

Numerous karst sinkholes (also referred to as dolines and cenotes) are found to the south of Mt Gambier, where the unconfined aquifer is typically calcareous. Sinkholes are formed by the dissolution of the carbonate matrix by infiltrating rainfall and are generally either partially filled by soil and sediments, or expose the water table. Other significant karst features include the ‘rising springs’ south of Mt Gambier, such as Ewens Ponds and Piccaninnie Ponds. Ewens Ponds consists of a series of three ponds which are fed almost entirely by groundwater discharge (through visible ‘bubbling sand’ springs). The ponds flow into Eight Mile Creek, which in turn discharges to the coast. Piccaninnie Ponds is a much larger karst spring wetland complex, with a main karst pond area that is up to 100 m deep in parts. Groundwater discharge from Piccaninnie Ponds also flows to the coast. Other springs feed creeks such as Deep Creek, Jerusalem Creek and Cress Creek. Flow has been periodically gauged in these creeks since the 1970s, and mean annual discharge to the coast from all these sites is ~97 GL/y.

One of the most significant surface water bodies in the South East is the Blue Lake, which is the primary source of town water supply for Mount Gambier. The Blue Lake is a volcanic crater lake, thought to have been formed at least 28,000 years ago (Leaney et al., 1995). It has a volume of ~ 30 GL, and is fed by groundwater discharge. A geochemical mass balance performed by Ramamurthy et al. (1985) suggested that groundwater discharges at a rate of ~5000 ML/y, 85% of which is sourced from the unconfined aquifer (15% comes from the underlying confined aquifer).

DETAILED REVIEW OF CONCEPTUAL MODEL AND INPUT DATA AVAILABILITY

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

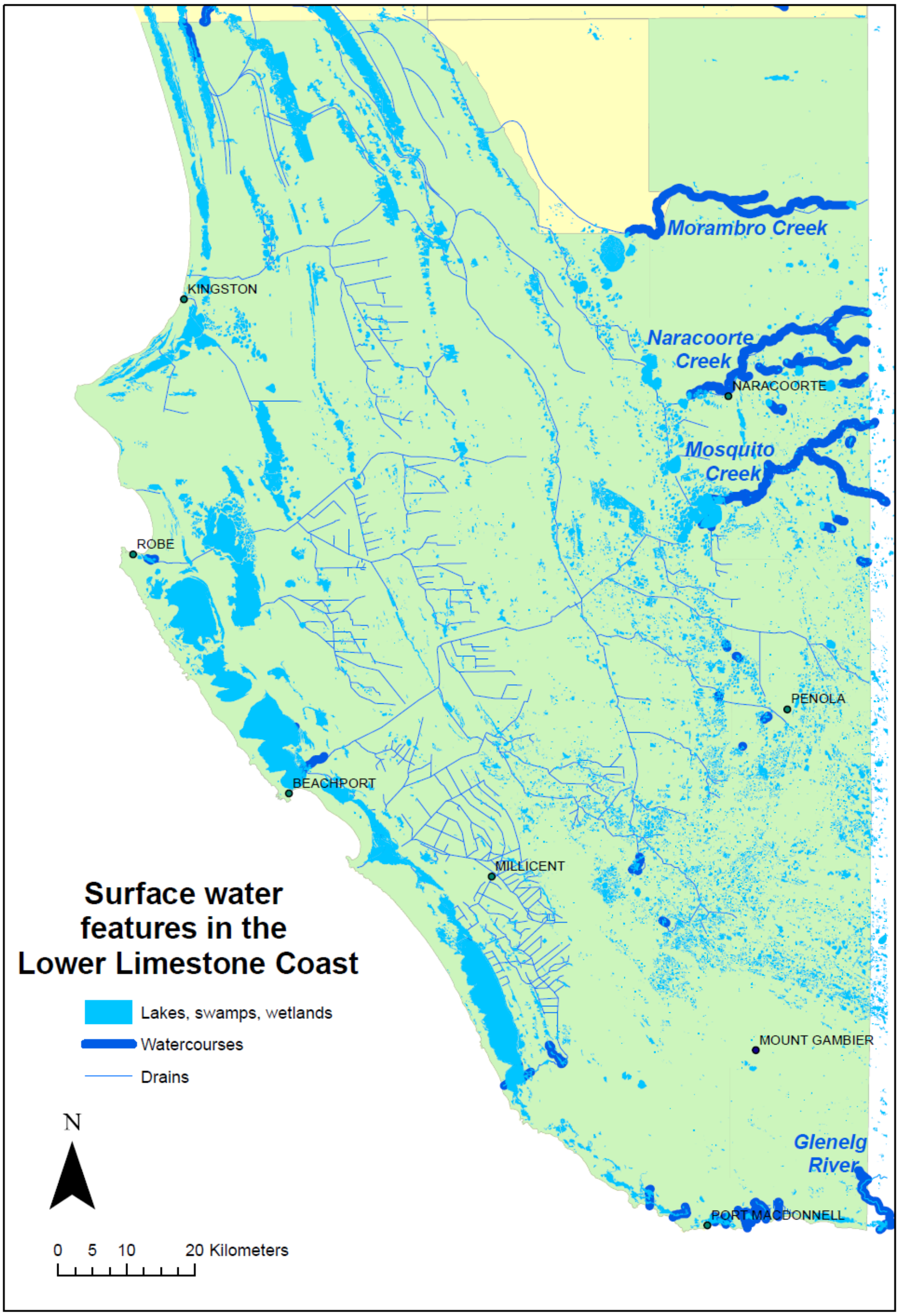

Figure 9. Surface water features in the South East

6.2. GEOLOGY AND HYDROGEOLOGY OF THE LOWER LIMESTONE COAST

6.2.1. GEOLOGICAL SETTING

The study area is located in the Gambier Basin of the Otway Basin. The latter is an east-west elongate basin of ~100 000 km^2 containing a thick accumulation of mixed marine and terrestrial sediments deposited during the Cretaceous and Tertiary eras (Figure 2). 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 is bounded in the east by the Dundas Plateau (Figure 2).

Sedimentation in the Gambier Basin commenced in the Late Palaeocene to Middle Eocene with the Paralic Wangerrip Group (Pebble Point Formation, Pember Mudstone and Dilwyn Formation). The Dilwyn Formation includes the Confined Dilwyn Sands Aquifer (TCSA) and the Dilwyn Clay aquitard. Increasing marine influence led to the deposition of the Middle to Late Eocene marginal-marine Nirranda Group (Mepunga Formation and Narrawaturk Marl, both aquitards), and the Late Eocene to Middle Miocene marine Gambier Limestone, the unconfined aquifer.

A number of prominent structural features occur within the Gambier Basin that are believed to have significant influence over groundwater flow. In particular, the north-west trending Kanawinka Fault occurs in the north east of the Basin, and the west – north west trending Tartwaup Fault occurs in the south of the basin (Fig. 2, Fig. 10). Both faults have a throw towards the southwest, with the magnitude of the discontinuity diminishing towards the surface. The Tartwaup Fault forms a major structural hinge line, with Cretaceous and Tertiary sediments rapidly increasing in thickness to the south of it (Gravestock et al., 1986). A number of smaller parallel faults are associated with the Tartwaup Fault (Fig. 10) (Lawson et al., 2009). An important structural high, the Gambier Axis (Kenley, 1971) occurs to the north of the Tartwaup Fault. The recent mapping of fault locations in the Tertiary sequences (Figure 10) have 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 in between Lucindale and Struan (Lawson et al., 2009). This can be approximated by following the northern extent of mapped faults in Figure 10.

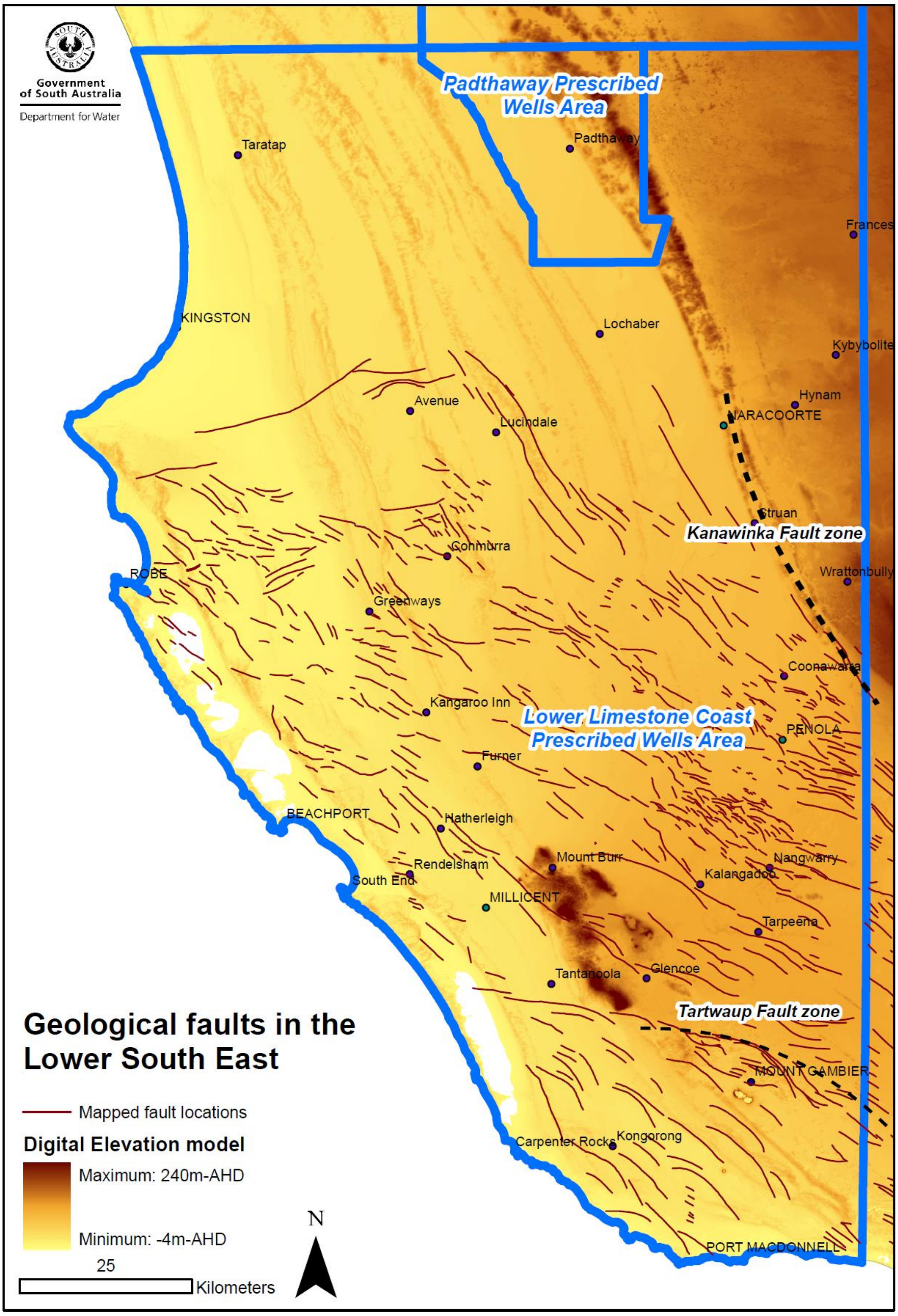

Figure 10. Location of stratigraphic faults in the South East (note: faults have only been mapped for the Otway Basin)

A 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 the Tertiary units. A series of fossiliferous sand dunes (Bridgewater Formation) 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 the inter-dunal areas. These units, where present, also form part of the unconfined aquifer for the region.

6.2.2. OVERVIEW AND HYDROSTRATIGRAPHIC MODEL OF THE LOWER LIMESTONE COAST

Groundwater of the Gambier Basin occurs in a number of different hydrogeological systems in the Cainozoic and Cretaceous sequences. The Cretaceous aquifers are possibly saline and generally too deep for economic utilisation. The two major low salinity groundwater systems occur within the Cainozoic sequence. These are the sand and clay Dilwyn confined aquifer system and the multilithological Gambier unconfined aquifer system. The confined system is separated in places from the underlying Cretaceous aquifers by the Lower Tertiary aquitard (Pember Mudstone), and from the overlying unconfined system by the Upper Tertiary Aquitard, comprising the Narrawaturk Marl, the Mepunga Formation (can occur in parts as discontinued aquifer) and a clayey unit of the Dilwyn Formation itself, known as the Dilwyn Clay. The unconfined aquifer system consists of the late Tertiary Gambier Limestone and the Quaternary Padthaway and Bridgewater Formations. The Gambier Limestone has been divided into a series of three sub-units, the Greenways, Camelback and Green Point members (Li et al., 2000). The entire hydrogeological sequence of the Gambier Basin is wedge shaped, thickening from north to south to up to 5 000 m offshore. The Cainozoic groundwater system itself can be up to 1 000 m thick near the southern coast.

A conceptual hydrostratigraphic framework for the Lower Limestone Coast was compiled as part of the South East NWI project, and a 3D model constructed from this (Figure 11). The model includes stratigraphic logs from a combination of groundwater observation wells, water supply and irrigation bores and petroleum exploration holes, which were available from the state drill hole database, SAGeodata, or as microfiche records held by DFW. Additional investigation holes that have been recently drilled are also included. Overall, the model includes data from 327 well logs, including 5 newly drilled wells in the Victorian Border Zone 3B. Additional stratigraphy data is available to extend the domain of the existing stratigraphic model north to the proposed regional model boundary.

The model adopts generalised lithologies, rather than strict stratigraphic definitions. For example, all unconfined aquifer units are grouped as the Tertiary Limestone Aquifer (Gambier Limestone, Murray Limestone, Bridgewater and Padthaway Formations).

As mentioned above, the existing stratigraphic model includes only 5 data points from the Victorian side of the Border. Additional hydrostratigraphic data from this side of the Border has been obtained from the Victorian DSE and, although the interpretations and unit descriptions are different, it is believed that the spatial coverage is good and this data can be interpreted to align with the South Australian stratigraphic model.

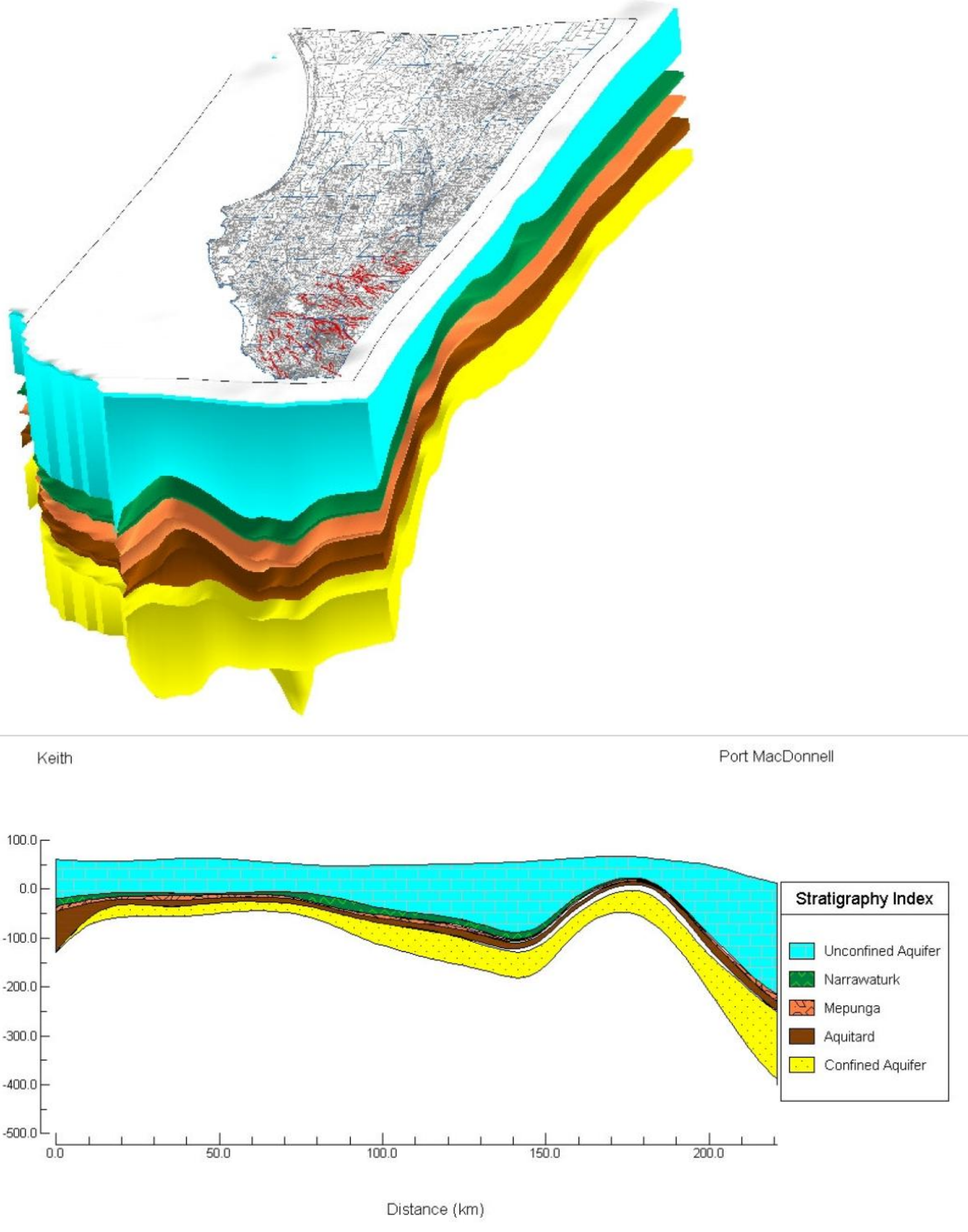

Figure 11. Stratigraphic model for the South East (from Lawson et al., 2009)

6.2.3. GROUNDWATER FLOW AND AQUIFER PROPERTIES

6.2.3.1. Tertiary Confined Sand Aquifer

The Tertiary Confined Sand Aquifer (TCSA) comprises interbedded gravels, sands, silts and carbonaceous clays of the early Tertiary Dilwyn and Mepunga Formations, and generally increases in thickness towards the south, being up to 800 m thick in the region to the south of Mt Gambier (Love, 1991). It is a multiaquifer system, but is treated as one aquifer unit for management purposes. There are few data and hence little understanding of the hydraulic interconnection between the sub-aquifers of the Dilwyn Formation. Most wells only penetrate the uppermost sand unit of the aquifer for economic reasons, but a number of deeper petroleum exploration wells have provided some valuable stratigraphic information (Brown et al., 2001).

