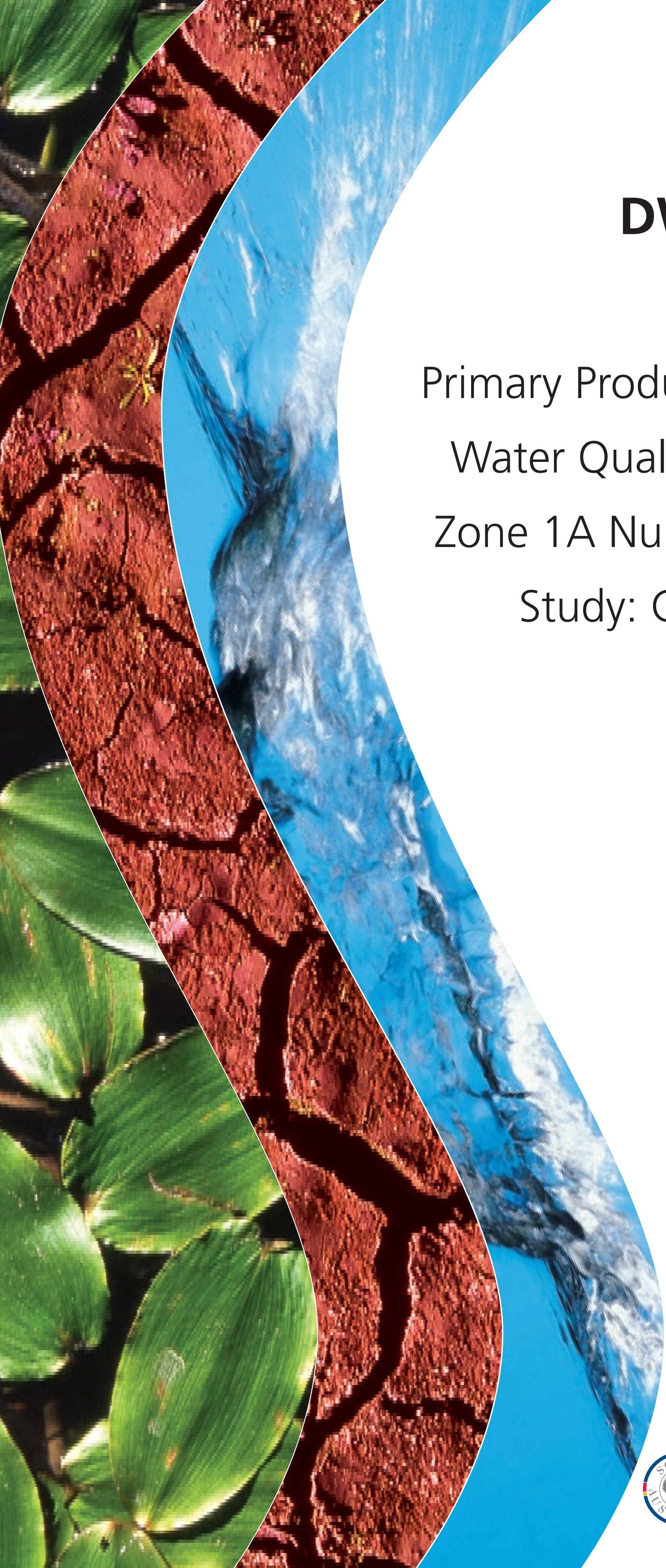

DWLBC REPORT

Primary Production to Mitigate Water Quality Threats Project Zone 1A Numerical Modelling Study: Conceptual Model Development

2008/12

Government of South Australia
Department of Water, Land and
Biodiversity Conservation

Primary Production to Mitigate Water Quality Threats Project

Zone 1A Numerical Modelling Study: Conceptual Model Development

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Resource Allocation Division
Department of Water, Land and Biodiversity Conservation

January 2007

Report DWLBC 2008/12

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Department of Water, Land and
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FOREWORD

South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Rob Freeman
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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EXECUTIVE SUMMARY

The Department of Water Land and Biodiversity Conservation (DWLBC) together with the South Australian Research and Development Institute (SARDI) and the Flinders University of South Australia (FUSA) commenced the collaborative “Primary Production to Mitigate Water Quality Threats” Project in March 2006. The project aims to assess and quantify the sources of diffuse pollution and the risk of groundwater contamination throughout the South East Region to mitigate the impacts of primary production on water quality.

The objective of this initial report is to construct a conceptual model for the first study area of the project, which is Zone 1A in the Border Designated Area. The conceptual model is based on previous work and incorporates factors such as aquifer properties, recharge rates and land use. This information is used to compile a preliminary water balance for the unconfined aquifer in Zone 1A. The water balance incorporates the major inflows and outflows to Zone 1A. The inflows considered include groundwater inflow at the northern boundary of the study area, rainfall recharge, upward leakage from the confined aquifer, stormwater drainage and irrigation return flows. Outflows include groundwater outflow at the coast, plantation forest recharge interception and plantation forest groundwater use, groundwater extraction via pumping for irrigation, stock and domestic use, surface water evaporation from the Blue Lake and downward leakage to the confined aquifer.

The water balance indicates a net loss of 41 700 ML/y from the unconfined aquifer in Zone 1A, which equates to an average drop in head of 0.4 m/y across the entire study area (assuming an average specific yield of 0.15). Considering the broad scale and approximate nature of our water balance calculations, the fact that it is within the same order of magnitude as observed water level declines (up to 0.4 m/y across some parts Zone 1A) suggests that the conceptual model adequately represents the hydrogeologic system in Zone 1A at a regional scale. The information provided in this report will be used as a basis for the construction of a 3D numerical groundwater flow and contaminant transport model of the groundwater system in the study area. This will require a more accurate representation of intermediate to local scale processes and calibration to individual groundwater hydrographs will be carried out during that phase of the project.

Several factors such as a lack of information on inter-aquifer leakage and diffuse groundwater discharge at the coast may limit the accuracy of a detailed numerical groundwater flow model. The impacts of these can be further assessed during the numerical modelling phase of the project. The largest impact on the contaminant transport model is likely to be caused by poor reliability of information and data sets regarding aquifer properties, particularly for the unconfined aquifer where there is large spatial variability.

1. INTRODUCTION

1.1 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 aims to mitigate the impacts of primary production on water quality throughout the South East of South Australia. The specific objectives of the project are 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 above objectives will be achieved through a combination of unsaturated zone and saturated zone modelling of contaminant movement through the landscape. Maps of Generalised Watershed Loading Functions (GWLFs) for the chosen contaminants will be derived by FUSA and SARDI using maps of land use and soil type and the unsaturated zone model, LEACHM. These GWLFs will then be used by DWLBC as inputs for numerical groundwater flow and solute transport models, which will model the movement of the contaminants in the saturated zone. The saturated zone model will be constructed by DWLBC in MODFLOW using the Visual MODFLOW interface (Waterloo Hydrogeologic, Inc., 2005). This methodology can then be used to investigate the likely outcomes of a range of scenarios, for example:

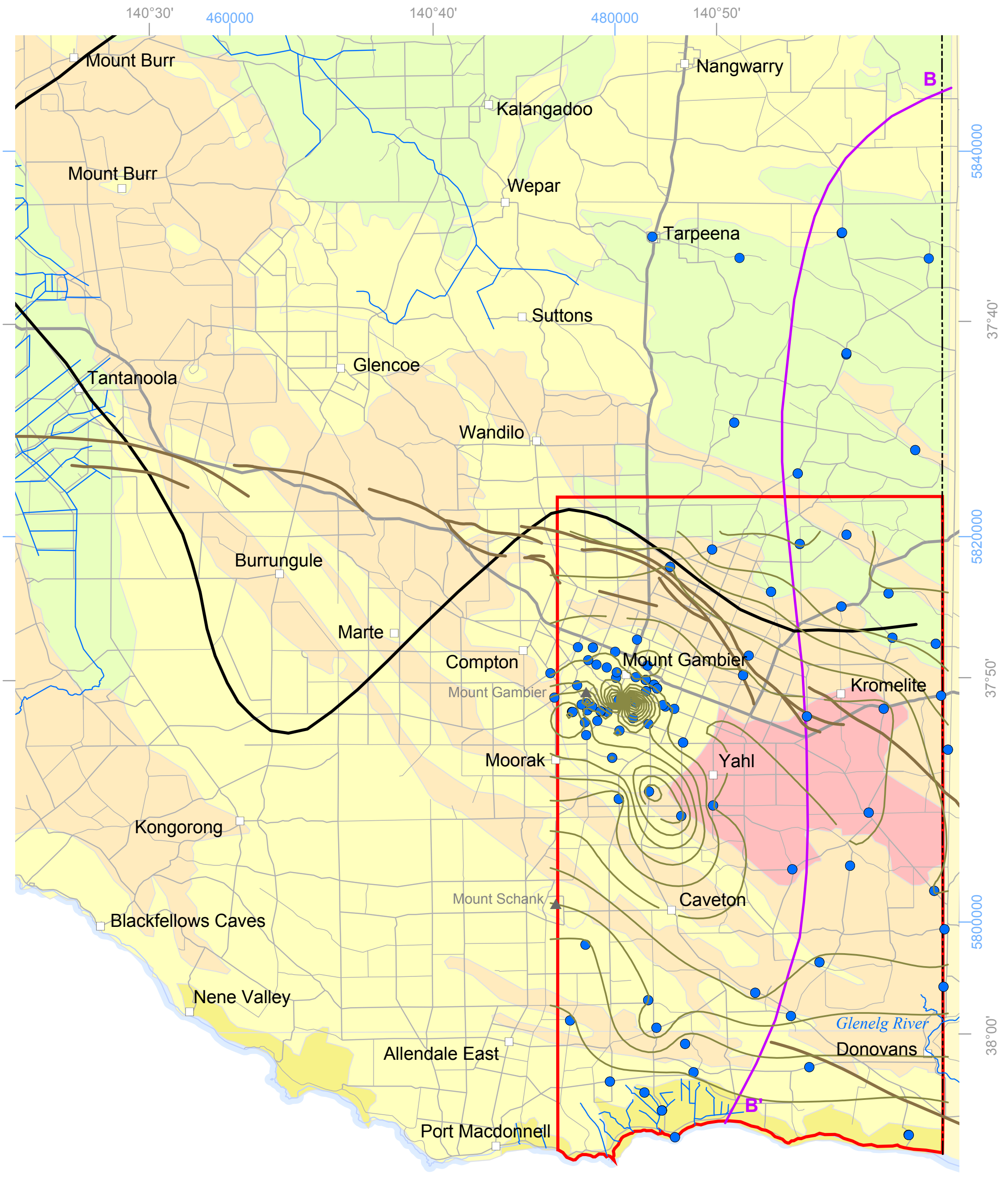
- Climate change.
- Changing groundwater extraction regime.
- Changes in land use.

For the purpose of the study, the South East has been divided into a number of regions to be modelled separately. The first region to be used as a trial for the methodology is 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 (Fig. 1). This report details the construction of the conceptual model for the groundwater system to be modelled in Zone 1A. A subsequent report will provide the details and outcomes of the numerical modelling exercise.

1.2 OBJECTIVES

The objectives of this report are to:

- Construct a conceptual model for the groundwater flow system to be modelled in Zone 1A of the Border Designated Area based on a review of previous work and all available data, including:
    - A stratigraphic model.



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Fault

Zero Head Difference (ZHD)

Surface water path

● Observation well

Topographic elevation contours (m)

Zone 1A study area

B B' Transect line

GEOLOGY

- Bridgewater Formation
- Coomandook Formation
- Padthaway Formation
- Saint Kilda Formation
- Semaphore Sand Member
- Marine limestones and unconsolidated sands

0 5 10 Kilometers

Projection: MGA Zone 54 Transverse Mercator
Datum: Geocentric Datum of Australia 1994
Produced by: Publishing Services
Primary Industries and Resources SA
Date: December 2006

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Zone 1A Numerical Modelling Study: Conceptual Model Development

SITE MAP

Figure 1

  - General aquifer and aquitard characteristics and hydraulic properties.
  - Important model boundary conditions.
  - Water inputs and outputs to the various stratigraphic units, including a water balance for the unconfined aquifer.
  - Trends in groundwater salinity.

This conceptual model will then be used directly as the basis for a numerical groundwater flow and solute transport model, the details and outcomes of which will be described in a subsequent report. Both the conceptual and numerical models from this study will also be used as a basis for future groundwater projects in Zone 1A.

1.3 METHODOLOGY

Part of the conceptual model development for Zone 1A involved reviewing existing reports on the region. The results of this review are summarised in the following sections of this report.

To construct the stratigraphic model, a review of all existing well logs was carried out, including observation wells, irrigation and water supply production wells and petroleum exploration holes in Zone 1A and within ~3 km of its boundary. These data were obtained both from the State database, SAGeodata, and from information held by DWLBC as microfiche records. The collated data were used to create a stratigraphic model using the Rockworks^{TM} software (Rockware Inc., 2004). The visual representation of the conceptual model provided by Rockworks^{TM} was considered necessary due to the complex nature of the geology in Zone 1A region.

To investigate the accuracy of the conceptual model, and for future validation of the numerical model, a water balance for the unconfined aquifer was constructed using the best information available on the following:

- Groundwater inflows and outflows to/from Zone 1A.
- Rainfall recharge, including direct recharge via the Blue Lake.
- Upward leakage from the confined aquifer.
- Downward leakage to the confined aquifer.
- Groundwater extraction.
- Evapotranspiration.
- Irrigation return flows.
- Drainage bore inputs and stormwater run-off.
- Surface water evaporation.
- Recharge interception and groundwater use by forestry.