Hydraulic data for the confined aquifer is sparse, but what is available suggests that hydraulic properties are not as spatially variable as for the unconfined aquifers. For the entire Otway Basin region, porosity values estimated from borehole geophysical logs vary from 20% to 30%, whilst transmissivity estimates range from 200 m^2/d to 1600 m^2/d (Floegel, 1972; Bowering, 1976; Waterhouse, 1977; Smith, 1978a&b; Cobb, 1976; Shepherd, 1978).

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

Harrington et al. (1999) estimated lateral flow velocities in the TCSA to range between 0.4 m/yr and 5.5 m/yr using their combined MODFLOW and Compartmental Mixing Cell approach.

6.2.3.2. Upper Tertiary Aquitard

Little information exists on the hydraulic properties of the Upper Tertiary aquitard. Vertical hydraulic conductivities were determined via triaxial permeability testing to range between 10^{-7} and 10^{-3} m/d in the northern portion of the Otway Basin, near Lucindale (Love & Stadter, 1990). Laboratory tests carried out on the Dilwyn Clay in the Nangwarry / Tarpeena Area provided vertical hydraulic conductivity values ranging between 3.4 x 10^{-6} m/d and 7.2 x 10^{-6} m/d (Brown et al., 2001). The recent NWI stratigraphy project (Lawson et al., 2009) obtained three porosity estimates for the aquitard through downhole geophysics. These were for the Mepunga Formation (7.1 % and 7.2%) and Narrawaturk Marl (9.5 %).

The Zero Head Difference (ZHD) line is a line along which the head difference between the unconfined and confined aquifers is zero (Fig. 12; Love, 1991). There is potential for downward groundwater flow across the aquitard to the north of the ZHD line and for upward flow to the south of the ZHD line (throughout most of the study area). Brown et al. (2001) suggested that any downward groundwater flow across the aquitard in the Nangwarry / Tarpeena area to the north of the study area occurs preferentially via faulting, fractures or sinkholes. Supporting this theory, ^{14}C activities of groundwater from the aquitard in the Tarpeena area measured by Brown et al. (2001) were below background levels, whilst significant concentrations of ^{14}C existed in the underlying confined aquifer. The aquitard is relatively thin in the Nangwarry / Tarpeena area (~2 m). However, it is possible that inter-aquifer flow also occurs through the clay via similar preferential flow mechanisms in areas where the clay is significantly thicker.

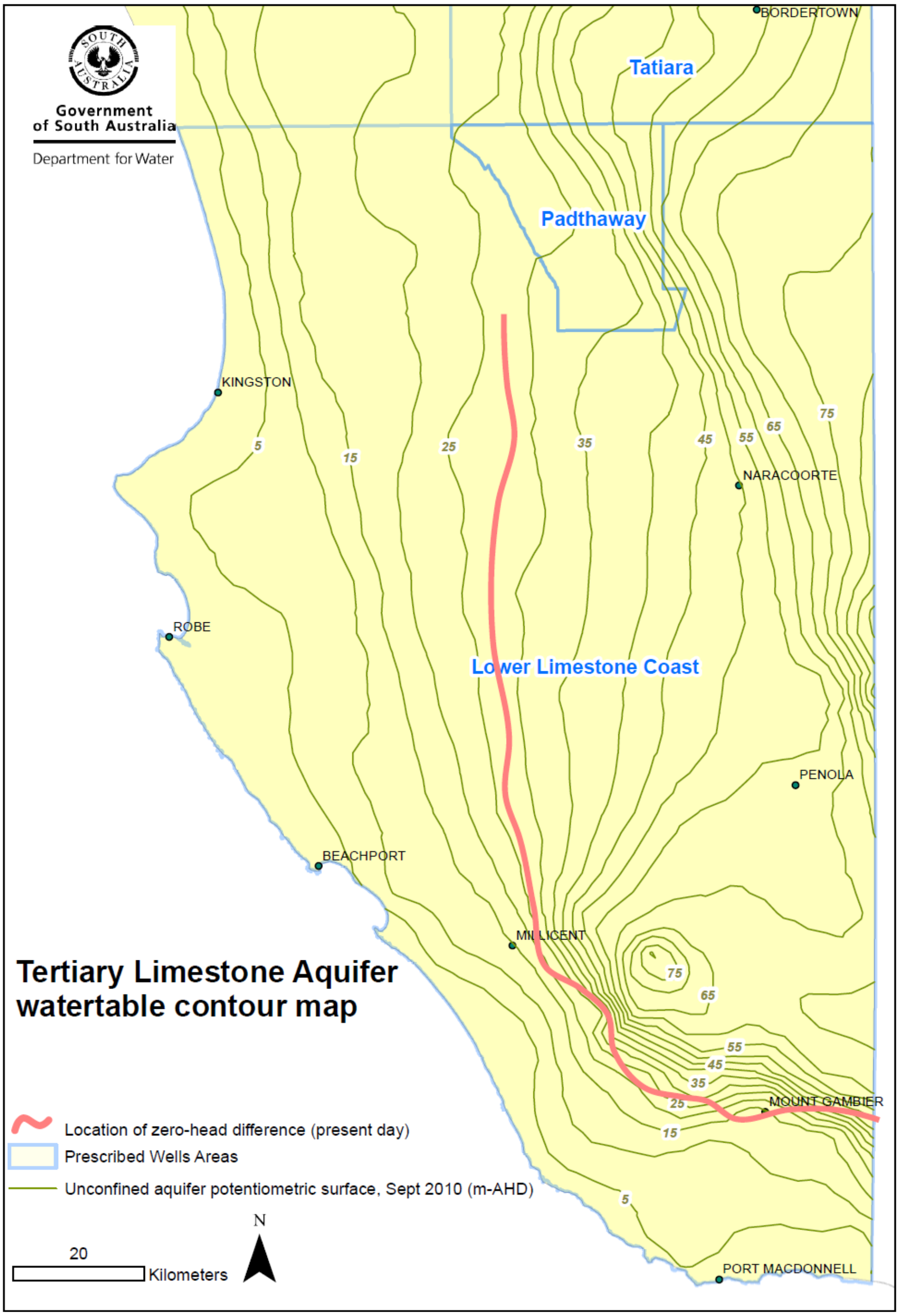

Figure 12. Map of Otway Basin, showing unconfined aquifer potentiometric surface and location of zero-head difference (ZHD) line

Groundwater sampled by Love (1991) from the unconfined aquifer observation well GAM28, located in the south-eastern corner of the study area, had a uranium concentration and atomic ratio similar to that of the confined Dilwyn Sand aquifer, suggesting upward leakage in that region. This is despite the presence of a 300 m thick aquitard between the two aquifers at this location. The location of a fault in that region (Fig. 10) suggests that it is possible that leakage may have occurred through a preferential pathway, although this is unconfirmed. It is currently unknown whether there are any other occurrences of upward leakage across the aquitard in the study area.

6.2.3.3. Tertiary Limestone Aquifer

The Gambier Limestone is part of the Quaternary/Upper Tertiary Unconfined Aquifer System and consists of various facies of fossiliferous limestone of Tertiary age, ranging in thickness from very thin to 300m. The Gambier Limestone is overlain and hydraulically inter-connected with the superficial Quaternary surface aquifers, the Padthaway, Bridgewater and Coomandook Formations, of which the Bridgewater Formation is predominant in the study area. The Gambier Limestone is divided into three main sub-units, the Greenways, Camelback and Green Point Members. It often becomes marly and dolomitic towards the base. This unit has recently been mapped across part of the study area (Lawson et al., 2009) but its regional extent is unknown due to a lack of penetrating wells (Love, 1991).

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

Groundwater flow in the unconfined aquifer in the study area is generally from east to west, towards the coast in areas north of Mount Gambier (Figure 12). To the south of Mt Gambier, flow is to the south or southwest, with discharge occurring at the coast. 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. A steep hydraulic gradient zone to the north of Mount Gambier coincides with the location of the Tartwaup Fault (Fig. 12). The exact influence of the fault on groundwater flow is complex, and not fully understood. However, recent drilling investigations indicate that significant stratigraphic displacement occurs across the areas where the fault structure has been mapped. Lawson et al. (2009) reported on drilling investigations across the Tartwaup fault north-east of Mt Gambier. They found ~100m of uplift occurred in the southern part of the transect (Figure 13). In these up-lifted sections, significant upper sub-units of the Gambier Limestone (Green Point Member sub-units) were not present. While Figure 13 displays the stratigraphy, it does not display the actual location of faults. However, these may be inferred from the locations of significant displacement. For example, at approximately the 1000m mark, uplift places much of the Camelback member (usually the most transmissive unit of the TLA) against the Greenways member (typically a marly, less transmissive formation). Such displacement is likely to hinder regional groundwater flow, and is likely to be the cause of the steep gradient.

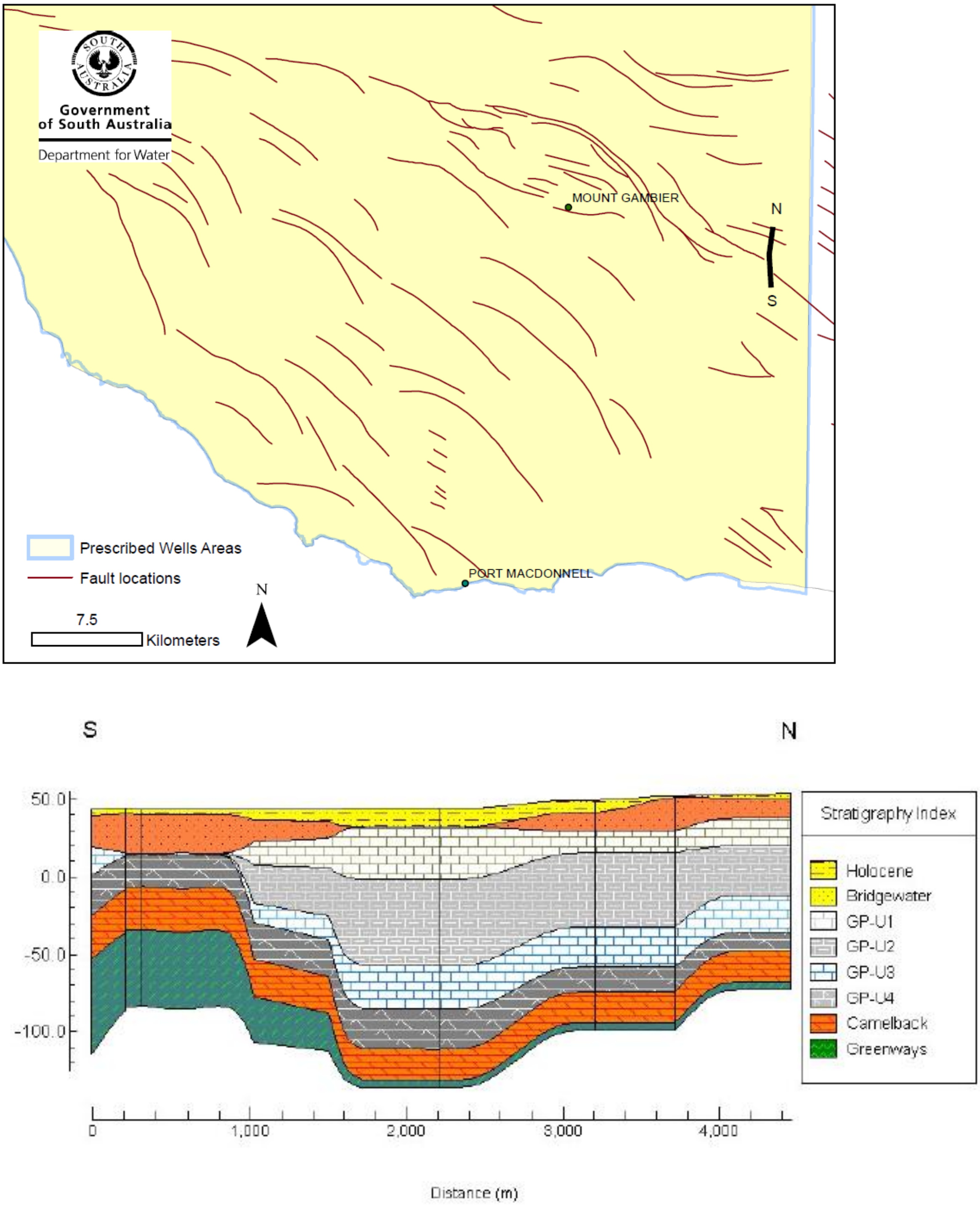

Figure 13. Geological cross section showing significant aquifer displacement around confirmed fault locations

A similar 'steep gradient' zone is observed in the watertable along the base of the Naracoorte Ranges (Figure 12). This steep gradient zone is associated with the Kanawinka Fault line, and is thought to be caused by thinning of aquifer sediments on the eastern side of the fault (Lawson et al. 2009).

Love (1991) identified that a number of potential local flow systems occur in the unconfined aquifer in the study area, and that the fact that the water table is close to and follows the topographic surface suggests a high importance of local recharge/discharge processes within the unconfined aquifer. Brown et al. (2001) inferred average groundwater residence times from CFC-12 values of ~30–35 yrs for shallow groundwater (between 1.5–2 m below the water table) in the Tarpeena and Nangwarry areas.

The Gambier Limestone has an intrinsic primary permeability, with a secondary fracture permeability occurring in many areas along structurally weak zones in the form of karstic features. In some areas, dissolution of the limestone along the karstic features has resulted in brecciation and collapse of the limestone near the ground surface, forming numerous sinkholes.

Porosity estimates for the unconfined aquifer range from 30% to 50% from borehole geophysics and 49% to 61% from measurements on outcrops (Andrews, 1974; Love, 1991; Lawson et al., 2009)). This data also includes the Padthaway and Bridgewater Formations (Love, 1991). More recent estimates of porosity from borehole geophysics are in the range of 6% to 18% for the Gambier Limestone, 5% to 20% for the Bridgewater Formation and 20% to 30% for fractured rock (Lawson et al., 2009). Transmissivities determined from aquifer pump tests range from 200 m^2/d to >10 000 m^2/d within karstic features, again also including the Padthaway and Bridgewater Formations (Waterhouse, 1977; Stadter, 1989). However, despite the extensive development of karst in the South East, Holmes and Waterhouse (1983) considered that they do not form an inter-connected system and that groundwater flow is predominantly intergranular (Love, 1991).

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

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

Harrington et al. (1999) estimated lateral flow in the TLA to range between 4 m/yr and 38 m/yr using their combined MODFLOW and Compartmental Mixing Cell approach.

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

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

6.3. *INPUTS TO THE UNCONFINED AQUIFER (TLA)*

6.3.1. RAINFALL RECHARGE

6.3.1.1. Rainfall Recharge Under Non-Forested Areas

The dominant inflow to the unconfined aquifer in the Lower Limestone Coast (LLC) is vertical recharge from rainfall. This occurs both as diffuse infiltration of rainfall through the unsaturated zone (diffuse recharge), and direct recharge to the water table through sink-holes and other karst features (point source recharge). Since the 1960s, several studies have been conducted in the South East to investigate and quantify recharge processes using a variety of methods. The majority of these studies have focused on areas in the Lower Limestone Coast (LLC), with an emphasis on the Border Designated Area.

Table 2 and Figure 14 summarise recharge studies in the LLC (not all study areas are displayed on Figure 14 due to spatial over-lap). Figure 15 from Brown et al. (2006) gives recharge rates for each groundwater management area in the LLC based on some of these studies. Updated estimates were reported in Wood (2010a) using chloride mass balance and CFC methods. However, Wood (2010a) reported a range of recharge rates for a variety of soil type and land use combinations, with the range reflecting the different assumptions in each method. In most cases, the 'management area' recharge rates reported by Brown et al. (2006) fall within the range of those reported by Wood (2010a).

Spatially, trends in recharge are similar to those in rainfall with higher recharge rates observed in the higher rainfall areas (in the southern part of the LLC), and lower recharge rates further north. Gibbs (2010) analysed the relationship between rainfall and recharge in the LLC, by comparing annual estimates of recharge based on the watertable fluctuation method with annual rainfall data. As could be expected, a statistically significant relationship was found between rainfall and recharge for the majority of observation wells used, especially when 'winter' rainfall (rainfall between April and September) was used. However, it is well known that factors other than rainfall influence recharge rates, such as:

- depth to water – with lower recharge rates in areas of greater depth to water
- soil type – with higher recharge under sandy soils
- land use – with reduced recharge under native vegetation and plantation forestry, and increased recharge under irrigation

Table 2. Recharge studies in the Lower Limestone Coast Prescribed Wells Area

Site/study	Land use	Methods	Recharge rates (mm/y except where specified)
Grassland hydrology (Holmes and Colville, 1970a)	Pasture	Lysimeters	63
Forest hydrology, Penola and Mt Gambier forests (Holmes and Colville, 1970b)	Softwood forest	Lysimeters	0
Forest hydrology, Penola and Mt Gambier forests (Colville and Holmes, 1972)	Softwood forest	Watertable fluctuation method	19 – 73
Forest hydrology, Penola and Mt Gambier forests (Allison and Hughes, 1972)	Softwood forest	Tritium	0
Padthaway Plains (Allison and Hughes, 1975)	Pasture and irrigation	Tritium and mixing cell model	27
Southern regions near Mount Gambier (Allison and Hughes, 1978)	Pasture	Chloride mass balance and tritium	70 – 270
Border zone Bradley et al. (1995)	Pasture, forestry and native vegetation	Watertable fluctuation method	5 – 130
Border zone lateral throughflow from Victoria Bradley et al. (1995)	Pasture, forestry and native vegetation	Darcy's Law	*~63 GL/y in the LLC*
Plantation forestry water use (Benyon & Doody, 2004)	Blue gum plantations, pine plantations and pasture	Water balance	~0 mm/y (blue gum) ~0 – 80 mm/y (pine) ~180 mm/y (pasture)
Padthaway salt accession project (Wohling et al. 2005)	Pasture, irrigation and native vegetation	Chloride methods and water balances	95.5 – 1450 mm/y (higher estimates are recharge from drainage under flood irrigation)
Bakers Range land use impacts project (Mustafa et al. 2006)	Pasture, forestry and native vegetation	Chloride and water balances	~200 mm/y (pasture), 8 mm/y (native vegetation) and 0 mm/y (plantation forestry)
Review of resource condition (Brown et al. 2006)	Pasture and forestry	Watertable fluctuation method	15 – 200 mm/y
Border Zone Salt Accession Project	Pasture, irrigation and native	Chloride methods and 1D	Mean rates =

(Wohling, 2008)	vegetation	models	8 mm/y (native veg) 42 mm/y (pasture) 130 mm/y (irrigation)
Land Use Impacts in Zone 3A (Harrington et al., in prep.)	Pasture, forestry, irrigation and native vegetation	Chloride and CFCs	Ranges = 4 – 12.5 mm/y (hardwood forestry) 0.8 – 11 mm/y (softwood forestry) 8 – 10 mm/y (native vegetation) 7 – 9 mm/y (irrigated vineyards) 9 – 18 mm/y (pasture)
National Water Initiative recharge project (Wood 2010)	Pasture and forestry (hardwood and softwood)	Chloride and CFCs	2 – 190 mm/y (pasture)

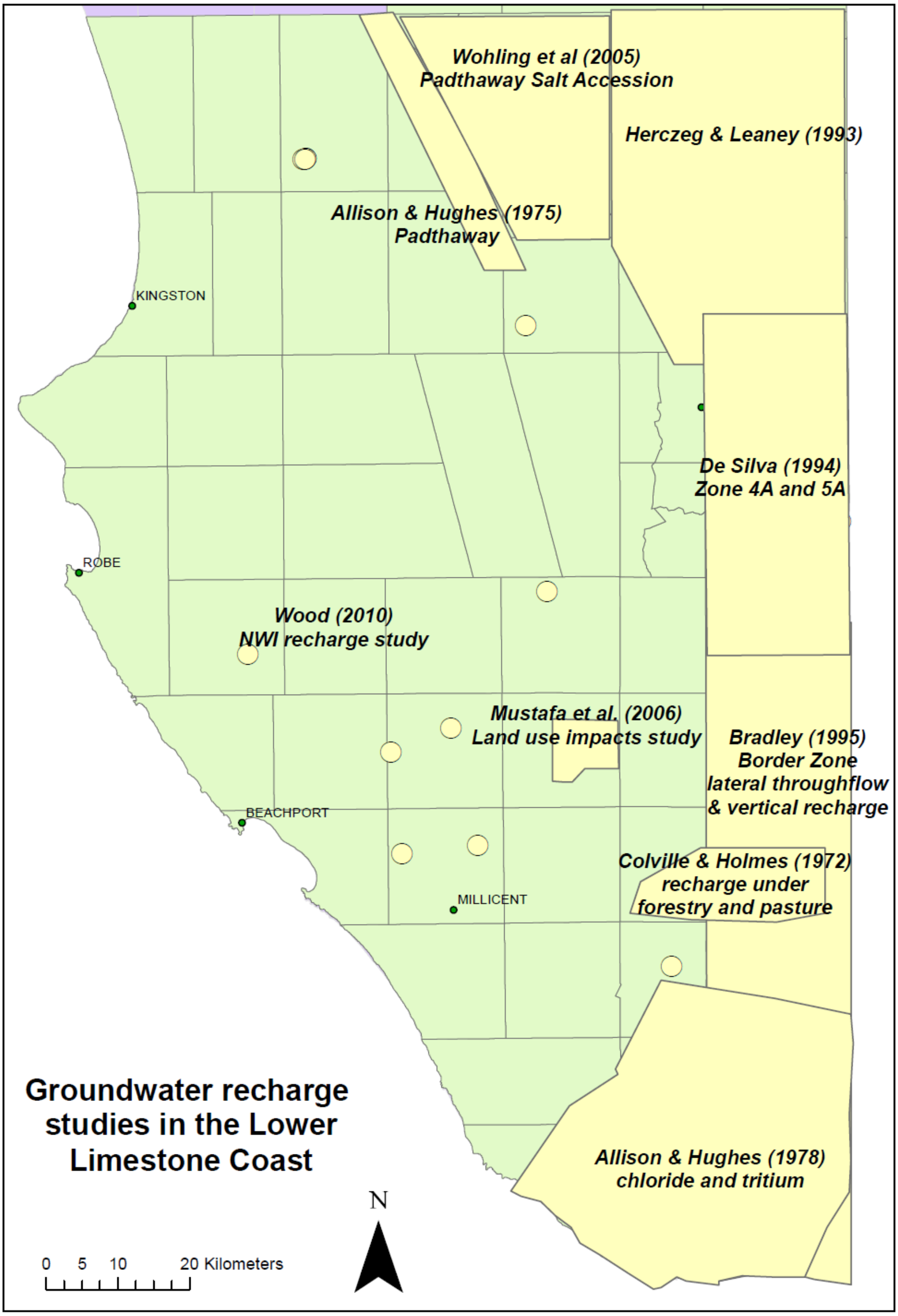

Figure 14. Summary of recharge investigations in the Lower Limestone Coast (excluding Brown et al. (2006))

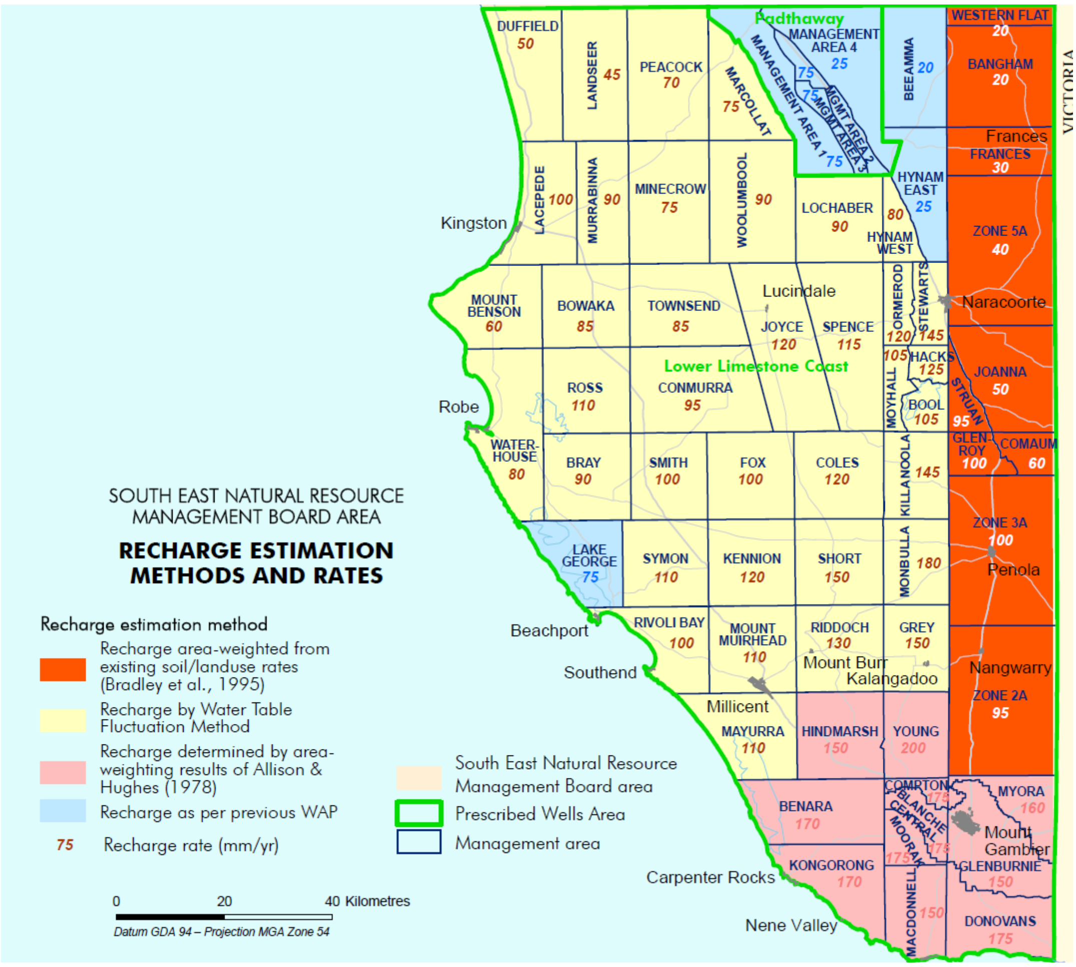

Figure 15. Estimates of recharge for each groundwater management area, taken from Brown et al. (2006)

6.3.1.2. Rainfall Recharge Under Plantation Forestry

Interception of rainfall recharge, referred to as a forest recharge debit (Brown et al., 2006), is one of two mechanisms for water use by plantation forestry. Forest recharge debits are calculated using an estimate of the total area of land covered by plantation and knowledge of the percentage of recharge that is intercepted by the forest canopy (Brown et al., 2006). The latter is estimated to be 83% for softwood plantations and 78% for hardwood plantations (Brown et al., 2006). The total estimated volume of recharge intercepted by commercial plantation forestry in the LLC PWA is 199,402 ML/y. A further 5446 ML/y is estimated to be intercepted by farm forestry.

6.3.2. LATERAL GROUNDWATER INFLOW

Cross-border groundwater flow from Victoria to South Australia occurs in all areas where the groundwater flow gradient is east to west (all areas along the South Australian-Victorian border except the management areas Zone 1A and Zone 2A). Lateral throughflow may be estimated using Darcy's Law:

$Q = KAI$

Where: Q = volume of lateral inflow from Victoria (m^3/yr)

K = hydraulic conductivity of the aquifer (m/yr)

A = area along the border where throughflow may occur (m^2)

I = hydraulic gradient (the difference in watertable elevation between Victoria and South Australia) (m/m).

Bradley et al. (1995) estimated throughflow to range from 6500 ML/y in Zone 6A, to 33,150 ML/y in Zone 3A, and totalling 66,545 ML/y in the LLC.
It should be noted that these estimates were made in 1995, and are based on watertable gradients at that time. Many observation wells in the Border Zone have shown declining groundwater levels over the past 5 to 10 years, which may have influenced the watertable gradient across the Border. Therefore updated throughflow estimates could be provided, using the same assumptions as Bradley et al. (1995) about aquifer transmissivity. Groundwater inflow to the regional model domain can be estimated in the same way once the eastern boundary of the model domain is finalized.

6.3.3. UPWARD LEAKAGE

In all areas to the south west of the ZHD line (Figure 12), the confined aquifer has a higher hydraulic head than the unconfined aquifer and as a result, upward leakage between the two aquifers is possible throughout that region. Post-depositional faulting has resulted in the potential for hydraulic connection between the unconfined and confined aquifers (Lawson et al., 1993; Lawson et al., 2009). The occurrence and magnitude of upward leakage is unknown, however the map of fault locations (Fig. 10) provides an initial indication of potential locations if leakage is fault-related.

At the ZHD line the quantities of inter aquifer leakage are unknown, however it is possible that leakage may be occurring in either direction.

As described in Section 6.2.3.2, there is unconfirmed evidence for upward leakage via preferential flow through the 300 m thick aquitard at observation well GAM28, in the south-eastern corner of the study area.

6.3.4. DRAINAGE OF STORMWATER

Drainage of stormwater occurs via a network of drainage wells located predominantly to the north of the Blue Lake in the vicinity of Mount Gambier. These drainage wells drain ponded surface water to the unconfined aquifer to prevent waterlogging at the surface. It is estimated that there are ~350 operational drainage wells throughout the city (Lawson et al., 1993), however a number of these may have been abandoned or backfilled.

Past findings by Emmett (1995) have estimated that ~2 800 ML of stormwater discharges to the unconfined aquifers annually. This approximation was based on estimates of rainfall and paved area over Mount Gambier. However, due to vast expansion of the city over recent years, the estimated amount of stormwater reaching the unconfined aquifer per year has been revised to about 3 200 ML (J. Lawson, DWLBC, Pers. Comm., 2006).

6.3.5. IRRIGATION DRAINAGE

Irrigation drainage refers to the volume of irrigation water that is surplus to crop water requirements and is therefore returned to the aquifer. The Volumetric Conversion Project (VCP) has demonstrated this process to be most significant beneath flood irrigation (Latcham et al., 2007). Drainage below flood irrigation is a highly variable parameter, depending on a range of factors such as volumes of water applied and the irrigation regime, climatic conditions, configuration of flood bays, crop type and soil type. It is therefore very difficult to spatially extrapolate the results of field investigations, of which there are very few in the South East. However, irrigation drainage is a fairly small component of the water balance of the LLC PWA and hence could be represented fairly approximately in a regional scale water balance model. Nevertheless, the local effects of irrigation drainage on water tables and groundwater salinities can be substantial and this may need to be taken into consideration in local-scale models.

Latcham et al. (2007) estimated volumes of deep drainage for individual management areas of the South East, based on volumes of groundwater extracted for flood irrigation and estimates of evaporation from flood bays and of crop water use. For the LLC, this is 60 GL/y. These estimates assume application of the full (100%) allocations and can be corrected (again, for individual management areas) for estimates of actual use of allocations given by Hodge (2009). This gives a total of 23 GL/y for the LLC PWA (Wood, 2010b). Such data is available on a management area scale for only the past couple of irrigation seasons, since metering was implemented. If necessary, digitising historical aerial photos may provide a means for adjusting historical values of irrigation drainage as well as groundwater extraction, with a number of assumptions.

6.3.6. SURFACE WATER INFLOW

As mentioned earlier, three main creeks flow into the Lower Limestone Coast – Naracoorte Creek, Mosquito Creek and Morambro Creek. All creeks are ephemeral and are highly dependent upon seasonal (winter) rainfall to generate flows. However, Paydar et al. (2009) estimate a mean annual inflow from these creeks of ~15 GL/y based on long term flow records.

6.3.7. RAINFALL ON SURFACE WATER BODIES

Paydar et al. (2009) estimated the volume of rainfall that falls on surface water bodies in the LLC, based on average regional rainfall from the BoM 1961-1990 reference period, to be 309,000 ML/y. Rainfall on land surface is not included as an input in this exercise, as it is accounted for (along with evapotranspiration of any rainfall) in estimates of groundwater recharge.