2. PREVIOUS STUDIES IN ZONE 1A

A number of previous hydrogeological studies in the South East have either focused on or at least included Zone 1A region. Information from these studies listed below have been summarised and used to develop the conceptual model for Zone 1A.

- Allison and Hughes (1978) used the environmental tracers, chloride and tritium to estimate rainfall recharge to the unconfined aquifer under dryland pasture at a selection of sites with different soil types in the region of Zone 1A. Results estimated mean annual diffuse recharge to the area between 47–270 mm/y and were based on using a range of different hydrologic units corresponding to surface geology and soil type.
- Love (1991) used environmental isotopes with hydrochemistry and hydrogeological data to evaluate recharge, water movement and palaeohydrology of Cainozoic groundwater systems in the Gambier Embayment of the Otway Basin. This was a regional scale study, with the objectives of (1) developing a conceptual understanding of groundwater flow in the Gambier Limestone and Dilwyn Sands aquifers, (2) identifying the recharge areas for the Dilwyn Sand, (3) determining groundwater residence times in the Dilwyn Sand aquifer and (4) developing a conceptual model for groundwater flow in the two aquifers in response to climate change.
- Stadter and Yan (2000) constructed a three layer numerical model of the region to the south of Mt Gambier, with the objective of assessing whether the Permissible Annual Volume (PAV) could be increased above the levels of vertical recharge. The model recommended that the PAV should be retained and not increased due to possible environmental impacts.
- Brown et al. (2001) investigated, through hydrochemical, isotopic and hydraulic data from a series of multi-piezometer wells, the mechanisms of vertical recharge to the confined aquifer in the Nangwarry and Tarpeena area, a known area of confined aquifer recharge. They concluded, based on ^{14}C data for the confined aquifer, that recharge to the aquifer along a downward gradient might be controlled by faulting, fractures and sinkholes through the aquitard.
- Mustafa and Lawson (2002) reviewed the reliability of available information on the hydraulic properties of the Tertiary Limestone aquifer in the lower South East. They found that the majority of transmissivity and specific yield values estimated for the lower southeast were all of low reliability. As a result, they calculated transmissivity values from specific capacity data, finding that when plotted spatially with water level contours, low transmissivity values were found to be overlying the steep gradient north of Mount Gambier and high values coincided with the flat gradient to the south of Mount Gambier.

3. PHYSICAL CHARACTERISTICS OF ZONE 1A

3.1 TOPOGRAPHY

The Gambier Embayment 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. 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. 1). 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. 1).

3.2 CLIMATE

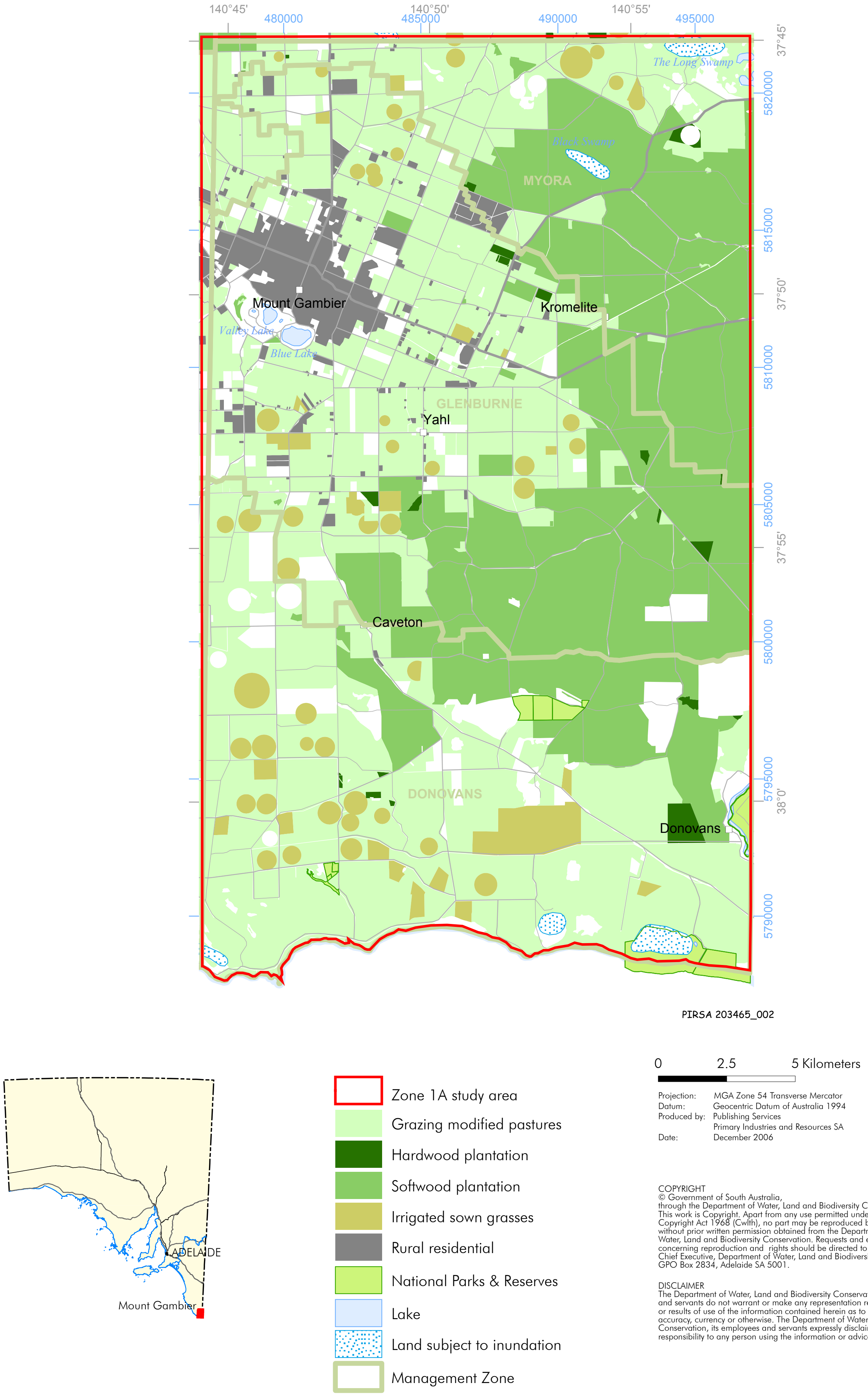
The South East maintains a Mediterranean climate of hot dry summers and cool wet winters. Daily maxima can be as high as 40°C in the summer months and as low as 10–12 °C during the winter months. Annual rainfall in Zone 1A ranges between ~500–900 mm/y.

3.3 LAND USE

There are four main land-use types in the study area which account for ~80% of the total area of Zone 1A; estimates include grazing modified pastures (~50%), softwood and hardwood plantation (~20%), and irrigated sown grasses (~10%) (Fig. 2).

3.4 SURFACE WATER

The only significant natural surface watercourse in the lower southeast is the Glenelg River, located to the east of the study area (Fig. 1). Natural watercourses are generally impeded by the low slope of the topography and the transverse dune system, resulting in the occurrence of numerous swamps, lakes and sinkholes in inter-dunal corridors. Numerous karst sinkholes 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. Swamps 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.



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Produced by:	Publishing Services Primary Industries and Resources SA
Date:	December 2006

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Zone 1A Numerical Modelling Study: Conceptual Model Development
MAJOR LAND USES IN ZONE 1A

Figure 2

4. GEOLOGICAL SETTING

The study area is located in the Gambier Embayment 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. The Gambier Embayment 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.

Sedimentation in the Gambier Embayment commenced in the Late Palaeocene to Middle Eocene with the Paralic Wangerrip Group (Pebble Point Formation, Pember Mudstone and Dilwyn Formation) (Fig. 3). Increasing marine influence led to the deposition of the Middle to Late Eocene marginal-marine Nirranda Group (Mepunga Formation and Narawaturk Marl), and the Late Eocene to Middle Miocene marine Gambier Limestone (Fig. 3).

A number of prominent structural features occur within the Gambier Embayment 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 Embayment, and the west – north west trending Tartwaup Fault occurs in the south of the basin. The latter runs through the study area (Fig. 1). 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 believed to be associated with the Tartwaup Fault. The locations and significance of these in relation to groundwater flow are being studied as part of a separate investigation. An important structural high, the Gambier Axis (Kenley, 1971) occurs to the north of the Tartwaup Fault and to the north of Zone 1A study area.

A sea level rise during the Pleistocene resulted in a number of marine transgressions that extended as far 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. Continued uplift during the Pleistocene also resulted in volcanic activity in the region, depositing lava flows and tuffs (Cook et al., 1977; Sheard, 1983).

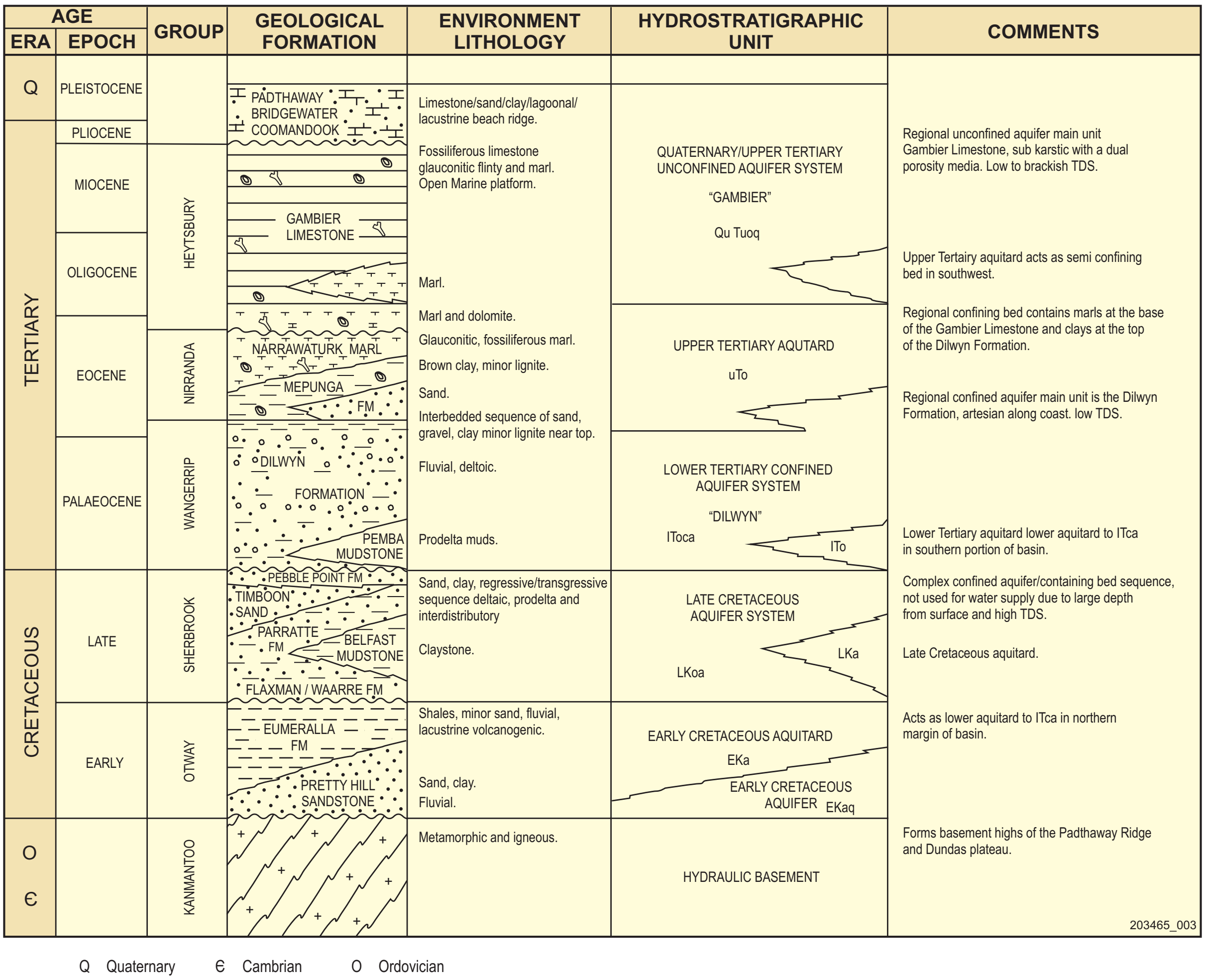

Figure 3. Schematic hydrostratigraphic column (Love, 1991)

5. HYDROGEOLOGY OF ZONE 1A

5.1 OVERVIEW AND STRATIGRAPHIC MODEL OF ZONE 1A

Groundwater of the Gambier Embayment occurs in a number of different hydrogeological systems in the Cainozoic and Cretaceous sequences (Fig. 3). 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 (Fig. 3). 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 (Fig. 3). 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 Embayment is wedge shaped, thickening from north to south to up to 5000 m offshore. The Cainozoic groundwater system itself can be up to 1000 m thick near the southern coast.

The conceptual hydrostratigraphic framework for Zone 1A model was compiled using 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 DWLBC. A large proportion of these records do not include surface elevation information and this was extracted from topographic maps, with a vertical resolution of 10 m across most of the study area and 1 m in the immediate vicinity of Mount Gambier.