6.4. OUTPUTS FROM THE UNCONFINED AQUIFER (TLA)

6.4.1. GROUNDWATER EXTRACTION

Figure 16 shows that groundwater use in the LLC, use can be separated into four main categories: irrigation, stock and domestic use, plantation forestry use and other uses (public water supply, aquaculture, industrial and recreational). Groundwater extraction for irrigation, industry, recreational use, aquaculture and public water supply is licensed in the LLC. Currently, all licensed groundwater users are required to have meters installed on pumping wells, so that accurate data on groundwater use may be recorded. However metering was only implemented in 2002, and metered data has only been collected since 2007. Metered extraction figures (and in the past, areas of land irrigated) are reported by licensees to the Department for Water on a yearly basis through Annual Water Use Returns (AWURs). While there is the possibility for incorrect figures to be reported (due to meter failures, non-compliance etc), the DFW does conduct its own meter reading programs for compliance purposes, and has reported 95% accuracy in licensee provided meter reads in the past (D. Laslett, pers comm.).

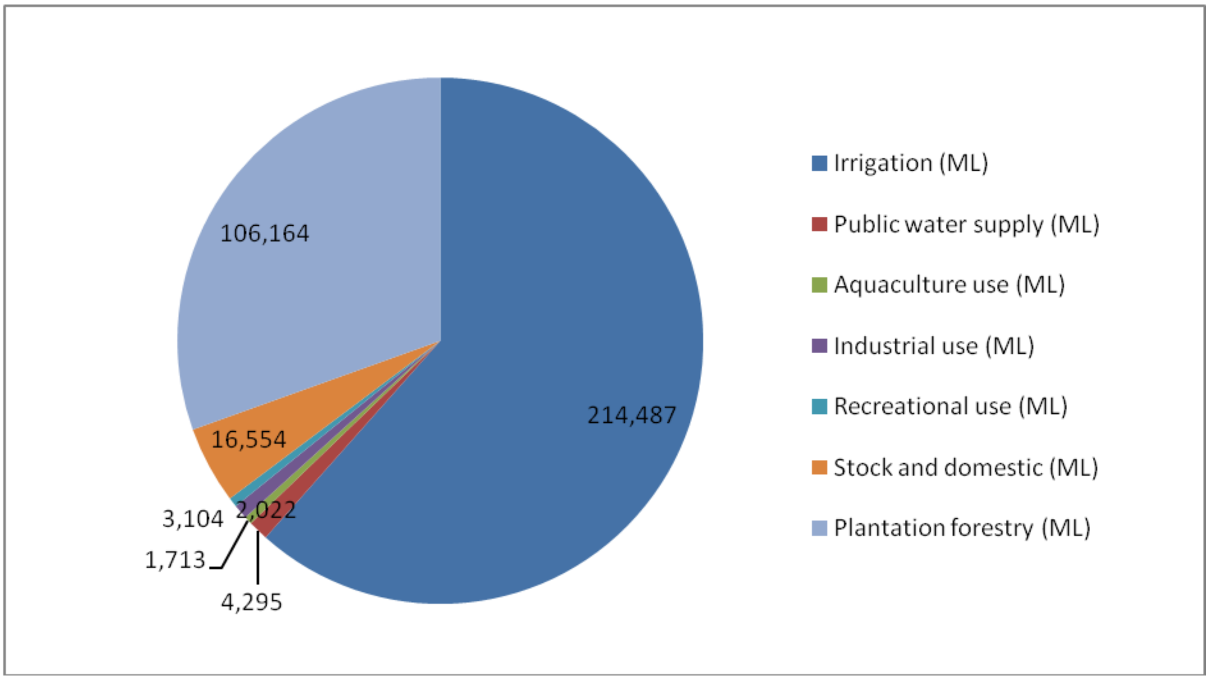

Figure 16. Groundwater use in the LLC PWA in 2008-09

6.4.1.1. Irrigation

Prior to the collection of metered data, irrigation water use figures (the dominant component of licensed water use) in the LLC were based on estimates of the area of land irrigated and theoretical crop water requirement relationships. Figure 17 gives an indication of trends in extraction for irrigation since 2001-02.

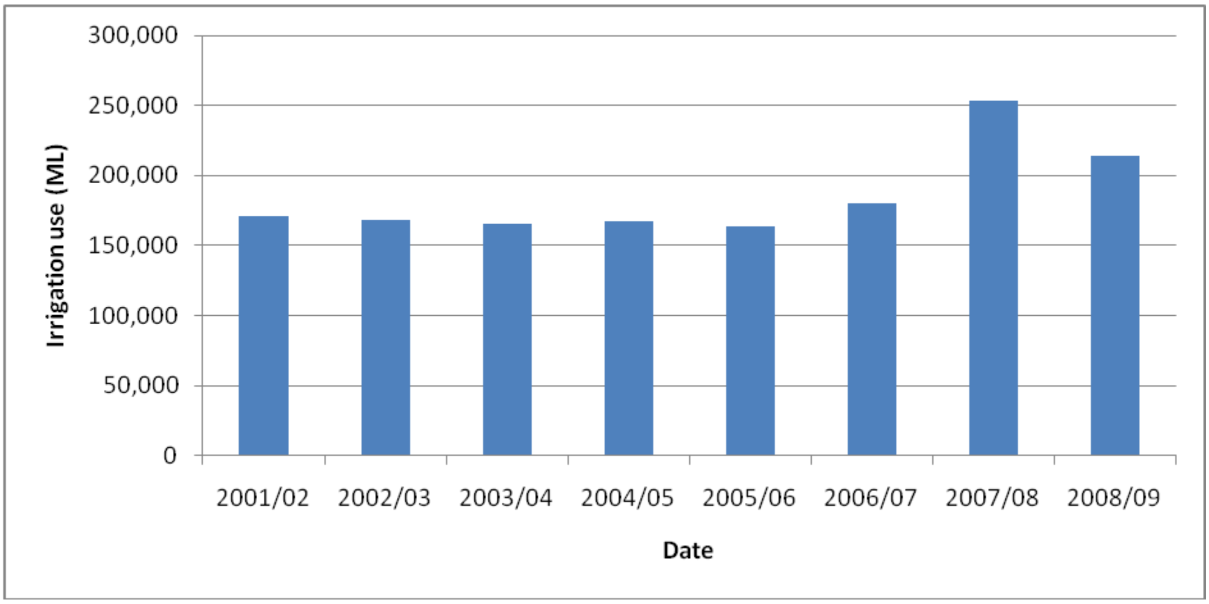

Figure 17. Irrigation use in the Lower Limestone Coast Prescribed Wells Area (based on estimates from 2001-2007, and metered data from 2007-2009)

Prior to 1998, estimates of groundwater use only exist for irrigation, and only for the management zones within the Border Designated Area (the Comaum-Caroline Prescribed Wells Area and the Naracoorte Ranges Prescribed Wells Area (Figure 18). The lack of historical water use in the old

Lacepede-Kongorong PWA relates to fact that the groundwater resources were only prescribed there in 1997. Data is also not available for 1999/2000 and 2000/2001. Figure 19 shows variations in groundwater extraction by the "other" users between 2004 and 2009.

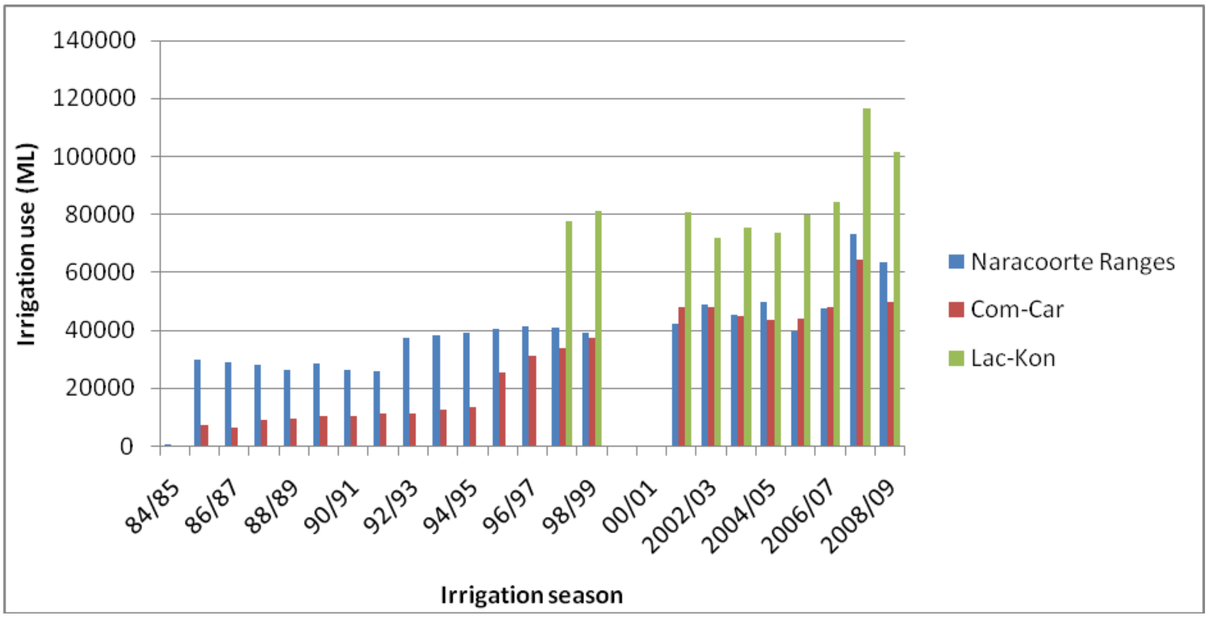

Figure 18. Historical estimates of groundwater use for irrigation in the Lower Limestone Coast (data not available for 2000–01)

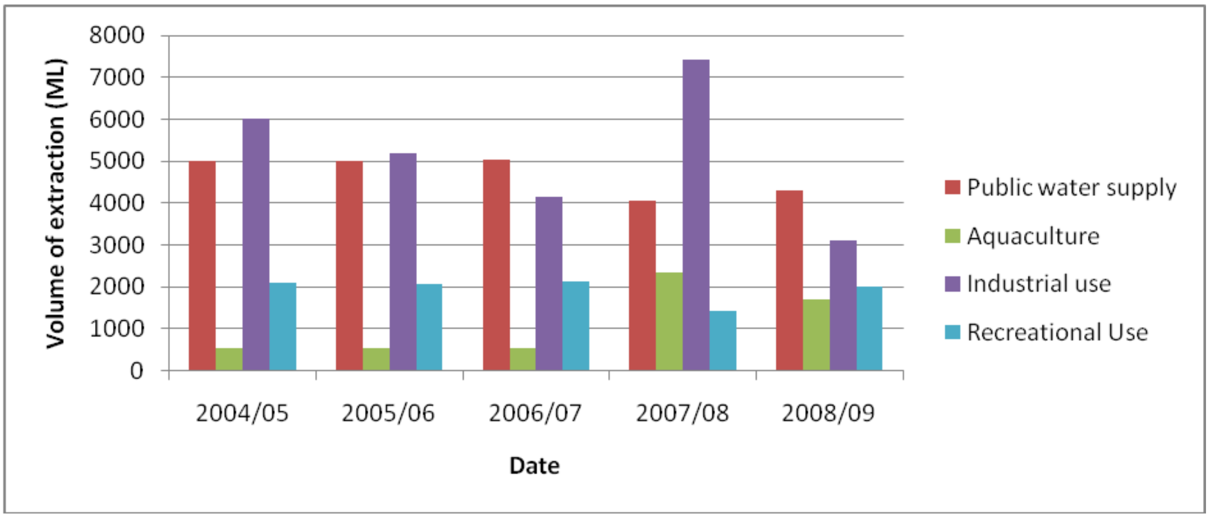

Figure 19. Groundwater extraction by users other than the irrigation industry in the LLC PWA

Data from licensed meters and meter readings in the LLC is administered by the DFW in Mount Gambier. Currently, data may be retrieved either directly through internally held databases, or through the South East Meter Data Management System (SEMDMS). The SEMDMS is a graphical user interface that allows users to retrieve licensee information and meter details, display them spatially, and in many cases link groundwater meters to groundwater extraction wells (providing important information on the depth in the aquifer from which groundwater is being extracted).

In summary, metered groundwater extraction data only currently exists for the 2008-09 irrigation season. Metered data will continue to be collected into the future, however it cannot be captured retrospectively. Therefore historic groundwater extraction data is only available as estimates of use (based on areas irrigated and theoretical crop water requirements) and the level of detailed information on estimates of use decreases with time, with no records of use in the Lacepede-Kongorong area prior to 1997. Digitisation of aerial photography from historical records may provide some basis for estimating historical water use. Metered data where it is currently available can be accessed through the SEMDMS.

6.4.1.2. Stock and domestic use and public water supply

Extraction of groundwater for stock and domestic purposes is neither licensed nor metered in the Lower Limestone Coast. Currently, estimates of extraction for stock use are based on Australian Bureau of Statistics stock numbers for the 1996-97 season, as well as NSW Department of Agriculture figures on daily stock consumption (Cobb and Brown, 2000). No specific data exists on domestic groundwater use in the Lower Limestone Coast, hence figures reported are purely estimates. Previous groundwater models have generally not incorporated stock and domestic use. This is because there are few reliable estimates of this groundwater use and it has always been considered an insignificant part of the water balance for modelling purposes. Current estimates are based on 1996-97 ABS data, and amount to 16,554 ML in the LLC (<2% of total use).

With the exception of the Keith township in the Upper South East, all public water supply is taken from groundwater. Public water supply (town supply) is metered by SA Water, hence use figures can be considered accurate. Table 3 shows public water supply data from the 2008-09 year (Hodge, 2009).

Table 3. Town water supply volumes in the Lower Limestone Coast (* indicates Confined Aquifer management area)

Town	Aquifer accessed	Allocation (ML/y)
Beachport	Confined	180
Kalangadoo	Confined	50
Kingston SE	Confined	560
Lucindale	Confined	100
Millicent	Unconfined	580
Mount Burr	Unconfined	130
Mount Gambier	Blue Lake	4000
Nangwarry	Unconfined	120
Naracoorte	Confined	800
Padthaway	Unconfined	20
Penola	Unconfined and confined	Unconfined = 170; Confined = 100
Pt Macdonnell	Confined	110
Robe	Confined	550
Tarpeena	Confined	60

6.4.1.3. Plantation forestry water use

Plantation forestry has been an acknowledged part of the groundwater cycle in the LLC since the earliest recharge investigations in the region (Colville and Holmes, 1970). More recent studies have focused on quantifying the forestry component of the water balance. Benyon and Doody (2004) investigated plantation forestry water use in the LLC, and reported groundwater use by plantations at eight out of nine research sites. They reported a mean annual extraction rate of 4.35 ML/ha/y for all sites (ranging from 1.08 ML/ha/y to 6.70 ML/ha/y).

For management purposes, the use of groundwater by plantation forests is considered to be 1.66 ML/ha/y for softwood plantations (radiata pine) and 1.82 ML/ha/y for hardwood plantations (Tasmanian blue gum), and, also for management purposes, groundwater extraction by forestry is only considered to occur in areas where the watertable is within 6m of the ground surface (Latcham et al., 2007). However, forest extraction has been observed to occur from water tables as deep as 8.9 m (Benyon et al., 2006) and current monitoring data suggests that the depth constraint may be site specific. The groundwater model of the Coles-Short hotspot area showed that the onset of direct extraction by forests had a more significant impact on groundwater levels than recharge interception and that this process is undoubtedly the cause of water table declines in that region (Aquaterra, 2010). For this reason, a better understanding of the spatial and temporal variation in this process is required to properly simulate groundwater levels in forested areas.

It is anticipated that there will be projects commencing in the near future that will seek to better quantify plantation water use at different spatial and temporal scales.

6.4.2. DOWNWARD LEAKAGE

There is potential for downward leakage of groundwater from the unconfined aquifer to the confined aquifer in the area to the north of the ZHD line shown in Figure 12. However, the spatial distribution and magnitude of this process is poorly understood. Downward leakage to the north of the ZHD line is supported by variations in groundwater chloride concentration observed in the confined aquifer, up to the ZHD line, which were attributed by Love (1991) to recharge inputs via downward leakage along the flow path. Brown et al. (2001) suggest that the area over which downward leakage occurs may be much smaller than that indicated by a downward hydraulic head gradient and the mechanism is probably via preferential flow along cracks, faults or sinkholes rather than matrix flow. In particular, this applies to the region known to be a confined aquifer recharge zone, located in the Nangwarry / Tarpeena area, identified by the observation of relatively high confined aquifer groundwater ^{14}C activities (>40 pmC) (Brown et al., 2001). In this area, there is a groundwater mound in the confined aquifer and a sink in the unconfined aquifer, accompanying a downward hydraulic gradient across the Upper Tertiary Aquitard. Some additional geochemical evidence for such leakage occurs in this region. For example, confined aquifer observation well Tarpeena Town Water Supply no.2, have both uranium concentrations and atomic ratios similar to that of the unconfined aquifer, indicating downward leakage to the confined aquifer at this location (Love, 1991). Much of the inferred recharge area is now covered in forest plantations, which are likely to limit recharge to both the unconfined and confined aquifers in this region. A relatively high confined aquifer groundwater ^{14}C activity also occurs adjacent the Tartwaup Fault to the northwest of the study area, possibly indicating preferential recharge along the fault (Brown et al., 2001).