In order to visualise the hydrostratigraphic framework for the conceptual model and check the consistency of the data, a three-dimensional stratigraphic model was created using the Rockworks^{TM} software (Rockware Inc., 2004) (Figs 4a–b). The top unit of the model represents a combination of topsoil or weathered material (including the Saint Kilda Formation, Semaphore Sand Member and unconsolidated sands shown on Fig. 1) and the Quaternary Bridgewater Formation, which occurs predominantly in the northern part of the study area (Fig. 1). The Gambier Limestone has been divided into three sub-units, the Green Point, Camelback and Greenways members. This subdivision was made due to the availability of good stratigraphic logs showing reliable distinctions between these members, and a knowledge that their hydraulic properties differ. Although distinctions were made in the logs between the five sub-units of the Green Point member (known as Units 1–5), these were not distinguished in the model due to a reduction in the consistency of the data and a lack of knowledge about the variation in hydraulic properties across these sub-units. The Dilwyn Clay, Mepunga Formation and Narawaturk Marl, for the purpose of the conceptual model, were represented as one aquitard unit. Inter-aquifer leakage across this aquitard is believed to be negligible in the study area and hence the top of the aquitard will form the lower

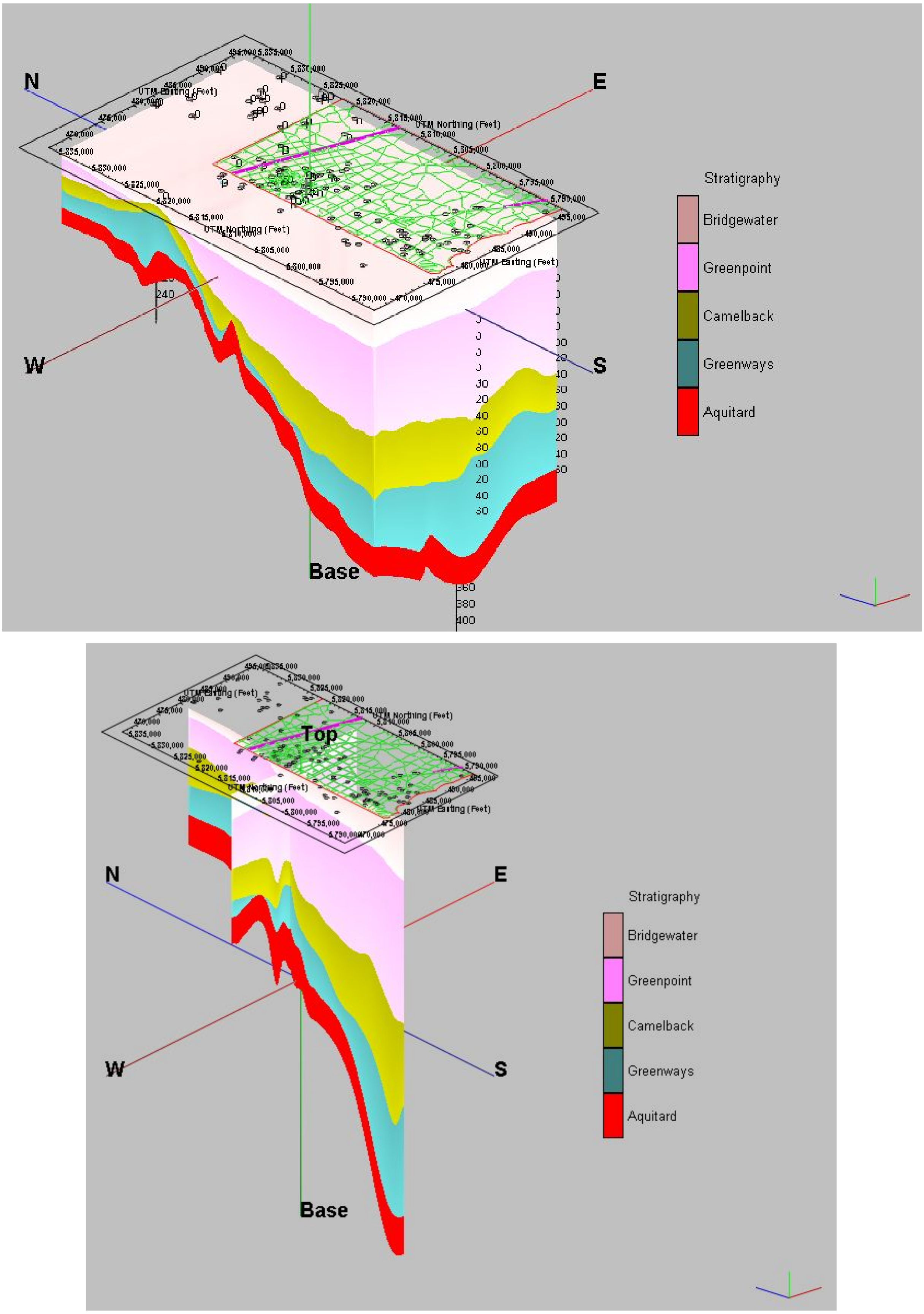

Figure 4. (a) Hydrostratigraphic model of the lower South East incorporating the Zone 1A region. (b) North-south cross section of the hydrostratigraphic model of the lower South East incorporating Zone 1A.

boundary for the conceptual model. Leakage of groundwater to or from the confined aquifer may occur via the faulting described earlier, however this has not yet been quantified.

The stratigraphic model shows two areas of uplift in the region of the Tartwaup Fault and a thickening of the Gambier Limestone (Green Point, Camelback and Greenways members) to the south of this, forming a wedge-shaped aquifer. The effects of a second fault in the south of the study area can also be seen.

The hydrogeological characteristics of the individual aquifer and aquitard systems are described in detail in the following sections. The main units considered are:

- The Bridgewater Formation.
- The Gambier Limestone.
- The Tertiary Aquitard.
- The Tertiary Confined Sand Aquifer.

For the purpose of this study, all aquifers and sub-units have been considered, even though the main aquifer of interest is the unconfined aquifer system, consisting predominantly of the Gambier Limestone. A detailed water balance is provided in section 5.4.7 for the unconfined aquifer.

5.2 TERTIARY CONFINED SAND AQUIFER (DILWYN FORMATION)

5.2.1 GENERAL CHARACTERISTICS

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

5.2.2 WATER SOURCES

5.2.2.1 Vertical Recharge

General

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). There is potential for this leakage in the northern part of the study area, where the hydraulic head in the unconfined aquifer is greater than that in the confined aquifer (Fig. 5). Further south, this trend is reversed at the Tartwaup Fault, with hydraulic heads in the confined aquifer being greater than those in the unconfined aquifer. The line defining the points at which this trend reverses and the hydraulic heads in the two aquifers are equal is known as the Zero Head Difference (ZHD) line (Fig. 5).

Downward leakage to the north of the ZHD line is supported by variations in groundwater chloride concentration observed in the confined aquifer along Transect BB' (Fig. 1), up to the ZHD line, which were attributed by Love (1991) to recharge inputs via downward leakage along the flow path. However, Brown et al. (2001) concluded, based on ^{14}C data for the confined aquifer, that the recharge area for the confined aquifer may be much smaller than that defined by the downward hydraulic gradient and may be controlled by faulting, fractures or sinkholes through the aquitard. A recharge area for the confined aquifer has been identified by the observation of relatively high confined aquifer groundwater ^{14}C activities (>40 pmC) (Brown et al., 2001). However, much of this area is now covered in softwood and hardwood forest plantations, which are likely to limit recharge to both the unconfined and

Figure 5. **Map of Potentiometric head difference between the confined and unconfined aquifers. Negative values indicate a potential for downward leakage between the two aquifers.**

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).

There is no potential for recharge to the confined aquifer from the unconfined aquifer to the south of the ZHD line, due to an upward hydraulic gradient in this region. Constant groundwater chloride concentrations, $\delta^{13}C$ signatures and low ^{14}C activities of confined aquifer groundwater support this (Love, 1991; Brown et al, 2001). There is a possibility of upward leakage from the deeper Cretaceous aquifer system, although no direct evidence of this exists (Love, 1991).

Recharge Via Conduits in the Gambier Limestone

Caves and fractures in the Gambier Limestone have been reported at depths of up to 150 m below the present water table. As the unconfined aquifer groundwaters are saturated with respect to calcite, dissolution of the Gambier Limestone to form these features must have occurred in the vadose zone rather than below the water table (Brown et al., 2001). This indicates that water tables have been much lower in the past than today. A possible consequence of this is an increase over time in recharge to the confined aquifer via conduits in the Gambier Limestone in those areas where a downward hydraulic potential allows this to occur.

Historical Recharge to the Confined Aquifer

Interpretation of carbon isotope and $\delta^{2}H$ and $\delta^{18}O$ data for the confined aquifer indicates that different climatic regimes have influenced the hydrogeologic system of the Gambier Embayment in the past (Love, 1991). To determine this, ^{14}C data were used to provide a chronological framework whilst variations in $\delta^{2}H$ and $\delta^{18}O$ signatures of groundwater were used to infer differences in climatic conditions during recharge. $\delta^{2}H$ and $\delta^{18}O$ data suggested two predominant recharge mechanisms for groundwater reaching the confined aquifer system:

- Rapid recharge via sinkholes or through very permeable soils. These data plot close to the Local Meteoric Water Line (LMWL)[1].
- Slower recharge, with more evaporation, due to storage in swamps and lower permeability soils. These data plot below the LMWL.

The relative importance of the two-recharge mechanisms appears to have changed over time. Confined aquifer groundwaters with ^{14}C ages greater than 10^4 years plot close to the LMWL, whilst younger groundwaters (from both the confined and unconfined aquifers) plot either close to or below the LMWL. This indicates that both mechanisms described above have been important during the last 10^4 years, but that evaporation was less important before that (Love, 1991). The relatively depleted stable isotope signatures of confined groundwaters to the south of the ZHD line, with ^{14}C ages greater than 10^4 years, suggest that these waters recharged under different conditions from the Holocene waters, possibly due to a colder climate or different atmospheric circulation patterns (Love, 1991).

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[1] The Local Meteoric Water Line (LMWL) is a line along which local rainfall samples plot on a $\delta^{2}H$ vs $\delta^{18}O$ diagram.

5.2.3 WATER OUTFLOWS

5.2.3.1 Groundwater Extraction

The majority of groundwater extraction for irrigation, stock and domestic use to the south of Mt Gambier is from the unconfined aquifer. However, there are six known water supply wells extracting from the confined aquifer, one owned by the Kraft cheese factory, two privately owned, and three owned by SA Water which supply the townships of Port MacDonnell and Mount Gambier (Stadter & Yan, 2000).

5.2.3.2 Offshore Groundwater Discharge

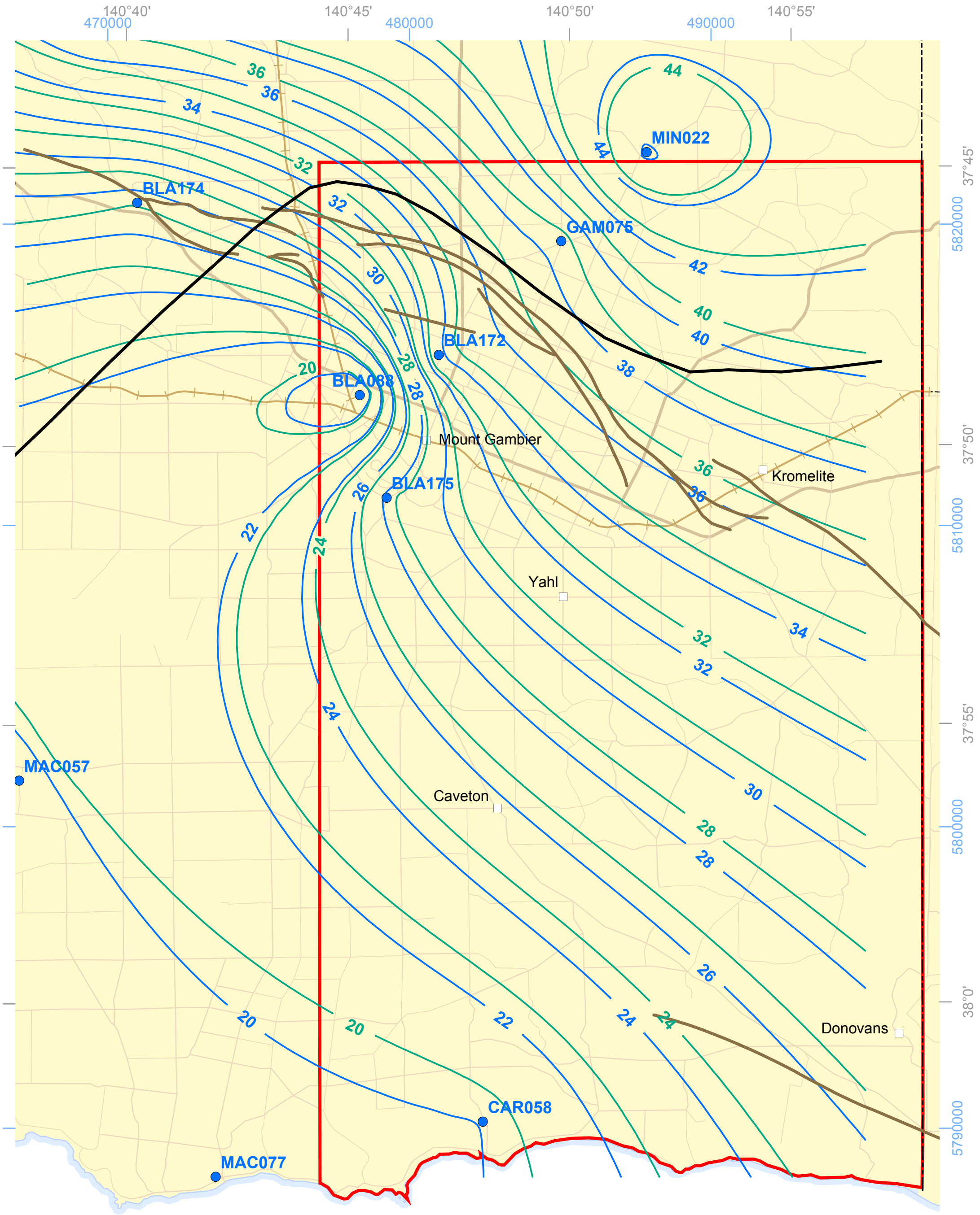
Upward discharge from the confined aquifer to the Gambier Limestone has been postulated to occur offshore, but no direct evidence of this exists (Blake, 1980). As it occurs beyond the boundary of the study area, any such discharge is not considered to be relevant to the conceptual model.