It is currently unknown whether any additional downward leakage occurs within the study area, particularly in the region to the north of the ZHD line. Love (1991) found that the $\delta^{13}C$ signature of confined aquifer groundwater was constant between the ZHD line and the coast, suggesting little downward leakage from the unconfined aquifer to the confined aquifer, as expected due to the upward hydraulic potential that occurs in that region.

6.4.3. EVAPOTRANSPIRATION (ET)

For the purpose of this project, evapotranspiration (ET) of rainfall prior to recharge is incorporated into estimates of groundwater recharge. However, it is widely regarded that groundwater may be lost directly to evapotranspiration in areas where the watertable is relatively shallow (generally <2m deep). Paydar et al (2009) investigated the importance of this process under dryland agriculture (the dominant land use) in the South East using SWAGMAN, a 1-D soil/crop/water use model. Over the area covered by dryland agriculture with a shallow watertable (~17000 ha), Paydar et al. estimated evaporation rates of 69 mm/y for 0.5 m water tables, 23 mm/y for 1 m water tables and 0 mm/y for 2 m water tables. This resulted in 7 000 ML/y being lost to evaporation by capillary upflow from shallow water tables in the Lower Limestone Coast region.

Previous numerical models developed for the South East have implemented ET in a variety of ways. ET In their model of the area to the south of Mount Gambier, Stadter and Yan (2000) used values derived from Waterhouse (1977), with averages for the summer irrigation period of October to March and the winter period of April to September being 560 mm and 210 mm respectively. Aquaterra (2008) implemented ET in their model of the Padthaway area at a rate of 500mm/y, and with an extinction depth of 2m. When implemented by the MODFLOW 'Evapotranspiration' package, this means that ET can only occur in areas where the watertable is within 2m of the surface. The maximum ET rate (500 mm/y) only applies at the surface, and decreases to 0 mm/y at the 2m extinction depth.

Outcomes from the recently completed Diffuse Impacts Project", a joint project between SARDI, Flinders University and DFW, include modelled maps (modelled using the unsaturated zone model LEACHM coupled with GIS) of evapotranspiration, as well as recharge, which may be of use to this study.

Evapotranspiration may occur from the areas covered by surface water, such as coastal lakes, swamps and wetlands. Paydar et al. (2009) used average potential evapotranspiration data from the 1961-1990 BoM reference period to estimate ET losses from the area covered by surface water bodies, and reported ~770 000 ML/y is lost via this process for the Lower Limestone Coast region.

6.4.4. SURFACE WATER – GROUNDWATER INTERACTIONS AROUND WETLANDS

Given the generally shallow depth to groundwater, it is widely acknowledged that groundwater and surface water systems throughout much of the South East are intrinsically connected. Investigations at a number of sites have provided an improved understanding of these processes. Fass and Cook (2006) measured chloride and radon-222 concentrations in 37 wetlands in the Lower South East, and used simple mass balance models to determine the level of groundwater dependence. They found that a majority of the wetlands surveyed had a moderate to high dependence on groundwater (Fig. 20). However these results were usually based on one measurement of radon-222 and chloride in each wetland, and hence considered preliminary.

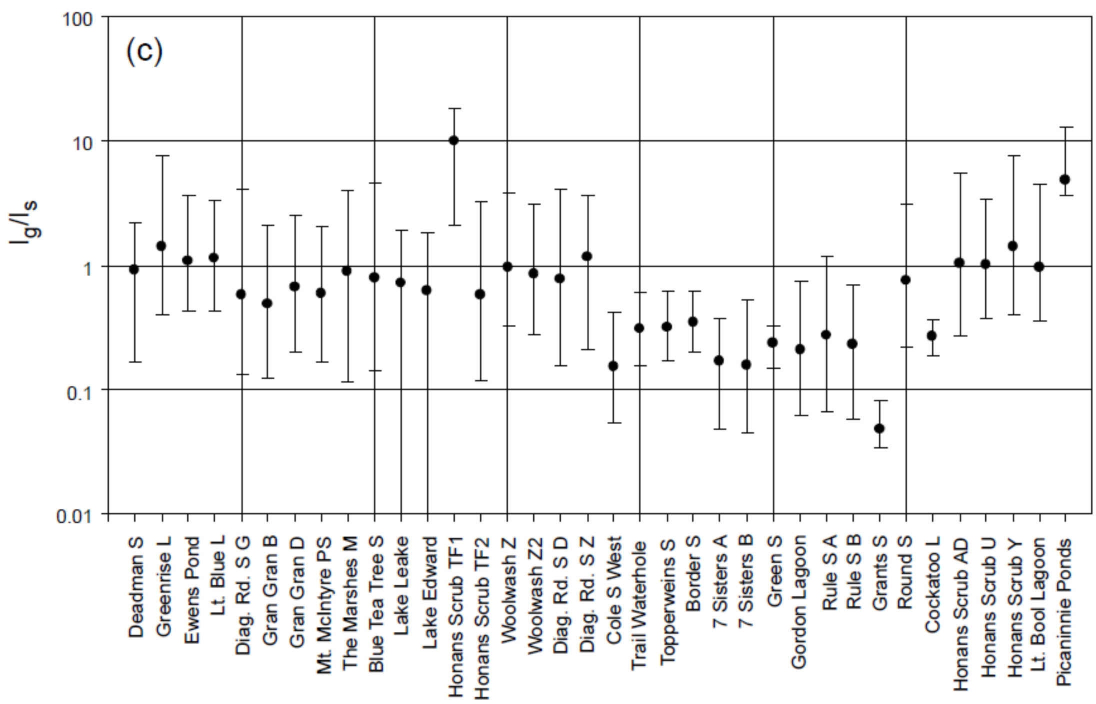

Figure 20. Ratio of groundwater inflow (Ig) to surface water inflow (Is) for wetlands assessed by Fass and Cook (2006). Relatively high values of Ig/Is suggest higher groundwater dependence

Cook et al. (2008) conducted more a more detailed investigation at a wetland located in Honans Scrub, ~12km north-west of Mt. Gambier. Radon-222 concentrations were measured in the wetland on multiple occasions in 2006, and used to construct a steady state and a transient model of groundwater discharge to the wetland, which was estimated to vary between 12 – 18 m^3/day.

Wood (2010a) used a variety of hydrochemical tracers to investigate groundwater discharge processes at a number of springs in the Lower South East, including Ewens Ponds and Piccaninnie Ponds. It was found that flow out of Ewens Ponds was dominated by discharge from the third pond, which has a higher salinity than spring discharge from the first two ponds, and a chemical signature that suggested discharge from one of the deeper sub-units of the unconfined aquifer. Results from Piccaninnie Ponds showed groundwater discharge occurred primarily in a deep karstic feature referred to as 'The Chasm.' Discharge was inferred to occur via seepage from the entire 'open' section of limestone aquifer, with higher discharge occurring at the interface between aquifer sub-units (where fracturing is thought to have an influence on transmissivity and flow).

SKM (2009) looked at the regional extent of surface water-groundwater interactions in the South East, by examining the relationship between the surface elevation of surveyed water bodies (determined from a high resolution DEM) and seasonal watertable elevations. They reported that 45% of wetlands had a high to very high potential for surface water-groundwater interaction, with the majority of these likely to be gaining systems (i.e. groundwater discharging to surface water).

Harding (2010) summarised all these studies in a recent assessment of the potential groundwater dependence of surface water bodies in South Australia. Figure 21 displays the results of this study for the LLC. This showed that the majority of surface water bodies are potentially groundwater dependent. The exceptions are wetlands located in the Naracoorte Ranges and Mt Burr areas, where the higher elevation (and greater depth to water) means they are unlikely to have any connection to or reliance upon the unconfined aquifer.

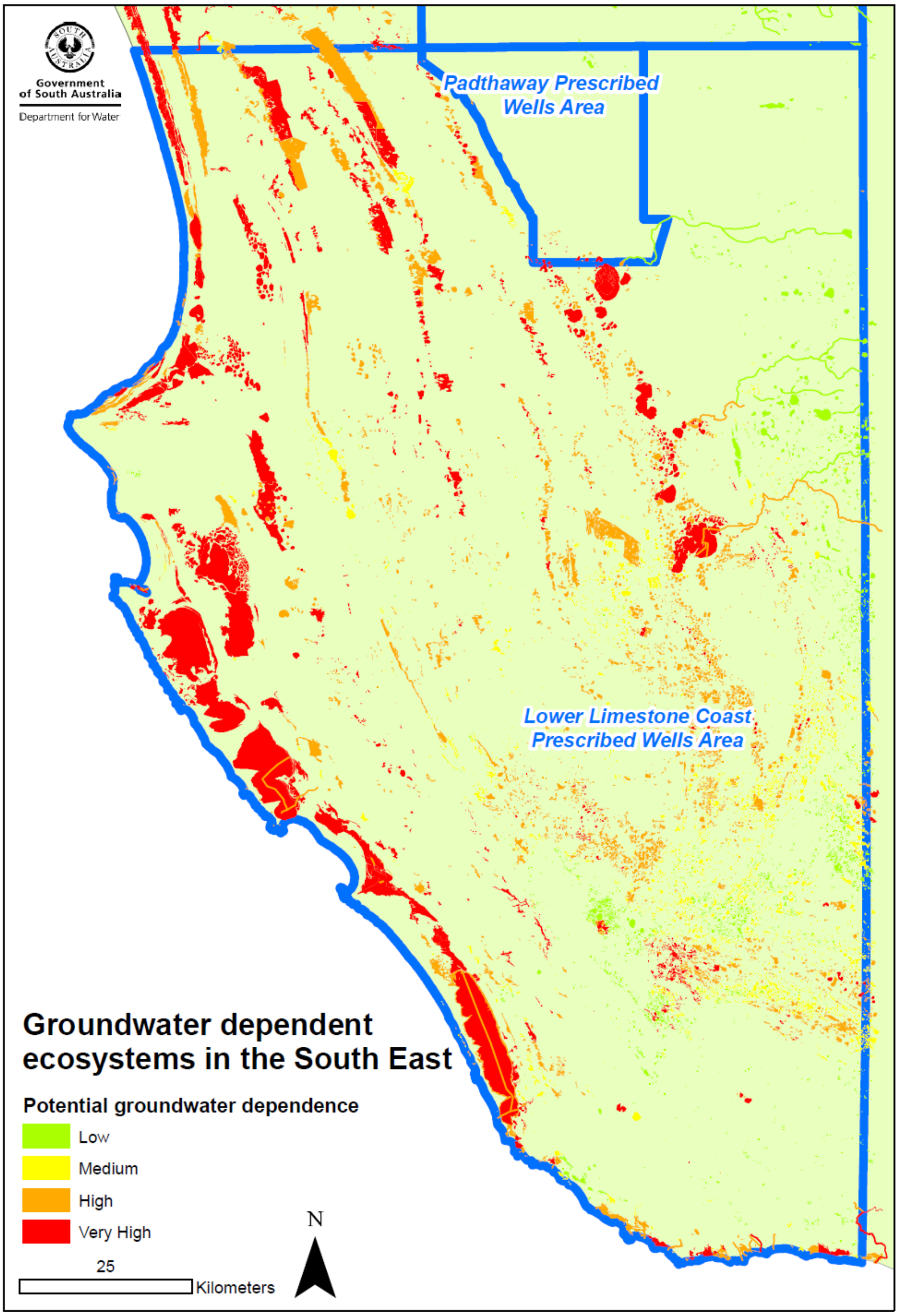

Figure 21. Potential groundwater dependent ecosystems in the South East

6.4.5. GROUNDWATER DISCHARGE AT THE COAST

There are significant coastal spring discharges at Eight Mile Creek, Deep Creek and Piccaninnie Ponds, with the total spring discharge estimated to be 160 000 ML/yr by Waterhouse (1977). This discharge is considered to be due to karstic flow within the Gambier Limestone. Monitoring of the springs from 1970–2000 yielded an estimate of average annual flow of 110 000 ML (Stadter & Yan, 2000). However, subsequent monitoring indicates discharge from Picanninnie ponds, Ewens Ponds, Deep Creek and Eight Mile Creek to be ~98 000 ML/yr over the past ten years. These measurements are expected to represent a fraction of the groundwater discharging at the coast, as discharge can be expected to occur as seeps and springs along the whole coastline from the South Australia/Victoria border to the Coorong. However, the occurrence and magnitude of this and any groundwater discharge via offshore seepage is currently unknown.

6.4.6. SURFACE WATER OUTFLOWS

Constructed drains, other than those fed by groundwater springs, are typically referred to as surface water drains. However, surface water-groundwater interactions in the South East are complex and not fully understood and, in reality, many of these receive groundwater discharge. For example, Stace and Murdoch (2003) estimated up to 75% of surface water flow may be derived from baseflow.

Paydar (2009) summarised all surface water drainage data for the South East, including estimates of flow at ungauged sites, and reported that 106 000 ML/y of surface water drainage in the South East discharges to the coast.

6.5. INPUTS TO THE CONFINED AQUIFER

6.5.1. RECHARGE (DOWNWARD LEAKAGE)

The only known outcrop of the Dilwyn Formation in South Australia occurs on an undulating erosional surface 10 km to the north west of Mt Gambier (Waterhouse, 1977). To the east, in Victoria, there are minor outcrops along the Glenelg River. Because of the limited outcrop of this aquifer, recharge is considered to occur predominantly via downward leakage through the unconfined aquifer and confining beds (Love, 1991). This process was described in detail in Section 6.4.2.

6.6. CONFINED AQUIFER OUTPUTS

6.6.1. GROUNDWATER EXTRACTION

The majority of groundwater extraction for irrigation, stock and domestic use in the LLC is from the unconfined aquifer. However the confined aquifer is still an important source of water for town supply in various towns in the LLC (Penola, Naracoorte, Lucindale, Robe, Port MacDonnell, Beachport, Kalangadoo, Tarpeena). It is also the emergency back-up water supply for Mount Gambier. Irrigation use from the confined aquifer is sparse across much of the LLC. Total use from the confined aquifer is estimated to be around 21,289 ML/y, ~70% of which is concentrated in an area where the aquifer is artesian, to the east of Kingston (Hodge, 2009).

6.6.2. OFFSHORE DISCHARGE

Upward discharge from the confined aquifer to the Gambier Limestone has been postulated to occur offshore, but no direct evidence of this exists (Blake, 1980). As it occurs beyond the boundary of the study area, any such discharge is not considered to be relevant to the conceptual model.

7. STATUS OF THE CONCEPTUAL MODEL: KNOWLEDGE GAPS AND LIMITATIONS IDENTIFIED THROUGH PHASE 1

The review of the conceptual model has identified that a great deal of knowledge and data exists for the Lower South East, upon which a conceptual model of the hydrologic system can be based. However, it is a complex system, both in terms of the hydrostratigraphy and its history of human development. The Technical Workshop (Section 5) gathered the opinions of a cross-section of people with experience working in the region. Despite the high level of information that clearly exists for the South East in comparison to other regions, there was an overwhelming feeling that there is still a need to develop good representations of spatial and temporal variations in:

- Land use
- Recharge
- Evapotranspiration
- Groundwater interactions with drains
- Forestry impacts
- Groundwater extraction.
- Surface water – groundwater interactions.
- Interactions between the confined and unconfined aquifers.

These areas are fairly broad, as is reflected in the fact that there are currently difficulties in developing a well-defined research program for the region. Based on the review of the conceptual model presented above, the discussions at the technical workshop and experience in other modelling projects in the region, the project team has developed a list of the knowledge gaps relevant to the outcomes of both a regional (Lower South East) numerical water balance model and local-scale models (Table 4). These have been prioritised in terms of the impacts of these knowledge gaps on the outcomes of regional and local-scale numerical models. This list is preliminary and the numerical modelling in Phase 2 of this project will help to (a) test their relative importance to the outcomes of numerical models and, (b) in many cases, determine the locations where these knowledge gaps really require further investigation.

Table 4. Prioritised list of knowledge gaps in the conceptual model of the groundwater system in the Lower South East

Knowledge Gap	Area of Influence	Current Level of Understanding (G=Good, M=Moderate, P=Poor)	Impact on Regional or Local Models		Influence on Model Outcomes	Mitigation Strategy	Priority Area of Investigation (based on current level of knowledge and impact on numerical model outcomes)?
			Regional	Local			
1. Groundwater flow around numerous faults in the region (i.e. impacts of faults on aquifer geometry, properties and preferential vertical flow).	Faulting occurs throughout the Lower South East	P	M	H	Inability to accurately model steep gradient zones around faults, and accurately model water balances due to losses/gains through vertical leakage.	Use NWI fault mapping study to inform possible location of 'low K' zones to simulate steep gradients around faults, and identify areas where losses/gains maybe occurring through vertical leakage.	1
2. Occurrence and magnitude of vertical leakage between unconfined and confined aquifers.	Entire model domain – south of ZHD for upward leakage and north of ZHD for downward leakage.	P	H	H	Inability to calibrate around areas where vertical leakage is of significance.	Fault mapping may be able to help understand reasons for non-calibration.	1
3. Spatial variability of aquifer properties	Unconfined aquifer – whole South East	M	L	M	If conduits or other high conductivity	If there are areas where modelled	3

and the role of karstic features in GW flow.					karst features are present, and not included the model (i.e. a lower regional conductivity value is used), this can result in modelled groundwater levels being too high. If preferential flow occurs along conduits, this would have a large impact on outcomes of any solute transport modelling undertaken.	heads are too high, use knowledge of location of karst features (caves, runaway holes etc) from NWI catchment data set, as well as drillhole records and historical pump test data to assess whether karst features are likely to be present. If they are and are considered crucial to calibration, then potentially incorporate 'high K' zones into the model domain.	
4. Historical groundwater extraction data	Mainly the intensely irrigated areas.	M	M	M	Inability to properly calibrate transient model to pre-2000 water levels results in reduced confidence in model's predictive capability.	Use well construction records and digitise aerial photos (prior to 2000) to construct a groundwater extraction history.	2
5. Land use prior to	Mainly the areas of	M	M	M	Inability to	Digitise aerial	2

2000 beyond the domains of the Coonawarra (Zone 3A) and WR2010 (Coles-Short) models (relevant to knowledge of temporal variations in recharge, irrigation drainage and forestry impacts).	forestry and intense irrigation development.				properly calibrate transient model to pre-2000 water levels results in reduced confidence in model's predictive capability.	photos to provide basic information on temporal land use changes. Anecdotal evidence.	
6. Spatial and temporal variability in historical groundwater recharge.	Whole region	M	H	H	Large impacts on water balance and on modelled regional and local flow systems.	Compared to other regions, there is a lot of data available and point measurements of recharge can be scaled up using knowledge of soil type, depth to water and land use. Simple methods can be used with rainfall data to generate temporally varying recharge. These methods have not been verified but comparison between model outputs and hydrographs	2

						displaying only impacts of recharge variability can be used to assess the methodology.	
7. Spatial and temporal variability in future groundwater recharge.	Whole region.	M	H	H	Large impacts on predicted water balance and on modelled regional and local flow systems.	The DFW project 'Impacts of Climate Change on Water Resources' will produce unsaturated zone recharge models for the South East region, showing the projected changes in recharge as a result of climate change, which could be incorporated into the regional model.	2
8. Spatial and temporal variability of SW-GW interactions around drains.	Shallow watertable areas (DTW<2-5m) around drains.	P	M	H	If drains are modelled with a MODFLOW Drains package (or similar package), drain flows may be too high or low (depending on type of interaction). Impacts on local	Calibrate drain flows to measured flows, and alter drain conductance value to achieve adequate model fit.	1

					heads and groundwater flow directions. Poor confidence in model results.		
9. SW-GW Interactions around wetlands.	Refer to map of potential groundwater dependence in main report – generally shallow watertable areas (i.e DTW<2-5m) where wetlands are present.	P	L	M	Local calibration problems. Lack of confidence in ability to model local scale processes around wetlands. Inability to interpret model results in terms of wetland health.	If the DEM is used as the top elevation in the model, and wetlands modelled using a MODFLOW Lakes package, it may be possible to asses those that fill from groundwater and those that don't. This may significantly add to understanding of SW-GW interactions at a regional scale, and build upon the DTW/GW dependence mapping done earlier (SKM, 2009). However, model outputs require groundtruthing to provide confidence.	2
10. Evapotranspiration from shallow water	Large portions of the Lower South	P	H	H	Significant uncertainty in	Access results of Diffuse Impacts	1

tables – Lack of field measurements.	East, where water tables are < 2 m deep. Large component of water balance so has wide-reaching (regional) effects.				water balance.	project, which modelled unsaturated zone fluxes across the whole lower South East. Adopt broad average rates based on these results and assess through calibration and sensitivity analysis.	
11. Spatial and temporal variability in direct extraction of groundwater by forest plantations.	Areas affected by current and future forest plantations.	M	L	H	Localised effects on simulated water tables around forestry. Inability to effectively interpret model results in terms of impacts of plantation forestry on groundwater dependent assets.	Use existing agreed values, information from the forestry industry, consider methodology from WR2010 (Coles-Short) model and/or assess model performance around these areas.	1-2
12. Quantification of deep drainage of irrigation water under flood irrigation.	Local areas around flood irrigation.	P	L	M	Localised calibration issues. Small component of regional water balance so small impact on regional model outcomes.	Use measured values from Padthaway Salt Accession and Volumetric Conversion Projects. Assess model results around these areas.	3

13. Coastal and Offshore Groundwater Discharge (includes understanding of seawater intrusion).	Coastal margins and coastal aquifer areas. Large component of regional water balance so has wide-reaching effects.	P	M	H	Again, a significant uncertainty in the water balance, over estimation of which may lead to poor decision support ability in coastal areas (i.e. may lead to over-exploitation in coastal areas, and enhance seawater intrusion).	Assessment of model results.	1-2

8. PROPOSED OVERALL (LONG-TERM) MODELLING APPROACH

8.1. BACKGROUND

Phase 1 of the Establishing Total Water Balance for Water Planning in the (Lower) South East Project has involved:

- Consultation with key stakeholders to understand the policy issues and framework into which numerical models should provide input and determine the model objectives (see Section 3 of this report).

- Review of available data and knowledge of the hydrologic system in the Lower South East

- Consultation with technical experts for guidance on a broad modelling approach that addresses the management needs of the region.

Based on this extensive consultation and review process, the following general issues / needs for a future modelling strategy for the region have been highlighted:

- Three-dimensional numerical groundwater flow models are essential to underpin the management of groundwater resources in the Lower South East through testing of our understanding of the resource and simulation of outcomes of proposed management scenarios.

- Previous approaches to groundwater modelling have focused on specific issues and have not been coordinated in any way. As a result, a number of models exist in various stages of development, with varied objectives and hence varied input data and conceptual models. The outputs of such models are not necessarily comparable or relevant for addressing the management questions that have been identified through this project.

- A suite of numerical models is required, with consistent conceptual models and input data, designed to address at both regional and local scales specific management questions / issues important to the WAP process. Such a product should be able to identify emerging and likely risks through simulation of specific climate and management scenarios.

- There is a preference amongst a number of stakeholders to move towards a fully-coupled surface water – groundwater modelling approach. However, the specific objectives of such an exercise, the data / knowledge requirements and hence feasibility (cost/benefit) of such an exercise have not been explored.

- There is an urgent need for a tool to assist with identifying and prioritising the research / data needs that are critical to water resources management in the (Lower) South East and to provide a link between current and proposed management scenarios and observed / modelled ecosystem responses.

8.2. THREE-STEP MODELLING APPROACH

In consultation with the Technical Reference Group, the following three-step modelling approach has been developed to address the objectives identified through the stakeholder consultation and support the WAP process:

1. Construct a regional three-dimensional numerical model (current project), with a domain targeting the Lower Limestone Coast Prescribed Wells Area but otherwise governed by aquifer extents where possible, with the following objectives:

- Identify and prioritise critical knowledge / data gaps at a regional scale.
- Assess / improve our knowledge of the regional water balance, including recharge, groundwater extraction, groundwater inflows from Victoria and outflows at the coast.
- Quantify available water (surface water and groundwater) at a regional scale.
- Provide first-pass assessments of current allocation approach – e.g. what are the implications at a regional scale of allocating 90% of recharge?
- Provide broad-scale information on likely locations and types of surface water - groundwater interactions and identify those groundwater dependent ecosystems (GDEs) likely to be impacted by up-stream activities.
- Identify areas of interaction between the confined/unconfined aquifers or areas where this is likely, but requires further investigation.
- Assist stakeholders with visualising the system and provide an educational tool.
- Provide a basis / boundary conditions for more detailed localised models and recommendations for a consistent modelling approach for these models (i.e. recommendations for step 2).

The broad details of the proposed regional water balance model, based on the detailed review of the conceptual model and the outcomes of consultation with the Technical Reference Group, have been provided in Section 8 of this report.

2. Develop a consistent framework for numerical groundwater flow modelling in the (Lower) South East, including:

- The regional numerical model to provide boundary conditions and regional conceptual framework for smaller scale models (step 1).
- Documentation of the possible approaches for translating the conceptual model into numerical models, i.e. approaches for representing key processes, e.g. historical recharge, groundwater extraction, evapotranspiration (ET), forestry impacts, surface water – groundwater interactions, etc, including their benefits and limitations to different modelling applications.

- A clear set of objectives for a suite of local-scale “hotspot” numerical models to be developed specifically to support the WAP. It is important to consider here (and to emphasise to stakeholders) that one size does not necessarily fit all in modelling, and that not all potential objectives may be able to be addressed by one model (see below).
- A consistent methodology for constructing local-scale numerical models to meet the above objectives.
- A mechanism for reviewing the framework and the numerical models to incorporate new knowledge.

3. Develop a suite of local-scale “hotspot” numerical models to address known and emerging risks that should be considered in any WAP review, using the framework proposed in step 2. Possible objectives of these models include:

- Identify and prioritise critical knowledge / data gaps at local scales.
- Assess validity of current resource condition triggers.
- Quantify water balances of individual management areas (current and proposed).
- Provide a better understanding of localised processes, e.g. confined-unconfined aquifer interactions, surface water-groundwater interactions (including GDEs) and the role of preferential recharge.
- Detailed (quantitative) assessment of impacts of potential future climate scenarios and proposed management scenarios or developments (e.g. irrigation, forestry and industry).
- Contaminant transport modelling or investigation of groundwater salinity issues.

8.3. METHODOLOGY FOR ALLOWING FEEDBACK BETWEEN REGIONAL AND LOCAL SCALE MODELS

It would be desirable for feedback to occur between the regional numerical model developed during this project (Step 1) and the smaller scale models developed during Step 3. The different ways in which this could occur are:

- Manual feedback approach. i.e. use output from the regional model to provide boundary conditions for smaller scale models and subsequently update the regional model based on the results of the smaller scale models.
- Telescopic Mesh Refinement (TMR). This is an established technique in which the boundary conditions for a finely discretized local/site scale model are defined from a coarser regional flow model in which the local model is nested. The traditional method of TMR does not allow feedback from the small grid back to the large grid (e.g. Ward et al., 1987; Leake and Claar, 1999; Davison and Lerner, 2000; Hunt et al., 2001). However, more rigorously numerically coupled methods allowing such feedback have recently been developed (e.g. Haefner and Boy, 2003; Schaars and Kamps, 2001; Szekely, 1998; Mehl and Hill, 2002) and are expected to be

available in the near future (Hugh Middlemis, pers. Comm.). TMR can currently be applied to the MODFLOW code in the Groundwater Vistas platform.

8.4. ADDRESSING SURFACE WATER – GROUNDWATER INTERACTIONS

A great deal of discussion around modelling of surface water – groundwater interactions has occurred during Phase 1 of this project. Amongst the stakeholders, there is a general preference to move towards “fully-coupled” surface water – groundwater modelling for the South East. A number of points that have been raised by the Technical Reference Group regarding this issue include:

- The objectives of such a modelling exercise must be clearly identified in order to determine whether a fully coupled model is likely to or necessary to address these objectives.
- MODFLOW (the proposed groundwater modelling platform for this project) incorporates surface water interactions through the drain, river and stream-routing packages. Fluxes between the surface water body and the aquifer are calculated using base elevation, stage height and bed conductance data.
- These fluxes can be calibrated against actual gaugings to obtain estimates of conductance and to ensure that surface water – groundwater interactions are being adequately represented.
- In order to provide more accuracy than the above approach, a fully coupled model would require detailed data such as:
    - Detailed bathymetry (e.g. LiDAR).
    - Unsaturated zone information (i.e. physical properties of soils in and around drains and creeks)
    - Detailed monitoring data (both surface water and groundwater) for calibration. The actual requirements in this area are yet to be determined.

For these reasons, a “fully-coupled” surface water – groundwater model has not been proposed for the long-term modelling approach. However, if this preference remains amongst the stakeholders, it is recommended that a feasibility analysis be carried out.

The surface water models developed as part of the Regional Flow Management project (Wood and Way, 2010) could provide useful input to an “un-coupled” MODFLOW model. Drain water level data taken from monitoring records could be used as an input to the MODFLOW model, and the catchment yield values determined by the surface water models could be used to calibrate the MODFLOW drain conductance values against. This would provide an opportunity to test the assumptions regarding groundwater interaction made in the surface water models, and help align the objectives of both areas of modelling. It would also build upon the surface water modelling, by allowing for temporal variation in interactions by simulating seasonal fluctuations in the watertable (a boundary condition not considered by the surface water models). Other options could be pursued for linking the outputs of the surface water models to the groundwater model, including the conversion of flow rates determined by the surface water models to drain levels (to act as input to the groundwater model). However this would require further post-processing of the surface water model outputs, and development of a hydraulic surface water model for the South East (which has not yet been developed). Regardless of the approach taken, there is clearly scope to incorporate the results of the surface water modelling into the development of a groundwater model.

Additionally, it is anticipated that, in the case that some field sites are located in the Lower South East, a proposed National Centre for Groundwater Research and Technology (NCGRT) project investigating groundwater fluxes to drains in the South East will provide some additional data against which the numerical groundwater flow model can be calibrated. It is also hoped that the NCGRT project may provide some insight into:

- The best ways to estimate groundwater fluxes to drains and the optimum level of data / instrumentation required to do this.
- A methodology for up-scaling site-specific information.

8.5. USING NUMERICAL MODELS TO GUIDE FUTURE RESEARCH AND WORK PLANS FOR THE LOWER SOUTH EAST

Numerical models are emerging as critical tools in water resources management and hence the quality of the conceptual models upon which these are based should be considered of high importance to water resource managers. It is usually the numerical models themselves that provide the best indication of the areas of the conceptual model that require improvement. Therefore, modelling is an iterative process and requires a long-term commitment if the best outcomes are to be achieved. The importance of numerical models as tools for testing conceptual models and identifying critical knowledge gaps has been emphasised by all parties throughout Phase 1 of this project.

The conceptual model review has shown that a large body of knowledge already exists, certainly enough to allow us to construct a regional model that can answer certain regional questions with confidence. However, the review, along with the Technical Workshop and other similar recent workshops, have also identified a range of research and data collection needs, including a better knowledge of aquifer properties, unconfined / confined aquifer interactions, spatial and temporal variations in forestry water use, evapotranspiration, groundwater recharge and interactions between groundwater and GDEs. How these perceived knowledge gaps should be prioritised has not been clear.

If numerical models are to be an integral part of future water resources planning for the Lower South East, then the outcomes from the Long-Term Modelling Approach proposed above should be closely coupled with the planning of water resources research and data collection efforts. Where the real knowledge gaps lie and the level of importance of these will become clearer as the conceptual model is tested in a numerical model.

9. REGIONAL WATER BALANCE MODELLING APPROACH

The fine details of the regional numerical modelling approach will be finalised during Phase 2 of this project. However, based on the consultation and review activities carried out during Phase 1, the following broad details have been determined.

9.1. MODELLING CODE AND PLATFORM

Following discussions with the Technical Reference Group, the MODFLOW code has been selected as the numerical modelling tool for this project, using the Visual MODFLOW or Groundwater Vistas platforms. The reasons for this selection are as follows:

- Visual MODFLOW and Groundwater Vistas are the industry standard for numerical groundwater modelling studies and are hence most easily used by the majority of modelling professionals.
- Groundwater Vistas interfaces well with ArcGIS.
- Despite its limitations discussed below, the benefits of using MODFLOW are that it has a good capability for calculating water balances at a range of scales and that Telescopic Mesh Refinement, with feedback from small scale to larger scale (as described in Section 7.3), is expected to be available soon.
- For these reasons, the Department For Water has adopted Visual MODFLOW and Groundwater Vistas as its preferred modelling packages and the current Groundwater Model Warehouse project will require all numerical groundwater models to be provided in either of these platforms.

The limitations of using the MODFLOW code for this project must also be acknowledged. These are that MODFLOW:

- Does not have the ability to represent density dependent flow and hence cannot accurately represent flow at the groundwater – seawater interface.
- Does not support a fully integrated surface water – groundwater modelling approach – i.e. it does not link with surface water models.

9.2. MODEL DOMAIN, LAYERS AND GRID

Consultation with stakeholders made it clear that there is a strong preference to have the model centred on the LLC PWA boundary. However, advice from the technical reference group was to use appropriate geological/hydrogeologic boundaries to assign the model domain. For these reasons it was decided that the same model domain adopted by Brown (2000) to model the confined aquifer would be used (Fig. 2). The model area is bounded to the north by the Padthaway Ridge, which approximately marks the transition between the Otway and Murray basins. To the east, the domain is bounded by the Dundas Plateau. The remainder of the model is bounded by the Southern Ocean.