5.2.4 GROUNDWATER FLOW AND HYDRAULIC HEADS

Confined aquifer groundwater flow in the study area is towards the south-west, with potentiometric heads to the south of Mount Gambier being 5–20 m above those in the overlying unconfined aquifer and artesian flows occurring near the coast (Figs 6–7). There is a steep gradient zone around the Tartwaup Fault, which is thought to be due to a decrease in aquifer thickness on the upthrow side of the fault (Fig. 6). A groundwater divide occurs at the Gambier Axis to the north of the study area (cf. Love, 1991) and corresponds to a groundwater mound. This is thought to be a potential zone for preferred recharge to the confined aquifer due to the close proximity of the aquifer to the surface, a thin confining bed in this region and the coincidence of the groundwater mound with a groundwater sink in the unconfined aquifer (Love, 1991; Brown et al., 2001).

Residence times of water within the confined aquifer system are at least 30 000 years and the average velocity of groundwater between the ZHD point and the coast is estimated from ^{14}C data to be ~2 m/y (Love, 1991). The velocity calculated from hydraulic data was 1 m/y (Love, 1991). Such a discrepancy was considered to be unusual for a large sedimentary basin and, as there are no major groundwater extractions from the confined aquifer in the southern part of the study area, it is thought that the lower hydraulic velocity estimated may be due to the fact that sea level has risen since about 18 000 years ago. The ^{14}C velocity would then represent the median velocity from ~30 000 years ago until present (Love, 1991).

Hydrographs for the confined aquifer in the study area are generally quite stable, with seasonal fluctuations of up to 1 m (Fig. 7). A recent short-term decline in hydraulic head in observation well MIN17 (Fig. 7(g)), located in the confined aquifer recharge area to the north of study area, has been suggested to have occurred due to below average rainfall since 1992 (Brown et al., 2001). Observation well MIN21 (Fig. 7(h)), located below a forested area in that region, shows a rise in water table elevation between 1983 and 1992, probably due to harvesting of the timber and increased recharge following the Ash Wednesday bushfires of February 1983. A subsequent decline in water level is attributed to below average rainfall



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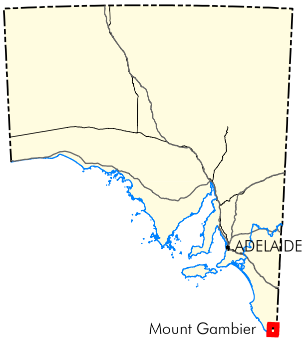

● Observation well

— Potentiometric head (m AHD) September 2005

— Potentiometric head (m AHD) March 2006

— Zero Head Difference (ZHD)

— Fault

🟥 Zone 1A study area

0 2.5 5 Kilometers

Projection: MGA Zone 54 Transverse Mercator
Datum: Geocentric Datum of Australia 1994
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Government of South Australia
Department of Water, Land and Biodiversity Conservation

Zone 1A Numerical Modelling Study: Conceptual Model Development

CONFINED AQUIFER POTENTIOMETRIC SURFACE DURING SEPTEMBER 2005 and MARCH 2006

Figure 6

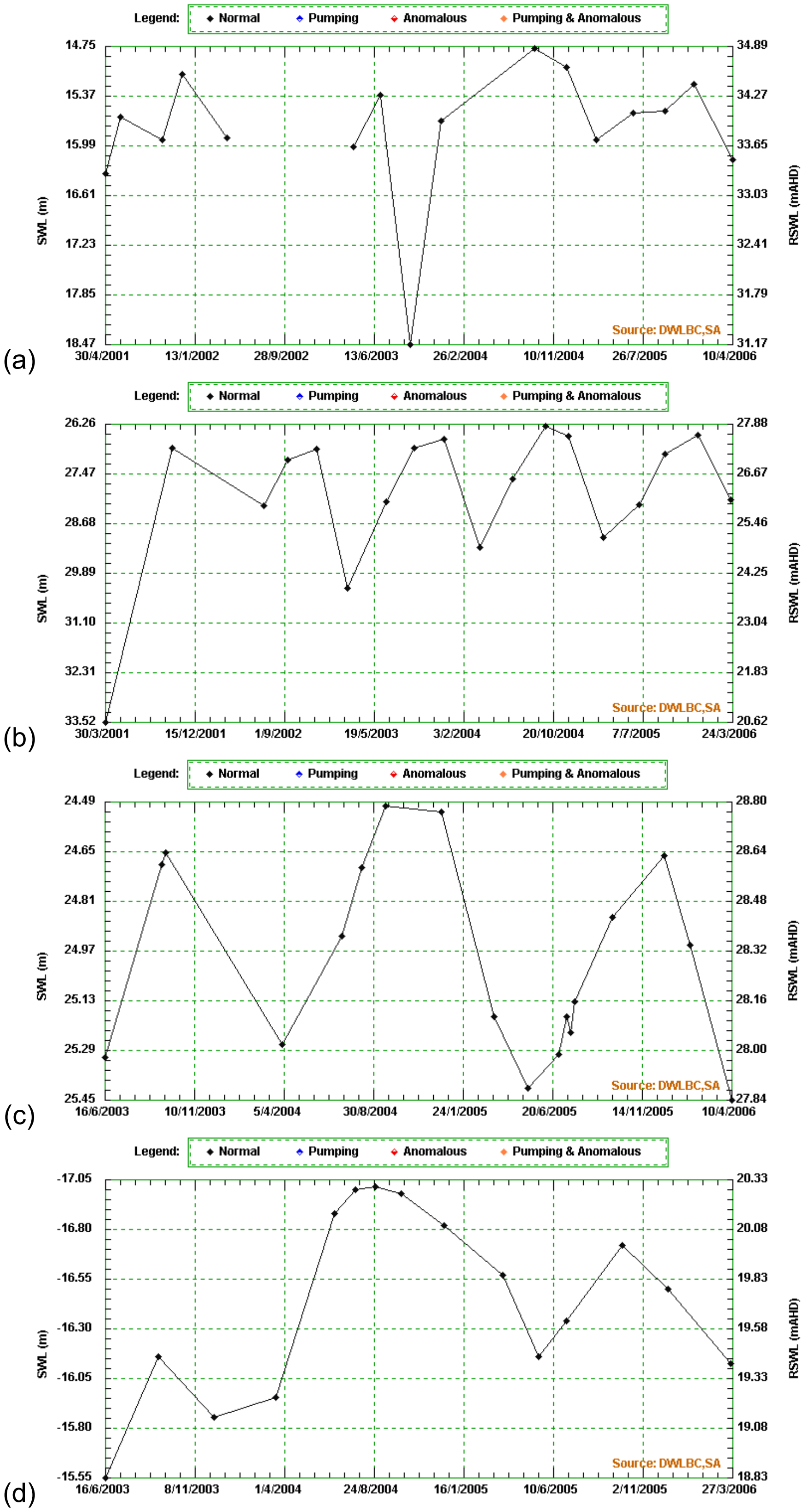


Figure 7. Representative groundwater hydrographs for the confined aquifer in the study area. (a) Observation well BLA172 (b) Observation well BLA174 (c) Observation well BLA175 (d) Observation well CAR058 (e) Observation well GAM075 (f) Observation well BLA256 (g) Observation well MIN017 (h) Observation well MIN021

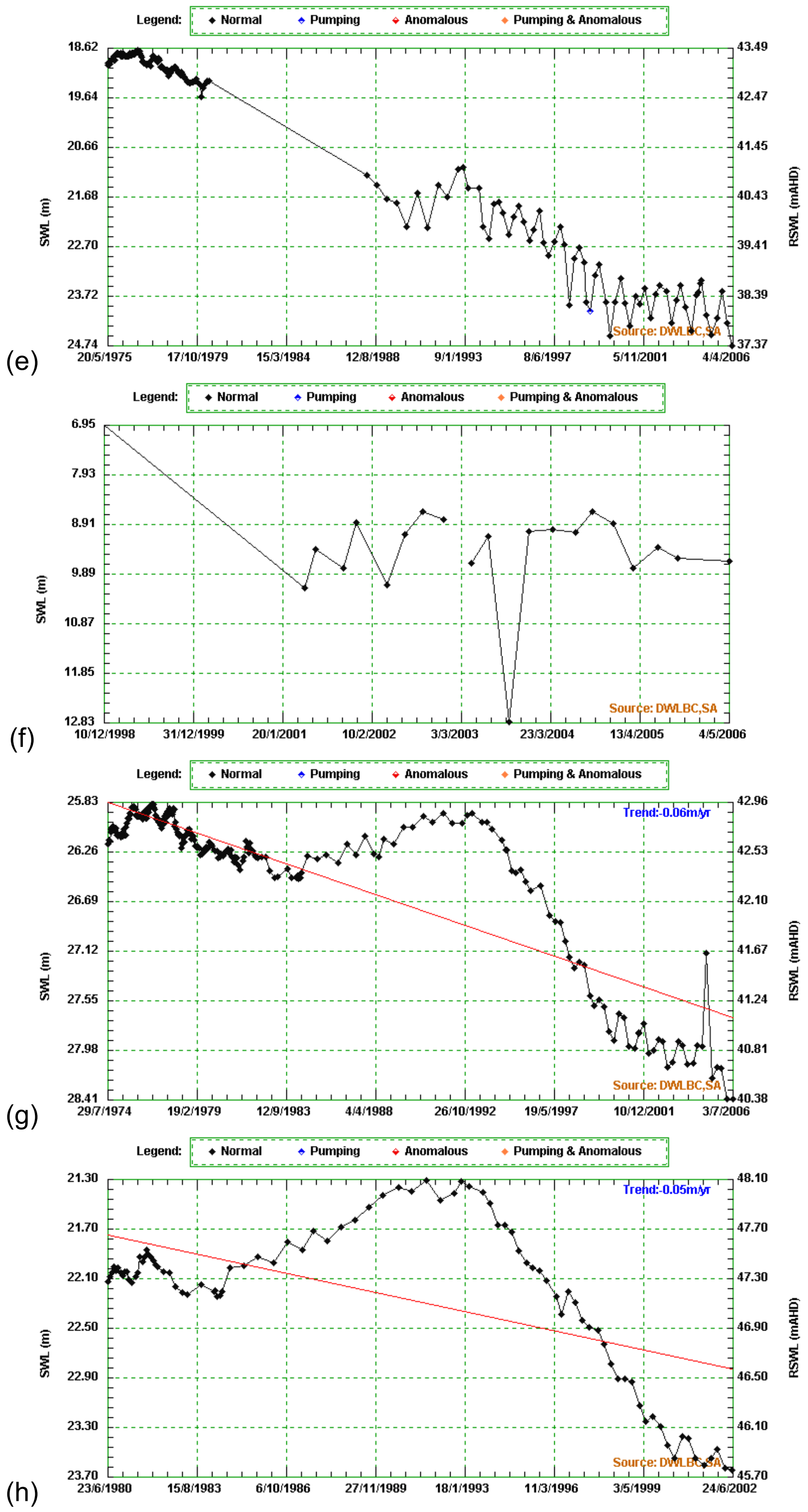


Figure 7. **Continued**

and reforestation in the area (Brown et al., 2001). The rapid response in the confined aquifer is attributed to pressure effects associated with changes in water level in the unconfined aquifer (Brown et al., 2001).

5.2.5 AQUIFER PROPERTIES

Hydraulic data for the confined aquifer is sparse, but what is available suggests that hydraulic properties are not as spatially variable as for the unconfined aquifers. For the entire Otway Basin region, porosity values estimated from borehole geophysical logs vary from 20–30%, whilst transmissivity estimates range from 200–1600 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.

5.2.6 GROUNDWATER SALINITY

Confined aquifer groundwater salinity in the study area is ~700 mg/L as TDS (Stadter & Yan, 2000).