The stratigraphic framework constructed for the NWI project will be used as the basis for layer elevations in the numerical model, with three layers representing the unconfined and confined aquifers and the intermediate aquitard. The model constructed by Brown (2000) used grid cells of 4km x 4km, as the emphasis was on modelling flow and trends in the confined aquifer, where less data is available. Given that this project intends to better model processes in the unconfined aquifer, where significantly more data is available, grid cells of 1km x 1km will be used for the majority of the grid. This grid size may be refined where necessary to represent more detail or localised processes. The unconfined aquifers (Gambier, Murray, Bridgewater, Padthaway etc), will be modelled as one grouped Tertiary Limestone Aquifer layer. Again, this may be refined to multiple layers if required during the modelling process.

The location and influence of significant faults was identified in the NWI project through detailed analysis of seismic records, and drilling and identification of aquifer displacement across known fault lines. Particular consideration will be given to layer boundaries and aquifer properties around the fault locations to ensure that the aquifer displacement identified through the NWI project is properly represented. These are likely to be areas where a more refined grid is required. Surface elevation will be taken from the DEM for the region, which has a vertical accuracy of 0.5m, and a horizontal accuracy and point spacing of <2m.

9.3. AQUIFER PROPERTIES

Estimates of aquifer properties for the Tertiary Limestone Aquifer are characterised by spatial variability of orders of magnitude (a result of karst development in the aquifer). However, confidence in the estimates of aquifer transmissivity and specific yield is generally quite low (Mustafa and Lawson, 2002). This limits the usefulness of all data for inclusion in any numerical modelling study.

Previous groundwater models in the Lower Limestone Coast have identified the variation in aquifer properties as a key uncertainty. The Phase 2 regional model will initially adopt aquifer properties from previous modelling studies, with note taken of the reasons behind the particular distribution of aquifer properties. These values take into account spatial variability, and have in some cases already been subjected to a sensitivity analysis. Aquifer properties will be adjusted appropriately through the calibration process.

9.4. MODEL BOUNDARIES

Preliminary discussions about model boundary conditions, particularly the benefits of constant vs general head boundaries, have been held with the Technical Reference Group. It is anticipated that, where no-flow boundaries are inappropriate, general head boundaries will be used at the extremities of the model domain, but groundwater flows across these boundaries will be carefully monitored to ensure that they are consistent with the conceptual model. A constant head boundary will initially be applied at the coast and this approach will, again, be reviewed during the modelling process.

9.5. RECHARGE

Several approaches have been used in the past to represent recharge in models in the LLC. These range from the use of long term averages (management area recharge rates), to modelling year to year variation in recharge based on the relationship between rainfall and recharge. As rainfall recharge is a large component of the water balance (~80% of total water inputs to the system (Wood, 2010b)), it is considered that it is important to implement this as accurately as possible in numerical groundwater flow models and that the approach taken be uniform across all models. For this study, a relationship between rainfall and recharge will be used to represent temporal variations in recharge. The recharge rates for each year will then be compared with long term averages reported in previous studies (those in

Table 2) to ensure they are realistic. Influences of land use will also been incorporated, with reduced recharge under plantation forestry and native vegetation, and increased recharge under flood irrigation. Care will also be taken in applying recharge rates to deep watertable areas, particularly in the Border Designated Area, around the town of Mount Gambier, and in the uplifted areas associated with the Mt Burr volcanics.

There are several SILO weather stations in the South East, and these can be separated into areas of similar long term recharge, based on recharge rates reported in Brown et al. (2006) (Fig. 22). Rainfall data from these stations will be used to assign recharge rates in these zones. Annual recharge rates will either be determined using the 'average winter rainfall' method used by Harrington (in prep.) or set as a percentage of winter rainfall, and compared with the average recharge rates shown in Figure 22. Recharge rates may be subject to change during model calibration, providing an indication of the applicability of this and other methods of recharge estimation. If this approach proves too coarse in applying recharge rates, further sub-zoning of recharge areas may be done based on the results of Wood (2010a), and additional rainfall stations used.

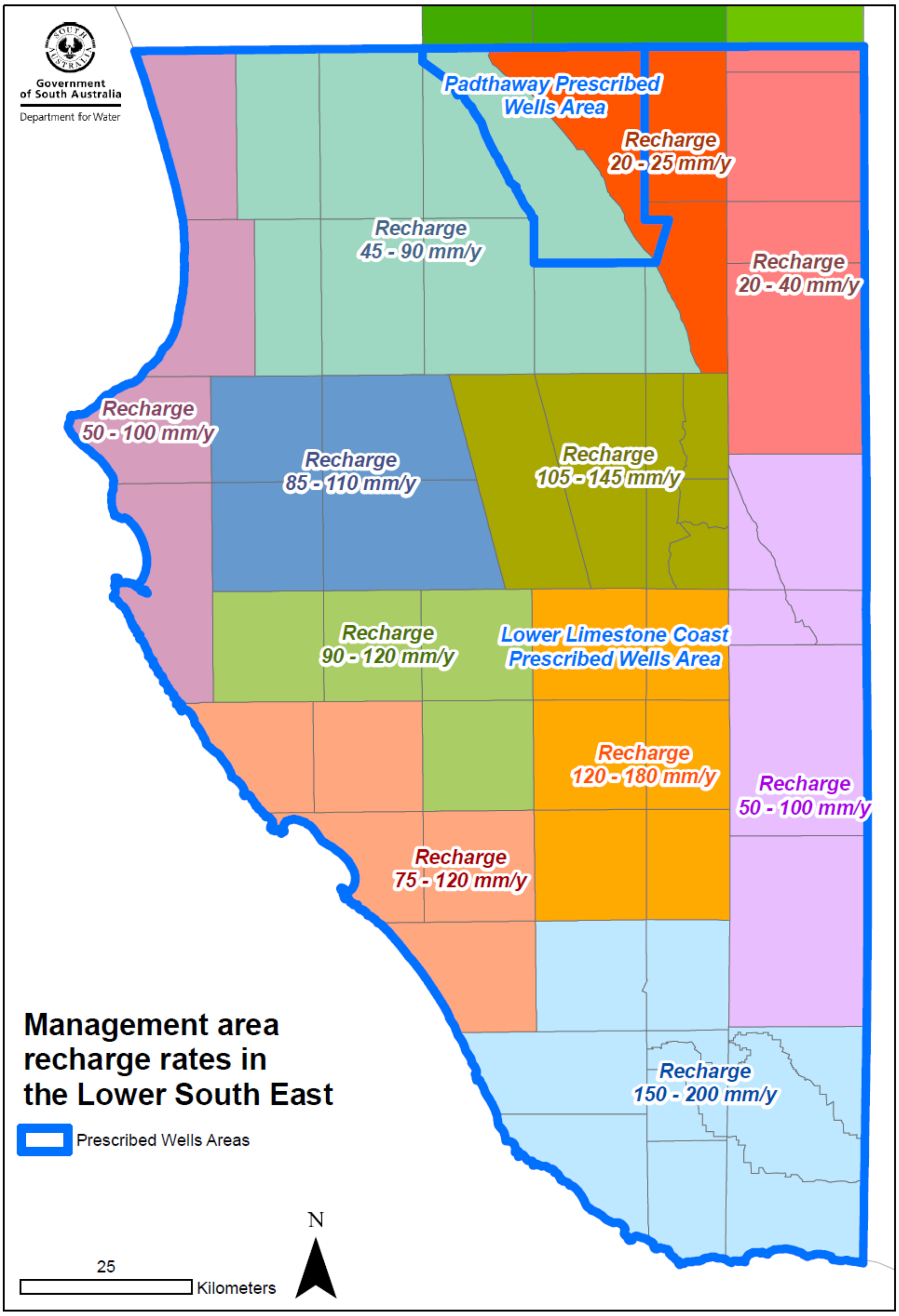

Figure 22. Proposed initial recharge zones for regional scale model based on locations of SILO weather stations and recharge zones of Brown et al. (2006). Further sub-zoning may be conducted if required based on results of Wood (2010a)

The data requirements of this methodology are as follows:

- Time series rainfall data (preferably monthly) to calculate April-October rainfall statistics. This can either be weather station data in key locations, or gridded SILO data.

- Land use maps to identify areas where alternative recharge estimation methods should be used (see Table 5).
- Observation well hydrographs to match against rainfall statistics (to confirm relationship between rainfall and recharge).
- Land use information, both current and past, especially in areas where changes in land use are thought to be responsible for groundwater trends (plantation forestry areas and areas of large scale irrigation development).
- Any information about the potential influence of point source recharge and extreme recharge events.

Table 5. Proposed methodology for applying recharge to different land uses in model

Land use	**Proposed recharge methodology**
Dryland/un-irrigated pasture	Recharge based on SILO rainfall data as outlined above. Recharge only applied during ‘winter rainfall months’ (i.e. ~April – September).
Native vegetation	Recharge applied at a set rate of 10 mm/y, as reported values range from 5 – 20 mm/y (see Table 2). Note: the accepted value for management purposes is 0 mm/y.
Irrigation	Receive rainfall recharge the same as dryland areas, but flood irrigation areas should receive additional recharge during ‘summer irrigation months’ (i.e. ~ October – March). Initially set at 20% of the volume of water applied, following the approach taken in the Padthaway model developed by Aquaterra (2008), however this may be altered during calibration.
Hardwood forestry	Receive rainfall recharge in the same way as dryland areas, but amount reduced by 78%. If information is available regarding the date of plantation establishment, this reduction may be staggered as in the Coles and Short model (Aquaterra, 2010).
Softwood forestry	Receive rainfall recharge in the same way as dryland areas, but amount reduced by 83%. If information is available regarding the date plantation establishment, this reduction may be staggered as in the Coles and Short model (Aquaterra, 2010).
Water bodies/urban areas	No recharge applied.

9.6. EVAPOTRANSPIRATION (NON-FORESTRY)

Regionally, evapotranspiration rates are not well understood. Previous modelling approaches have treated evapotranspiration in non-forestry areas as a process that only affects shallow watertables (generally where the depth to water is less than 2-3 m). Maximum evapotranspiration rates are set based on site specific information, and extinction depths set at 2-3 m. Initially, maximum evapotranspiration will be set at 500mm/y for the entire region, with an extinction depth of 2 m. Initial model runs will show how significant evapotranspiration is in controlling hydraulic heads and groundwater flow, and comparisons will be made with the volumes estimated by Paydar et al. (2009). If additional information becomes available through the Diffuse Impacts Project work, these ET rates may be incorporated into the model as required.

9.7. GROUNDWATER EXTRACTION

As described in Section 6.4.1.1, metered groundwater extraction data only exists for the LLC PWA from about 2007. Prior to this, records of groundwater use are based on estimated use. Estimates of use go back to 1998 for the whole LLC PWA, and back to 1985 for the areas formerly known as Comaum-Caroline PWA and Naracoorte Ranges PWA.

Extraction from 2007 – 2010 will be based on metered records, obtained from the South East Meter Database System (SEMDMS). In many cases, extraction data from the SEMDMS will be related to a drillhole recorded in the State drillhole database (SA Geodata), so extraction depth should be able to be assigned from this. Where drillholes have not already been assigned to meters, they will be manually created in the model, and given a depth based on the depth of nearby extraction wells.

Extraction data prior to 2007 will have to be based on estimates. Initially, existing estimates from recent years could be compared to current metered records, to ensure that estimates of use are not unrealistically different to metered records. The date of drillhole construction may also be obtained from SA Geodata and used to 'introduce' extraction wells into the model. To test that this method of 'introducing' wells into the model realistically simulates the expansion of irrigation in the LLC, total extraction volumes over time will be compared to estimated trends in use (Fig. 23). If some uncertainty in modelled and estimated trends in use arises, historical aerial imagery could be consulted to understand the difference.

Irrigation extraction in the model will be averaged over an approximate 'summer irrigation season.' That is, all extraction wells will be assigned constant daily pump rates between October and March.

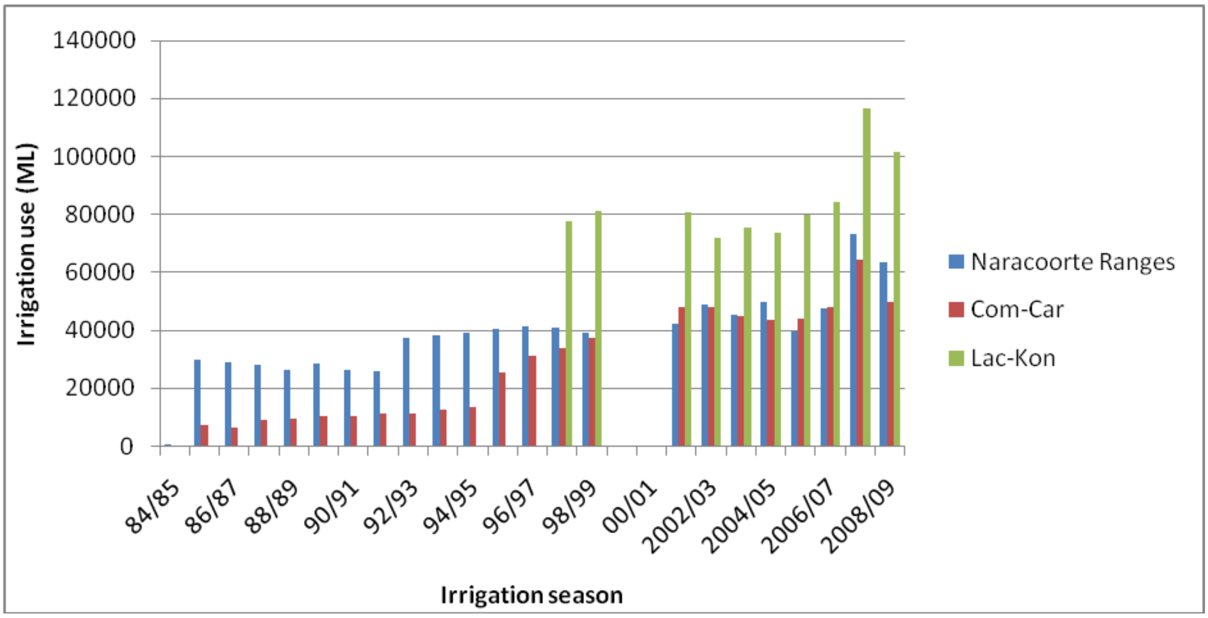

Figure 23. Expansion in estimated irrigation use in the LLC PWA

9.8. IMPACTS OF PLANTATION FORESTRY

The method for incorporating the impacts of plantation forestry in the regional model is yet to be decided and this will be done early in Phase 2 of the project in consultation with stakeholders and the Technical Reference Group. It is important that the method used be consistent or comparable between the regional model and any smaller-scale models and this must be carefully considered. One possible methodology is that employed in the recent model of the Wattle Range (Coles-Short) area (model WR2010), developed for DFW by Aquaterra (2010). In this model, the impact of direct extraction by forestry is not limited to areas where the depth to water is <6m, but applied to all areas occupied by commercial plantations. Extraction rates were implemented as 'negative recharge' in the model, and rates varied over a theoretical 'crop rotation' cycle to give average extraction rates of 1.82 ML/ha/y under blue gum plantations, and 1.66 ML/ha/y under pine plantations. Recharge interception was dealt with in a similar fashion, with recharge values decreasing to 0 mm/y over a plantation cycle. Table 6 and Table 7 give examples of the extraction and recharge models used for blue gum plantations in the Wattle Range model (taken from Aquaterra, 2010).

Table 6. Groundwater extraction model for blue gum plantations in Wattle Range model (Aquaterra, 2010)

		All values expressed as ML per hectare		
	forest rotation year	annual extraction	cumulative extraction	annualised extraction value
	year	ML/ha	ML/ha	ML/ha/year
planting	1	0	0	1.82
	2	0	0	1.82
	3	0	0	1.82
canopy closed	4	0.91	0.91	1.82
	5	1.82	2.73	1.82
	6	2.73	5.46	1.82
	7	3.64	9.1	1.82
	8	3.64	12.74	1.82
	9	3.64	16.38	1.82
clear fell	10	3.64	20.02	1.82
clean up	11	0	20.02	1.82

Table 7. Groundwater recharge model for blue gum plantations in Wattle Range model (Aquaterra, 2010)

		All values expressed as percentage of management area recharge rate (MARR)		
	forest rotation year	as per cent of MARR	cumulative	annualised value
planting	1	120	120	21.8
	2	80	200	21.8
	3	40	240	21.8
canopy closed	4	0	240	21.8
	5	0	240	21.8
	6	0	240	21.8
	7	0	240	21.8
	8	0	240	21.8
	9	0	240	21.8
harvest	10	0	240	21.8
clean up (single rotation)	11	0	240	21.8
		Recharge impacts for a coppiced regeneration for second harvest		
	12	0	0	0
	13	0	0	0
	14	0	0	0
	15	0	0	0
	16	0	0	0
	17	0	0	0
clear fell	18	0	0	0
clean up	19	0	0	0

It is anticipated that there will be projects commencing in the near future that will seek to better quantify plantation water use at different spatial and temporal scales. Depending on the timing of the work, this may provide an improved basis for representing forestry impacts in the model.