5.2.7 SUMMARY OF TERTIARY CONFINED SAND AQUIFER CONCEPTUAL MODEL

The main features of the Tertiary Confined Sand Aquifer conceptual model can be summarised as follows:

- It is a multi-layered aquifer, comprising interbedded Tertiary sands, silts, gravels and carbonaceous clays.
- It generally increases in thickness towards the coast, being up to 800 m thick to the south of Mount Gambier.
- Recharge occurs predominantly via downward leakage from the unconfined aquifer and is probably controlled by fractures, faults and sinkholes through the aquitard. This occurs mainly to the north of the study area, where there is a downward hydraulic gradient between the unconfined and confined aquifers.
- Downward leakage from the unconfined aquifer is considered to be negligible across most of the study area.
- There may be some recharge occurring along the Tartwaup Fault.
- Much of the confined aquifer recharge area to the north of the study area is now covered by plantation forestry and recent recharge to both the confined and unconfined aquifers is therefore expected to be limited.
- There is little groundwater extraction from the confined aquifer.
- Groundwater flow is towards the southwest to the south of the ZHD line, with potentiometric heads between 5–20 m above those in the unconfined aquifer.

- Groundwater residence times are estimated to be at least 30 000 years, with an average velocity over this time scale of about 2 m/y. Due to sea level rise over the past 18 000 years, groundwater velocities are now lower now than in the past (~1 m/y).
- Hydraulic heads in the confined aquifer in the study area have been either really stable or gradually declining over the period of monitoring.
- Aquifer porosity values are estimated to be between 20–30%, with transmissivity ranging from between 200–1600 m^2/d.
- Hydraulic conductivity to the south of Mount Gambier has previously been estimated at between 0.5–10 m/d for modelling purposes.
- Groundwater salinity is ~700 mg/L.

5.3 UPPER TERTIARY AQUITARD (DILWYN CLAY, NARRAWATURK MARL AND MEPUNGA FORMATIONS)

5.3.1 GENERAL CHARACTERISTICS

The aquitard separating the Dilwyn Sands confined aquifer and the Gambier Limestone unconfined aquifer consists of poorly consolidated, fossiliferous and glauconitic marls and clays of the Narrawaturk Marl and Mepunga Formation and sands of the Mepunga Formation. These formations are often difficult to distinguish from one another due to rapid lateral facies interfingering (Love et al., 1990). Throughout the study area, the aquitard also includes the laterally intermittent marls of the Greenways Formation at the base of the Gambier Limestone, and brown to black clay and lignite horizons in the top of the Dilwyn Formation (Love, 1991).

The Upper Tertiary Aquitard has a generally uniform thickness of between 20–40 m in the study area, thinning out to the north in the Nangwarry area to less than 10 m due to elevation above the Gambier Axis. In the region to the south of Mount Gambier, the unit dips and generally thickens towards the south (Fig. 4).

5.3.2 GROUNDWATER FLOW

There is potential for downward groundwater flow across the aquitard to the north of the ZHD line (in the north of the study area) 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 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.

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. However, this was considered to be unlikely due to the presence of a 300 m thick aquitard between the two aquifers at this location. The location of a fault in that region (Fig. 1) 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.

5.3.3 AQUITARD PROPERTIES

Little information exists on the hydraulic properties of the 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 3.4×10^{-6} m/d and 7.2×10^{-6} m/d (Brown et al., 2001).

5.3.4 GROUNDWATER SALINITY

Little data exists on the salinity of groundwater in the Tertiary aquitard. However, the available data suggests that salinity is less than half that in both the overlying unconfined aquifer and the underlying confined aquifer at both the Nangwarry and Tarpeena sites of Brown et al. (2001). This further supported the theory that any flow across the aquitard must occur through cracks or fractures rather than via matrix flow.

5.3.5 SUMMARY OF TERTIARY AQUITARD CONCEPTUAL MODEL

The main features of the Tertiary Aquitard conceptual model can be summarised as follows:

- The aquitard includes the Narrawaturk Marl, Mepunga Formation and clays of the Gambier and Dilwyn Formations and consists mainly of poorly consolidated, fossiliferous and glauconitic marls and clays.
- It may also include low-yielding and non-continuous sand layers.
- The unit generally has a thickness of between 20–40 m, but thins out to the north towards the Nangwarry area and becomes thicker towards the south in the study area.
- Vertical flow across the aquitard may occur via faults or fractures. This is still poorly understood.
- Vertical hydraulic conductivity, measured near Lucindale in the northern portion of the Otway Basin, ranged between 10^{-7} m/d and 10^{-3} m/d.
- Vertical hydraulic conductivity of the Dilwyn Clay in the Nangwarry/Tarpeena area was measured to be between 3.4×10^{-6} m/d and 7.2×10^{-6} m/d.
- There is little data available on groundwater salinity in the Tertiary aquitard, but in some places it may be less than in the surrounding aquifers.

5.4 GAMBIER LIMESTONE (UNCONFINED AQUIFER)

5.4.1 GENERAL CHARACTERISTICS

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 300 m. 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 (see Section 5.5). The Gambier Limestone is divided into three main sub-units, the Greenways, Camelback and Green Point Members (Fig. 4). It often becomes marly and dolomitic towards the base, although the extent of this marl has not been mapped regionally due to a lack of penetrating wells (Love, 1991). Nevertheless, this unit has been mapped across Zone 1A (Lawson et al., in prep.).

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.

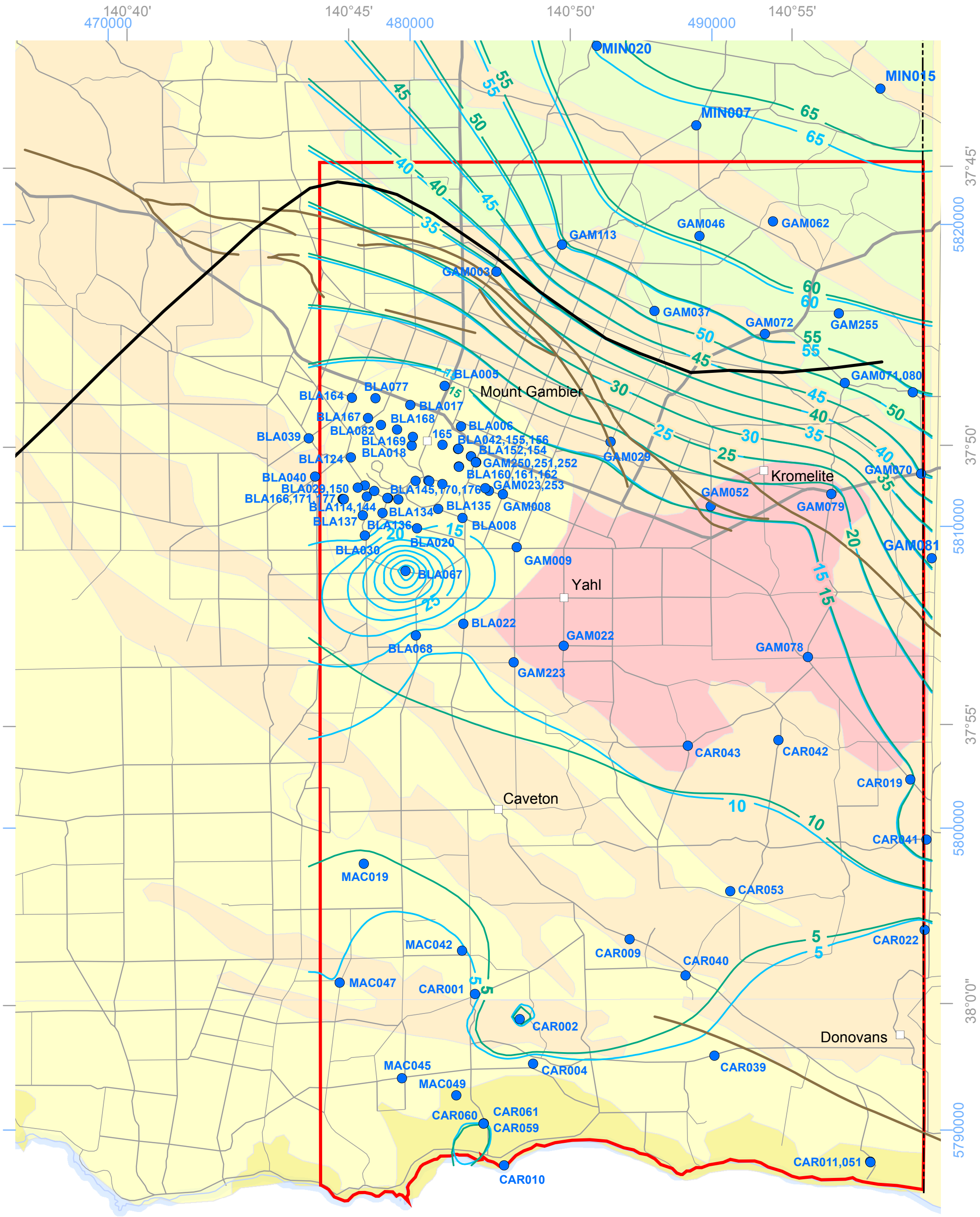
5.4.2 WATER SOURCES

5.4.2.1 Rainfall Recharge

General

Love (1991) suggests that the dominant inflow to the unconfined aquifer system is vertical recharge from rainfall. This occurs as both diffuse recharge through the soil matrix and point source recharge via surface discharge into numerous sinkholes and swamps (Love, 1991). A large spatial variability in the rate and salinity of vertical recharge to the unconfined aquifer was inferred through variations in groundwater chloride concentrations, δ^2H, δ^{18}O and ^{14}C signatures, particularly for the area along Transect BB' to the north of the ZHD line (Fig. 1) (Love, 1991). δ^2H and δ^{18}O data for Transect BB' were observed to lie on or below the meteoric water line on a δ^2H vs δ^{18}O diagram, indicating some evaporation, but with no discernable spatial trend. The exceptions were some more isotopically enriched groundwater's occurring in the inter-dunal corridors, indicating greater evaporation of recharge waters in those regions.

Groundwater hydrographs for the unconfined aquifer show seasonal fluctuations of up to 1 m, but generally less than 0.5 m, which are the result of rapid responses to recharge, even in areas with large irrigation withdrawals (Love, 1991) (Fig. 9). The rapid response is due to the shallow depth to water table (<10 m in inter-dunal areas) and permeable soils (Love, 1991).



0 2.5 5 Kilometers

GEOLOGY

●	Observation well and name
—	Potentiometric head (m) – September 2005
—	Potentiometric head (m) – March 2006
—	Zero Head Difference (ZHD)
—	Fault
🟥	Zone 1A study area

▨	Bridgewater Formation
▨	Coomandook Formation
▨	Padthaway Formation
▨	Saint Kilda Formation
▨	Semaphore Sand Member
▨	Marine limestones and unconsolidated sands

Projection:	MGA Zone 54 Transverse Mercator
Datum:	Geocentric Datum of Australia 1994
Produced by:	Publishing Services Primary Industries and Resources SA
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UNCONFINED AQUIFER WATER TABLE ELEVATION WITH SURFACE GEOLOGY