9.9. GROUNDWATER-SURFACE WATER INTERACTIONS

While fully-coupled surface water-groundwater models are seen as ideal tools to assess interactions, the availability of appropriate data sets and capabilities of current modelling platforms limit our ability to build a fully coupled model in Phase 2 of this project. However, the MODFLOW groundwater modelling platform contains a number of mechanisms for incorporating surface water – groundwater interactions.

9.9.1. DRAINS AND CREEKS

It is expected that drains and creeks in the South East will be modelled using the MODFLOW Drains Package. This package builds the drain (based on its elevation) into the model domain. The water level in the drain is set based on observations, and losses or gains to/from groundwater are calculated based on the hydraulic gradient between surface water and groundwater, and the conductivity of the material lining the drain. Surface water modelling has been conducted as part of the Regional Flow Management Strategy , and results of this can be used to estimate in-flows to the drain along defined sections, which can then be compared to model results through the zone budget function in Visual Modflow. It is envisaged that calibration will be achieved by altering the drain conductance value. This will help give a first order estimate and assessment of surface water-groundwater interactions in the South East.

It is recognised that there are small areas where drains may be losing systems, i.e. where the water table has dropped below the base of the drains. These will need to be represented differently in the model and the methodology for this will be developed during Phase 2 of the project.

9.9.2. WETLANDS

In the initial stages, how well the model represents the occurrence of entirely groundwater-fed wetlands (i.e. where the water table is at or above the ground surface), through the interaction between topography, groundwater levels and evapotranspiration, compared with mapped wetlands, will be assessed. In many cases, this may adequately represent the occurrence and dynamics of wetlands in the South East. Some permanent water bodies may be better represented using the MODFLOW Lakes package.

9.10. MODEL CALIBRATION

The objectives of the model are outlined in Section 7.2. As its main purpose is as a tool for investigating processes and our understanding of the conceptual model, a detailed formal calibration is not required at this stage. However, the model's performance against observation well hydrographs will be assessed and model parameters will be optimised within reasonable limits. Assessment will predominantly be against hydrographs showing regional trends, as local-scale processes will not be represented in this model. However, a process of assessment of model performance against a range of hydrographs will be carried out to gain a better understanding of the knowledge gaps and smaller-scale modelling requirements.

As well as comparison with observation well hydrographs, the model outcomes will also be compared with measured and estimated components of the water balance, e.g. measured surface water flows, lateral inflow and outflow, inter-aquifer leakage and groundwater flow rates (e.g. those estimated by Harrington et al. (1999)).

10. CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations from Phase 1 of the Lower South East Water Balance Modelling Project are as follows:

- The Lower South East is a region rich in hydrologic data and knowledge and therefore any conceptual and numerical models developed for water resource management will be well-founded, albeit not without limitations.

- A groundwater flow model is the appropriate platform for a water balance model given that the system is groundwater dominated and that groundwater models have facilities for including surface water-groundwater interactions at the level that is required and justified by the data available.

- A feasibility study for fully coupled surface water – groundwater modelling should be carried out as soon as possible if this is still considered to be a desirable option.

- To address the needs of water resource management, identified through consultation with stakeholders, and through consultation with the Technical Reference Group, a three-stage modelling process should be carried out, involving:

    - Development of a regional scale water balance model (groundwater modelling platform) to address regional scale objectives (Phase 2 of this project).

    - Development of a modelling framework, including the regional water balance model itself, guidelines for the development of local scale "hotspot" models, and a methodology for allowing feedback between the two scales of model.

    - Development of local scale "hotspot" models to address local scale objectives.

- An approach for development of the regional water balance model has been formulated as part of this report.

- Any hydrological models are limited by the quality and quantity of data available to them and the level of understanding of the relevant processes. The following priority areas for improvement of the conceptual model of the Lower South East have been identified, based on (a) the current level of knowledge and (b) the likely impacts on outcomes of regional and local scale models (see Table 4 for the full list of knowledge gaps identified):

    - Groundwater flow around numerous faults in the region (i.e. impacts of faults on aquifer geometry, properties and preferential vertical flow).
    - Occurrence and magnitude of vertical leakage between unconfined and confined aquifers.

    - Spatial and temporal variability of SW-GW interactions around drains.

    - ET from shallow water tables.

    - Spatial and temporal variability in direct extraction of groundwater by forest plantations
    - Coastal and offshore groundwater discharge (includes understanding of seawater intrusion).

- This list will be revised based on outcomes of the proposed regional water balance model (Phase 2 of this project) and it is also anticipated that the proposed Phase 2 will allow us to be more specific about the work that needs to be carried out in these general areas.

APPENDICES

A. CURRENT ADMINISTRATIVE BOUNDARIES FOR THE SOUTH EAST, INCLUDING CONFINED AND UNCONFINED AQUIFER MANAGEMENT ZONES

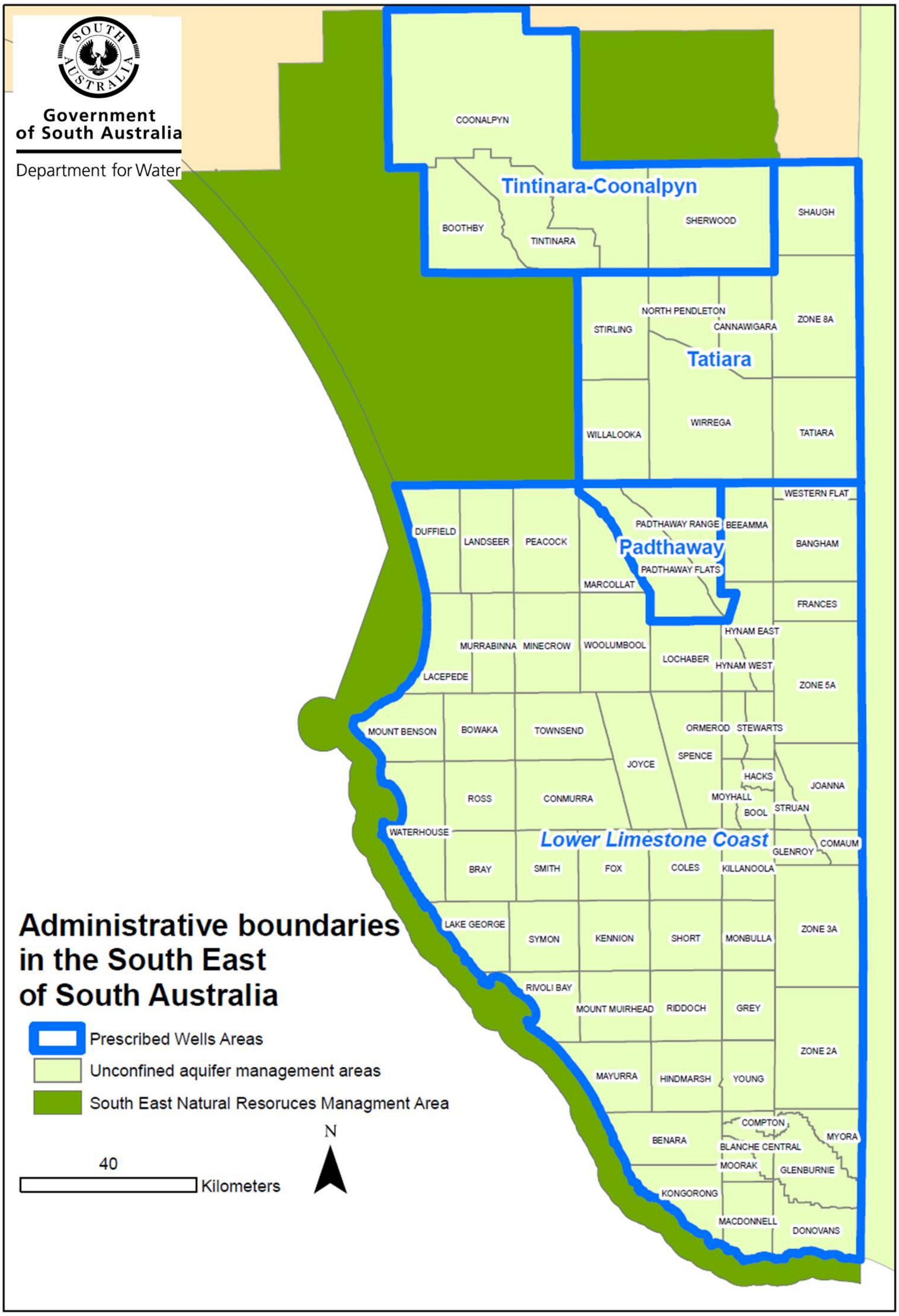
Government
of South Australia
Department for Water
Administrative boundaries
in the South East
of South Australia
Prescribed Wells Areas
Unconfined aquifer management areas
South East Natural Resouces Managment Area
40
Kilometers
N
Tintinara-Coonalpyn
Tatiara
Padthaway
Lower Limestone Coast
COONALPYN
BOOTHBY
TINTINARA
SHERWOOD
SHAUGH
NORTH PENDLETON
CANNAWIGARA
STIRLING
ZONE 8A
WILLALOOKA
WIRREGA
TATIARA
WESTERN FLAT
PADTHAWAY RANGE
BEEAMMA
DUFFIELD
LANDSEER
PEACOCK
BANGHAM
PADTHAWAY FLATS
MARCOLLAT
FRANCES
HYNAM EAST
MURRABINNA
MINECROW
WOOLUMBOOL
LOCHABER
HYNAM WEST
LACEPEDE
ZONE 5A
MOUNT BENSON
BOWAKA
TOWNSEND
ORMEROD
STEWARTS
SPENCE
JOYCE
HACKS
JOANNA
ROSS
CONMURRA
MOYHALL
BOOL
STRUAN
WATERHOUSE
COMAUM
GLENROY
BRAY
SMITH
FOX
COLES
KILLANOOLA
LAKE GEORGE
ZONE 3A
SYMON
KENNION
SHORT
MONBULLA
RIVOLI BAY
MOUNT MUIRHEAD
RIDDOCH
GREY
ZONE 2A
MAYURRA
HINDMARSH
YOUNG
COMPTON
BENARA
MYORA
BLANCHE CENTRAL
MOORAK
GLENBURNIE
KONGORONG
MACDONNELL
DONOVANS

Figure A-1.

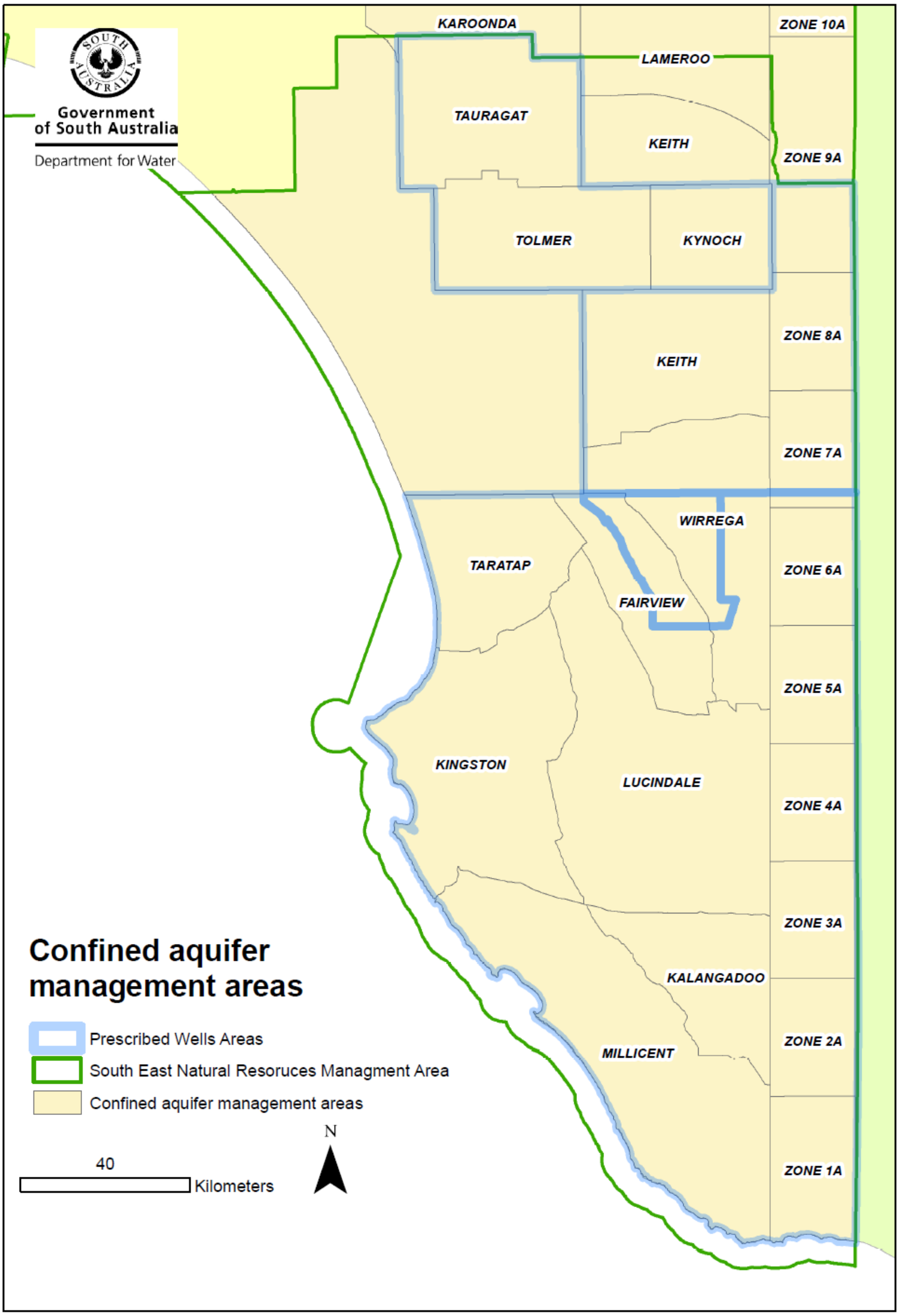
Government of South Australia
Department for Water
KAROONDA
LAMEROO
ZONE 10A
TAURAGAT
KEITH
ZONE 9A
TOLMER
KYNOCH
ZONE 8A
KEITH
ZONE 7A
WIRREGA
TARATAP
FAIRVIEW
ZONE 6A
ZONE 5A
KINGSTON
LUCINDALE
ZONE 4A
ZONE 3A
KALANGADOO
ZONE 2A
MILLICENT
ZONE 1A
Confined aquifer management areas
Prescribed Wells Areas
South East Natural Resoruces Managment Area
Confined aquifer management areas
40
Kilometers
N

Figure A-2.

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

~	approximately equal to
bgs	below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity
pMC	percent of modern carbon
ppb	parts per billion
ppm	parts per million
ppt	parts per trillion
w/v	weight in volume
w/w	weight in weight

GLOSSARY

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

Artesian — An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure, and hence rises in any well which penetrates the overlying confining aquifer

Baseflow — The water in a stream that results from groundwater discharge to the stream; often maintains flows during seasonal dry periods and has important ecological functions

Basin — The area drained by a major river and its tributaries

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

^{14}C — Carbon-14 isotope (percent modern Carbon; pmC)

Catchment — That area of land determined by topographic features within which rainfall will contribute to run-off at a particular point

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

DFW — Department for Water (Government of South Australia)

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ecosystem — Any system in which there is an interdependence upon, and interaction between, living organisms and their immediate physical, chemical and biological environment

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Hydrology — The study of the characteristics, occurrence, movement and utilisation of water on and below the Earth's surface and within its atmosphere; see also 'hydrogeology'

Irrigation — Watering land by any means for the purpose of growing plants

Irrigation season — The period in which major irrigation diversions occur, usually starting in August–September and ending in April–May

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Obswell — Observation Well Network

Piezometer — A narrow tube, pipe or well; used for measuring moisture in soil, water levels in an aquifer, or pressure head in a tank, pipeline, etc

Prescribed water resource — A water resource declared by the Governor to be prescribed under the Act, and includes underground water to which access is obtained by prescribed wells. Prescription of a water resource requires that future management of the resource be regulated via a licensing system.

Prescribed well — A well declared to be a prescribed well under the Act

PWA — Prescribed Wells Area

PWRA — Prescribed Water Resources Area

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DWLBC, respectively. DWLBC should be contacted for database extracts related to groundwater

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Water allocation — (1) In respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence. (2) In respect of water taken pursuant to an authorisation under s.11 means the maximum quantity of water that can be taken and used pursuant to the authorisation

WAP — Water Allocation Plan; a plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with the Act

Water-dependent ecosystems — Those parts of the environment, the species composition and natural ecological processes, that are determined by the permanent or temporary presence of flowing or standing water, above or below ground; the in-stream areas of rivers, riparian vegetation, springs, wetlands, floodplains, estuaries and lakes are all water-dependent ecosystems

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

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