Figure 8

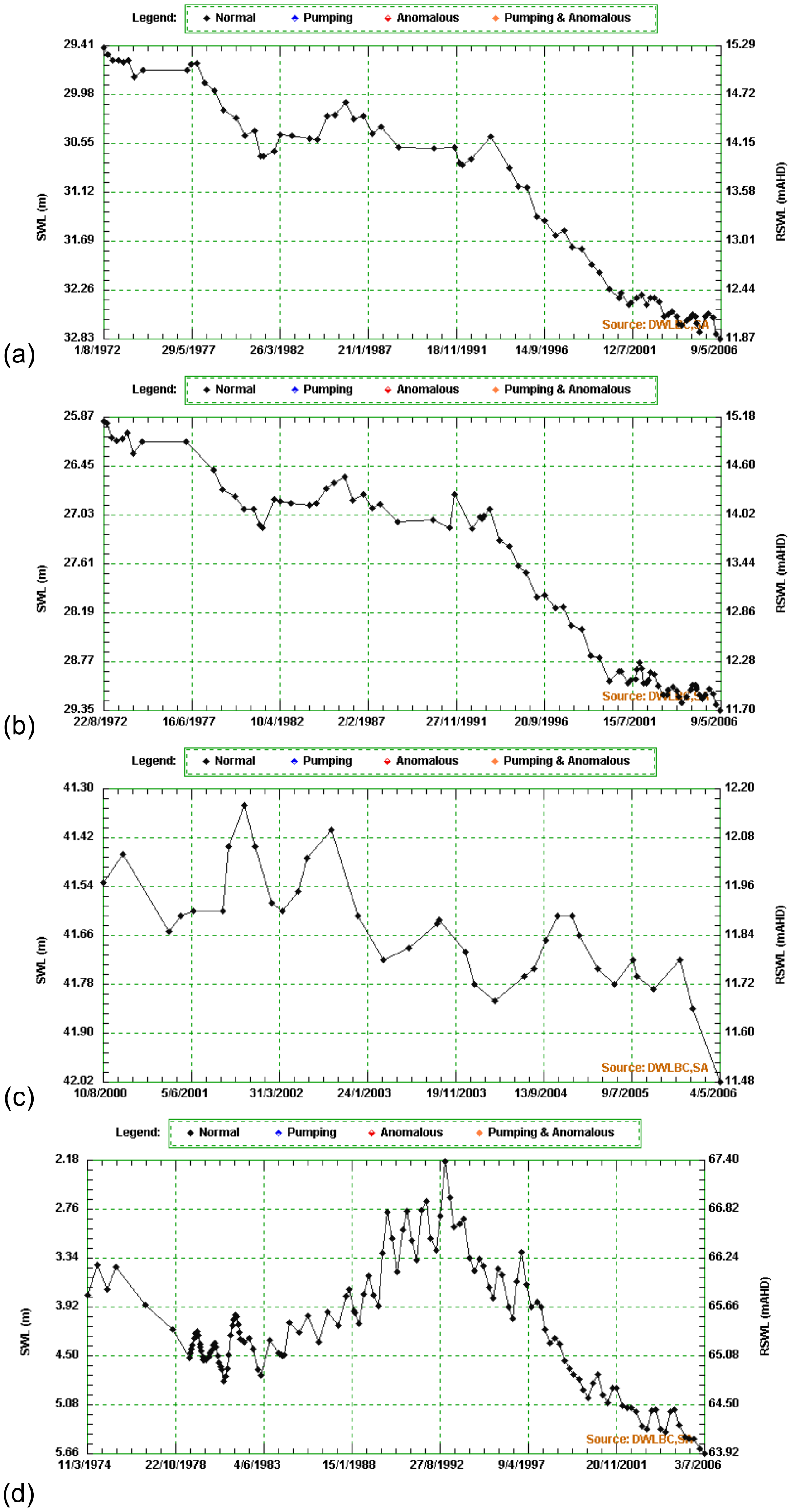
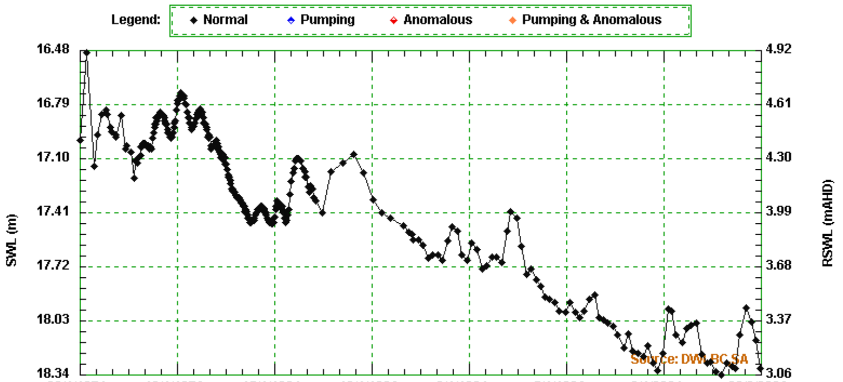
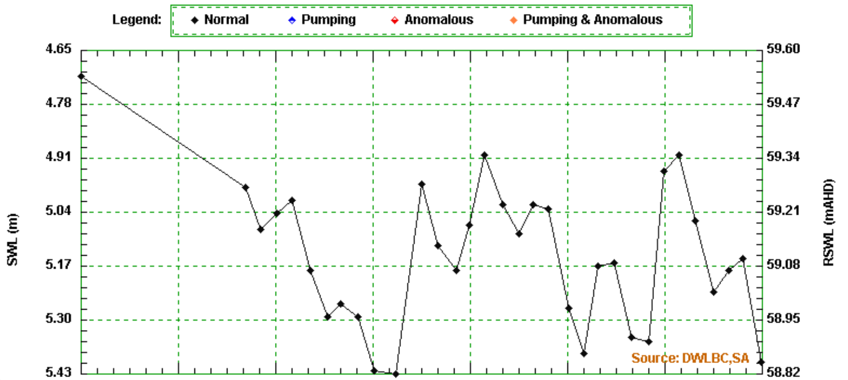


Figure 9. Representative groundwater hydrographs for the unconfined aquifer in the study area. (a) Observation well BLA020 (b) Observation well BLA042 (c) Observation well BLA170 (d) Observation well MIN016 (e) Observation well CAR022 (f) Observation well GAM255 (g) Observation well BLA077

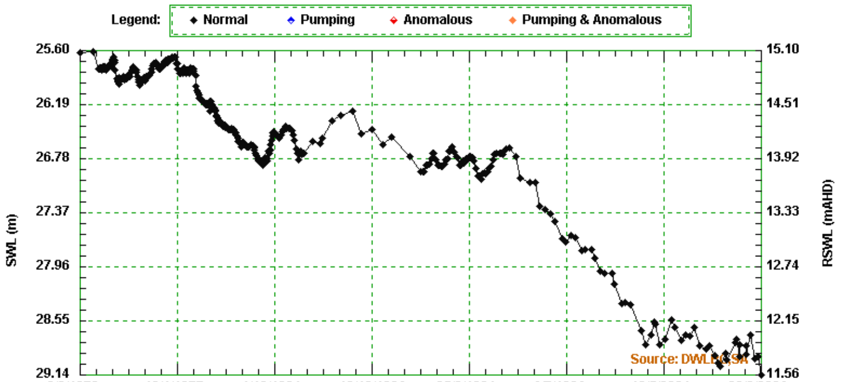
(e)



(e)



(f)

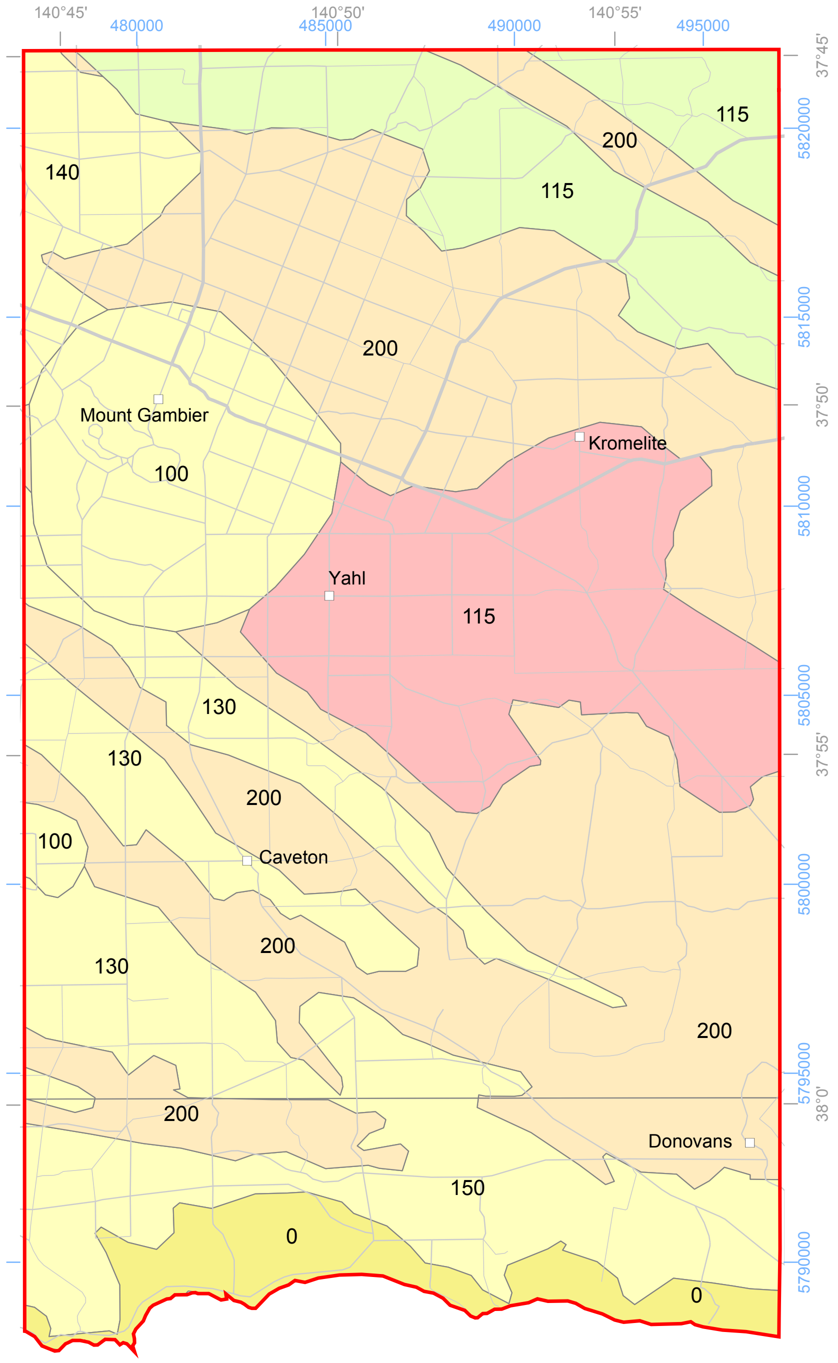


(g)

Figure 9. Continued

Recharge Rate Estimates

Using lysimeters, chloride and tritium techniques, Holmes and Colville (1970a&b) and Allison and Hughes (1978) estimated mean annual diffuse recharge for the study area to be between 47–270 mm/y, with all sites located on improved pasture. Allison and Hughes (1974) showed that local recharge is dependent on soil type. The field sites of Allison and Hughes (1978) covered a range of different “hydrologic units”, which corresponded to surface geology and the soil types of Blackburn (1959). These hydrologic units have been found to be represented sufficiently by a surface geology map and hence groundwater recharge zones can be roughly drawn based on this map (Brown et al., 2006) (Fig. 10).



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GEOLOGY

🟧 Bridgewater Formation

🟥 Coomandook Formation

🟩 Padthaway Formation

🟨 Saint Kilda Formation

⬜ Marine limestones and unconsolidated sands

□ Zone 1A study area

200 Recharge rate (mm/yr)

0 2.5 5 Kilometers

Projection: MGA Zone 54 Transverse Mercator
Datum: Geocentric Datum of Australia 1994
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RECHARGE ZONES DERIVED FROM A MAP OF SURFACE GEOLOGY AND THE DATA OF ALLISON and HUGHES (1978)

Figure 10

The recharge rate estimates of Allison and Hughes (1978) and the map shown in Figure 10 were used as the basis for the most recent determination of Permissible Annual Volumes (PAVs) for Zone 1A by Brown et al. (2006). This method results in a total recharge to the study area of 102 000 ML/y. Prior to that, the hydrograph fluctuation approach of Stadter (1989) and De Silva (1994) was used with estimated recharge rates ranging between 5–130 mm/y (Bradley et al., 1995) (Fig. 11). The latter results in a total recharge volume to Zone 1A of 31 000 ML/y (Bradley et al., 1995). There is a significant difference in the recharge volumes estimated by the two methods, some of which can be attributed to the incorporation of land use influences (particularly recharge interception by plantation forestry) in the latter method. The impacts of these differences in recharge totals on the overall water balance for the unconfined aquifer in Zone 1A will be discussed in Section 5.4.7.3.

In their model of the area to the south of Mt Gambier, Stadter and Yan (2000) applied the recharge estimates of Bradley et al. (1995), with recharge applied throughout the winter period, April to September (185 days) only.

Recent Changes to Groundwater Recharge

A change in land use over the past 130–150 years from native vegetation to cleared pasture has resulted in an increase in total recharge to the unconfined aquifer. Allison and Forth (1982) estimated that recharge in the study area has increased by ~40% since European settlement. Conversely, the plantation of *Pinus radiata* forests has caused a significant reduction in recharge to some areas (Holmes & Colville, 1970b; Allison & Hughes, 1972).

5.4.2.2 Upward Leakage

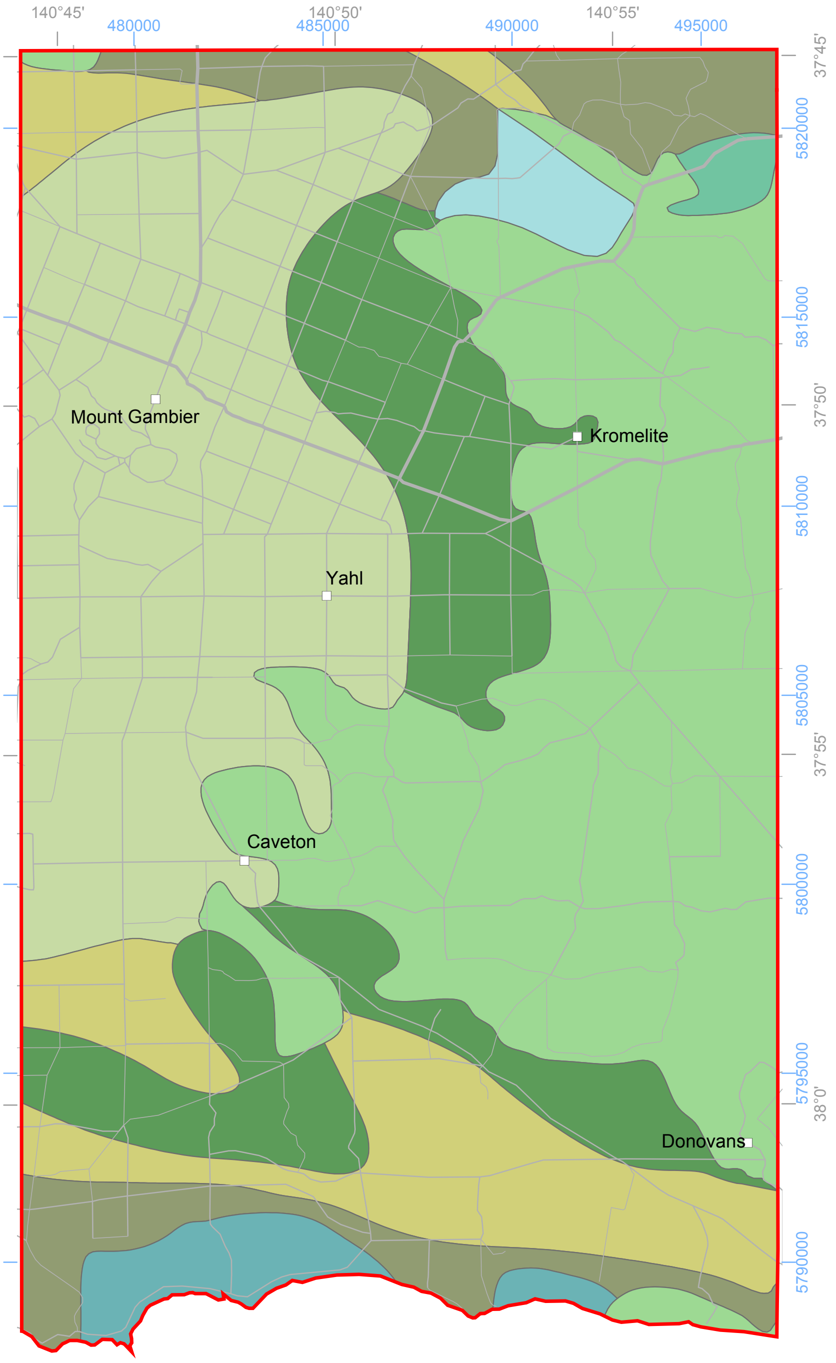
In all areas to the south of the ZHD line, the confined aquifer has a higher hydraulic head than the unconfined aquifer and, as a result, upward leakage between the two aquifers is possible throughout that region. Post depositional faulting has resulted in the potential for hydraulic connection between the unconfined and confined aquifers in the vicinity of the Blue Lake (Lawson et al., 1993).

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

5.4.2.3 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 Emmet (1995) have estimated that ~2800 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 3200 ML (J. Lawson, DWLBC, Pers. Comm., 2006).



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RECHARGE RATE (mm/yr)

🟩	5	🟩	65
🟦	15	🟨	80
🟦	40	🟫	90
🟩	60	🟩	130

0 2.5 5 Kilometers

Projection: MGA Zone 54 Transverse Mercator
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RECHARGE ZONES OF BRADLEY et al. (1995)

Figure 11

5.4.2.4 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 to be most significant beneath flood irrigation, which is absent in the study area. Some irrigation drainage may occur beneath pressurised systems such as pivot irrigation, overlying shallow soils south of Mount Gambier, but this has not yet been quantified.

5.4.3 WATER OUTFLOWS

5.4.3.1 Groundwater Extraction

Water losses from the study area were estimated using knowledge of groundwater extraction for stock and domestic use, irrigation and town and industry water supplies.

Groundwater extraction for irrigation was calculated from the 2003–04 Annual Water Use Return Statements (Latcham et al., in prep.) and equates to 19 004 ML/y. Industrial and town water supplies amount to ~5933 ML/y (Brown et al., 2006). Stock and domestic use is estimated to be 3900 ML/y (Brown et al., 2006).

In their model of the southern portion of Zone 1A, Stadter and Yan (2000) used spatial distributions of 1999 groundwater use and allocation data and local knowledge of irrigation sites to develop a distribution of groundwater extraction. The date of irrigation well construction was used to determine the commencement of irrigation at these sites, and a constant extraction rate, equivalent to that derived from 1998 water usage data, was applied.

5.4.3.2 Evapotranspiration

Evapotranspiration was applied in a numerical model of the area to the south of Mount Gambier by Stadter and Yan (2000). The values used were 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.

Recent work by the Volumetric Conversion Project (Latcham et al., in prep.) has shown that drainage below irrigation developments is negligible in Zone 1A and hence all groundwater extracted for irrigation (see Section 5.4.3.1 above) can be considered to be evapotranspired and lost from the system. Similarly, evapotranspiration of rainfall prior to recharge is included in estimations of recharge described in Section 5.4.2.1. Hence it is not considered necessary to include evapotranspiration as a separate component of the water balance for Zone 1A.

5.4.3.3 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 1. However, the spatial distribution and magnitude of this process is poorly understood. As described in Section 5.2.2.1 above, Brown et al. (2001) suggest that the area over which this 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. 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 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).

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 along cross section BB’, 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.

5.4.3.4 Impacts of Plantation Forestry on Groundwater

Softwood and hardwood forest plantations are now considered to be water users (Brown et al., 2006). There are large areas of softwood plantations in the study area and hence this is likely to have a significant impact on the water balance (Fig. 2).

Direct extraction of groundwater by forestry plantations, where they overly a water table less than 7 m deep, is estimated to be 2.6 ML/ha/y for softwood and 2.3 ML/ha/y for hardwood over the average growth span of a plantation from planting to clearing (Brown et al., 2006). There are few hardwood plantations in Zone 1A and those overlying water tables less than 7 m are negligible. Of the three Groundwater Management Areas present in Zone 1A (Myora, Glenburnie and Donovans), only the Myora Management Area contains softwood plantations overlying water tables shallower than 7 m. Here, based on the extraction rate of 2.6 ML/ha/y, 2600 ha of softwood plantations are estimated to use an average of 6760 ML of groundwater annually (Brown et al., 2006).

Interception of rainfall recharge, referred to as a forest recharge debit (Brown et al., 2006), is an additional mechanism 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 (Brown et al., 2006). The total volumes of forest recharge debits under softwood plantations are estimated to be 10 960 ML/y, 11 170 ML/y and 5600 ML/y in the Myora, Glenburnie and Donovans Groundwater Management Areas respectively, with a total of 27 730 ML/y for Zone 1A (Brown et al., 2006).

5.4.3.5 Surface Water Evaporation (Blue Lake)

The mean annual rainfall recorded at the Mount Gambier airport between 1942–2006 is 707 mm, with mean pan evaporation between 1970–2003 being 1336 mm/y. This results in a net evaporative loss from the ~70 ha surface of the Blue Lake of ~440 ML/y.

5.4.3.6 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/y 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/y 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 right along the coastline. However, the occurrence and magnitude of this and any groundwater discharge via offshore seepage is currently unknown.

5.4.4 GROUNDWATER FLOW

Groundwater flow in the unconfined aquifer in the study area is to the south or southwest, with discharge occurring at the coast (Fig. 8). A steep hydraulic gradient zone to the north of Mount Gambier coincides with the location of the Tartwaup Fault (Fig. 8). A groundwater divide occurs to the north of the study area due to uplift above the Gambier Axis (Love, 1991). The water table generally ranges between 5–25 m below ground level, but the water table is within 2 m of the ground surface adjacent the coast.

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 phreatic 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 years for shallow groundwater (between 1.5–2 m below the water table) in the Tarpeena and Nangwarry areas.

In a study of sediment cores from the Blue Lake at Mt Gambier, Leaney et al. (1991) found that, during the period 17 000–18 000 years ago, lake levels were probably around 65 m lower than today, with less than 5 m of water present in the lake at its deepest location. It follows that groundwater levels in the unconfined aquifer would have been correspondingly low during this time. The study also found that lake levels have been about the same as present for approximately the last 8000 years.

5.4.5 AQUIFER PROPERTIES

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 30–50% from borehole geophysics and 49–61% from measurements on outcrops (Andrews, 1974; Love, 1991). This data also includes the Padthaway and Bridgewater Formations (Love, 1991). More recent estimates of porosity from borehole geophysics are in the range of 8–12% for the Gambier Limestone, 15–20% for sandstone and 20–30% for fractured rock. Transmissivities determined from aquifer pump tests range from 200–>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).

Based on data from previous reports and production test results, hydraulic conductivity values between 10–300 m/d and specific yield values between 0.1–0.25 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 0.5–90 m/d and a specific yield value of 0.1 produced optimum results.

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. There were no data of high or medium reliability available for the study area. Of the data for the entire lower South East, transmissivities ranging between 35–560 m^2/d were considered to be of medium or high reliability. The majority of these values were between 200–500 m^2/d. 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 (Fig. 12). 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.

5.4.6 GROUNDWATER SALINITY

Groundwater salinity in the unconfined aquifer is generally less than 500 mg/L as TDS, although salinities in some areas close to the coast can be up to 1500 mg/L.

5.4.7 WATER BALANCE FOR THE UNCONFINED AQUIFER IN ZONE 1A

In order to improve our understanding of the conceptual model for Zone 1A and to provide a quantitative basis for our assessment of the numerical model outcomes, an overall water balance was calculated for the unconfined aquifer based on the information described in Sections 5.4.1 to 5.4.6. The methods of calculation of each of the components of the water balance are described below.

The water balance for the TLA in Zone 1A is represented schematically in Figure 13 and can be described by the following equation:

$$\Delta S = \sum \text{Inputs} - \sum \text{Outputs} \quad (1)$$

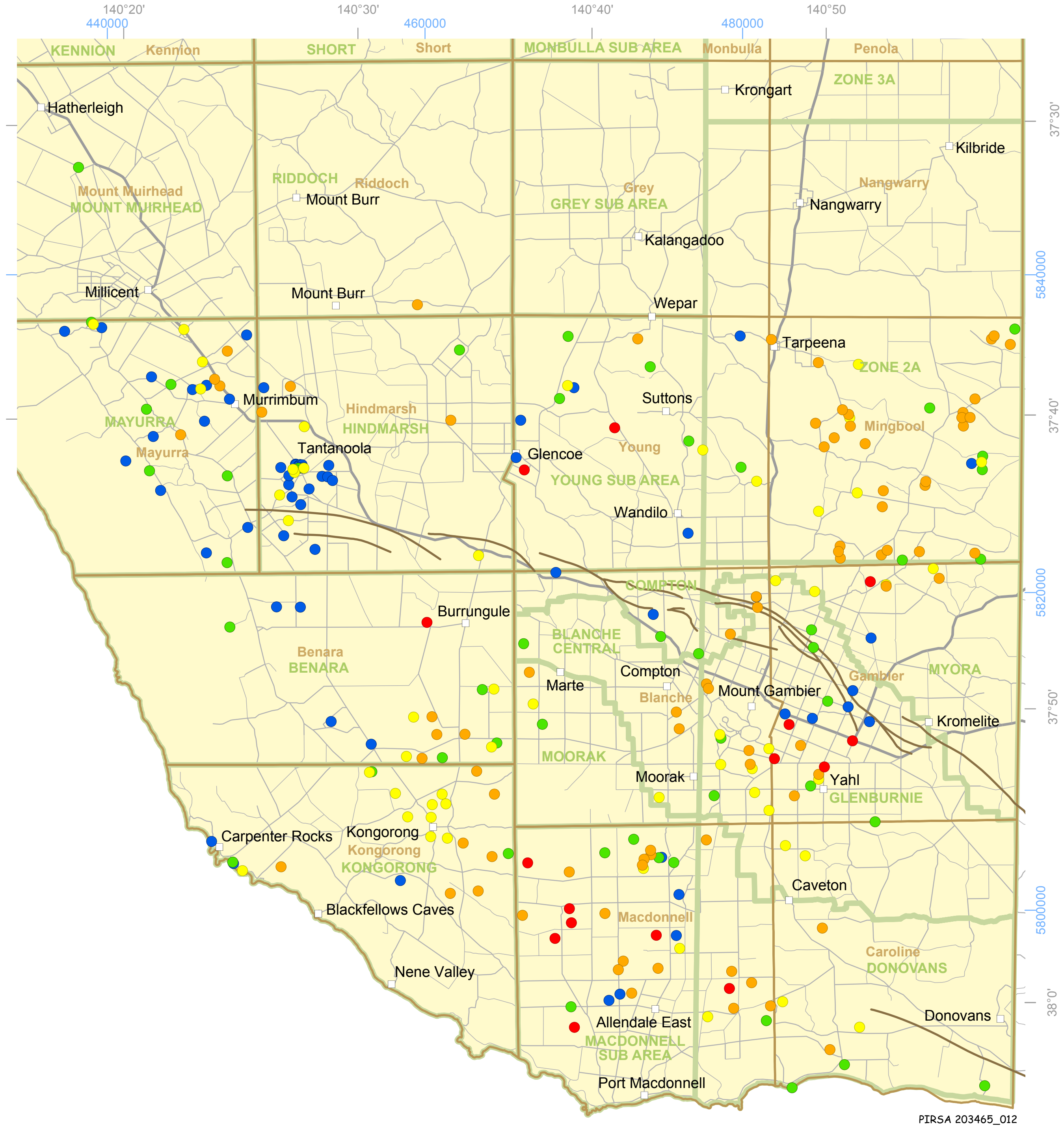
Where:

ΔS = change in groundwater storage

$\sum$ Inputs = Sum of all inputs into the study area

$\sum$ Outputs = Sum of all the outputs into the study area.

$$\text{Hence } \Delta S = (I + R + L_U + D + D_I) – (O + E + ET + L_D + F + E_{SW}) \quad (2)$$



Transmissivity values
(Mustafa and Lawson 2002)

- ● Greater than 5000 m²/day
- ● 1000-5000 m²/day
- ● 500-1000 m²/day
- ● 200-500 m²/day
- ● Less than 200 m²/day
- Fault
- Management Zone
- Hundred boundaries

Projection:	MGA Zone 54 Transverse Mercator
Datum:	Geocentric Datum of Australia 1994
Produced by:	Publishing Services Primary Industries and Resources SA
Date:	December 2006

Government of South Australia
Department of Water, Land and Biodiversity Conservation

Zone 1A Numerical Modelling Study: Conceptual Model Development

SPATIAL DISTRIBUTION OF UNCONFINED AQUIFER TRANSMISSIVITY VALUES

Figure 12

Where:

I = Groundwater inflow on the northern boundary

R = Diffuse recharge

L_U = Upward leakage from the TCSA

D = Recharge by drainage of stormwater

D_I = Irrigation drainage returns

O = Groundwater outflow at the coast

E = Groundwater Extraction

ET = Evapotranspiration (ET)

L_D = Downward Leakage to TCSA

F = Impacts of forestry on groundwater (including recharge interception and direct groundwater extraction)

E_{SW} = Surface water evaporation

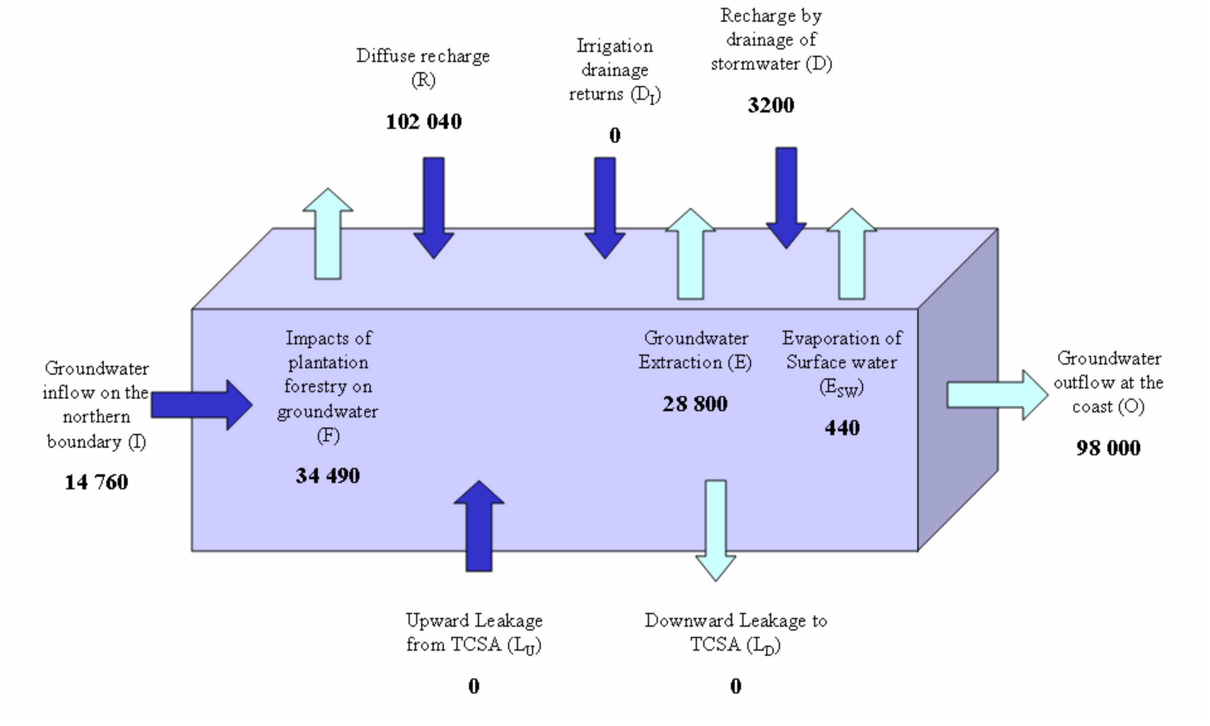


Figure 13. Schematic diagram of the water balance for the unconfined aquifer. Volumes are in ML/y.

5.4.7.1 Inputs

Groundwater Inflow at the Northern Boundary (I)

Groundwater inflow to the north of the study area was approximated very broadly using Darcy's Law. Based on the analysis of Mustafa and Lawson (2002) (see Section 5.4.5), a transmissivity (T) of 350 m^2/d was selected. The hydraulic gradient in the northern part of the study area is ~7 x 10^{-3} (Fig. 8). With an approximate cross section length of 16.5 km, this results in an estimate of groundwater inflow of 14 760 ML/y.

Diffuse Recharge (R)

As described in Section 5.4.2.1, two methods have historically been used to estimate rainfall recharge for Zone 1A.

1. Bradley et al. (1995) used a hydrograph fluctuation method and distributions of soil associations, vegetation and land use to determine the recharge rates and sub-areas shown in Figure 11. The total volume of vertical recharge to Zone 1A was estimated based on this method to be 31 000 ML/y (Bradley et al., 1995). Recent use of a GIS-based approach to calculate the areas of the recharge zones of Bradley et al. (1995) (Fig. 11), provided a total recharge volume of 30 960 ML/y (Table 1).

Table 1. Recharge volumes derived from Bradley et al. (1995)

Recharge Rate (mm/y)	**Area** (ha)	**Total recharge** (ML/y)
5	22 444	1 122
90	5 592	5 032
80	7 553	6 042
130	447	581
40	947	379
65	17 956	11 671
60	10 083	6 050
15	541	81
Total	**65 563**	**30 958**

2. Brown et al. (2006) used the recharge rates and zones derived by Allison and Hughes (1978) (Fig. 10; Section 5.4.2.1) to estimate net recharge volumes for the Donovans, Glenburnie and Myora groundwater management areas. The sum of these provide a total recharge volume for Zone 1A of 102 041 ML/y (Table 2).

Table 2. Recharge volumes derived from Brown et al. (2006)

Management Area	**Total Recharge** (ML/y)
Donovans	38 215
Glenburnie	40 876
Myora	22 950
Total	102 041

The results of methods (1) and (2) differ substantially. The reason for this is that the method of Brown et al. (2006) estimates recharge rates based on area weightings of soil type in each management area only, whilst that of Bradley et al. (1995) also incorporates land use, particularly forestry, where recharge is considered to be negligible (5 mm/y). As the impacts of forestry on recharge are considered as a separate water use in the water balance calculations, the recharge rates of Brown et al. (2006) have been used in our calculations and total rainfall recharge to Zone 1A is considered to be 102 040 ML/y.

Upward Leakage from TCSA(L_U)

As described in Section 5.4.2.2 above, very little is known about the occurrence of upward leakage from the confined aquifer. However, it is likely that this is a relatively small part of the water balance for the study area and is therefore considered to be negligible for the purpose of the calculations provided below. However, it should be noted that further work is required to properly confirm this.

Recharge by Drainage of Stormwater (D)

As described in Section 5.4.2.3 above, the most recent estimate for stormwater discharging via drainage bores into the upper unconfined aquifer is 3200 ML/y (J. Lawson, DWLBC, Pers. Comm., 2006) This value has been used as an input in the water balance calculation.

Irrigation Drainage Returns(D_I)

Due to the absence of flood irrigation developments in the study area, drainage of irrigation water into the unconfined aquifer is assumed to be negligible for the purpose of the water balance calculations (cf. Section 5.4.2.4). Irrigation drainage could possibly be significant under pivot irrigation, which are overlying shallow soils, however this has not yet been quantified.

5.4.7.2 Outputs

Groundwater Outflow (O)

The most recently measured value for discharge from the major groundwater-fed outflows at the coast of 98 000 ML/y (see Section 5.4.3.6) was selected for this water balance calculation as this is consistent with our use of other recent data, for example hydraulic head and groundwater extraction data. It must be noted that this may be an extremely conservative representation of the actual groundwater outflow at the coast and the water balance should be interpreted accordingly.

Groundwater Extraction (E)

As described in section 5.4.3.1, groundwater extraction is estimated to be 3900 ML/y for stock and domestic use, 5933 ML/y for volumetric allocations and 19 004 ML/y for irrigation volumes pumped (Brown et al., 2006). The total ground water extraction is therefore assumed to be 28 800 ML/y in the study area.

Downward Leakage to TCSA (L_D)

At this stage, the volume of water leaking from the unconfined aquifer into the confined aquifer is unknown but, based on the discussion in Section 5.4.3.3, is considered to be negligible for the purpose of the water balance calculations.

Impacts of Plantation Forestry on Groundwater (F)

As described in Section 5.4.3.4, the volume of groundwater directly extracted by forestry plantations is estimated to be 2.6 ML/ha/y for softwood where water tables are less than 7 m below the ground. Hardwood plantations overlying water tables less than 7 m deep are negligible in Zone 1A and have therefore not been included in the water balance calculations. However, there are ~2600 ha of softwood plantations overlying water tables less that 7 m deep, resulting in an estimated average groundwater use by plantation forestry of 6760 ML/y (Brown et al., 2006).

As described in Section 5.4.3.4, ~83% of rainfall recharge is believed to be intercepted by softwood plantations, resulting in a total recharge debit of 27 730 ML/y for Zone 1A (Brown et al., 2006).

Including both direct groundwater extraction and recharge debits, the total water use by plantation forestry in Zone 1A is estimated to be 34 490 ML/y.

Surface Water Evaporation (Blue Lake) (E_{SW})

As described in Section 5.4.3.5, based on mean pan evaporation and rainfall data, and an average surface area of 70 ha, net surface water evaporation from the Blue Lake is estimated to be ~440 ML/y.

5.4.7.3 Water Balance

The water balance for the unconfined aquifer in Zone 1A is shown in Table 3.

Table 3. Water Balance for Zone 1A.

Inputs (ML/y)	
Diffuse recharge(R)	102 040
Upward leakage from TCSA (L_U)	0
Irrigation drainage returns (D_I)	0
Recharge by drainage of stormwater (D)	3 200
Groundwater Inflow on northern boundary (I)	14 760
Total (ML/y)	**120 000**
Outputs (ML/y)	
Groundwater outflow at the coast (O)	98 000
Groundwater Extraction (E)	28 800
Evapotranspiration (ET)	0
Downward leakage to TCSA (L_D)	0
Impacts of plantation forestry on groundwater (F)	34 490
Evaporation of surface water (E_{SW})	440
Total (ML/y)	**161 730**
Water Balance (inputs-outputs) (ML/y)	**-41 730**

The water balance shown in Table 3 suggests a net annual loss of 41 730 ML of water from storage across all of Zone 1A. Assuming an area of 660 km^2 and a specific yield of 0.15, this would correspond to a drop in hydraulic head of ~0.42 m/y across all of Zone 1A. Considering the broad scale and approximate nature of the water balance, this is relatively consistent with an observed decline in water levels in the study area of up to 0.4 m/y (Brown et al., 2006).

This agreement suggests that the conceptual model for the unconfined aquifer described above is reasonable and that no major components of the water balance have been left out. However, due to the broad approximations made for each of the components, some inaccuracies are inherent and the level of uncertainty for each of these components cannot be properly quantified. In particular, it must be noted, as discussed in Section 5.4.7.2, that the value adopted for groundwater outflow at the coast (O) may be extremely conservative. A greater value for O would result in a greater water balance deficit. This suggests that either (a) most groundwater discharge actually does occur via the four main surface water bodies that discharge at the coast, or (b) there are significant errors in some other component(s) of the water balance. This can be kept in mind whilst assessing the results of the numerical groundwater flow model.

A major outcome of the water balance exercise is in the assessment of the two methods for determining recharge to Zone 1A described in Section 5.4.2.1. The recharge volume of 102 000 ML/y derived using the method of Brown et al. (2006) was applied in the water balance calculation given above. However, if the total recharge estimate of ~31 000 ML/y of Bradley et al. (1995) were used, the estimated annual head drop would be even greater. As described in Section 5.4.2.1, the difference between the two estimates can be partially accounted for in the treatment of forestry impacts on recharge (~27 700 ML/y). This is included in the estimate of Bradley et al. (1995), but not in the estimate of Brown et al. (2006) and is therefore included as an output in the water balance calculation given above. However, the remaining difference between the two estimates is still 36 540 ML/y. This suggests that, if the lower recharge estimate of Bradley et al. (1995) was used in the water balance, an average hydraulic head decline of 0.8 m/y would be estimated, significantly greater than any observed declines in water level.

5.4.8 SUMMARY OF GAMBIER LIMESTONE CONCEPTUAL MODEL

Figures 13–15 provide an overview of the conceptual model for groundwater flow in the unconfined aquifer in the Zone 1A region. The main features of this can be summarised as follows:

- Groundwater flow is to the south or southwest, with discharge occurring at the coast.
- The water table generally ranges between 5–25 m below ground level, and is within 2 m of the ground surface at the coast.
- There is a steep hydraulic gradient zone to the north of Mount Gambier with a groundwater divide occurring to the north due to historical uplifting.
- The Gambier Limestone has an intrinsic primary permeability, with a secondary fracture permeability.
- Estimates of porosity range between 30–50%, and hydraulic conductivity between 10–300 m/d. Specific yields range between 0.1 and 0.25.
- Groundwater salinity in the unconfined aquifer is generally less than 500 mg/L, although higher concentrations of up to 1500 mg/L can be found at the coast.
- The dominant inflow to the unconfined aquifer system is via vertical recharge of rainfall. This occurs as both diffuse recharge through the soil, and via surface water discharge to sinkholes and swamps.

- Recharge rates are controlled by soil type. Hence areas of different recharge rate can be defined by distributions of soil type or surface geology.
- Changes in land use over the past 100 years from clearing of native vegetation has resulted in an increase in total recharge to the unconfined aquifer.
- Total rainfall recharge into the study area is currently estimated to be ~102 000 ML/y.
- However, ~24 000 ha of the study area is covered by forest plantations, which intercept ~27 700 ML of rainfall recharge annually.
- The volume of groundwater directly extracted by plantations in Zone 1A is estimated to be 6760 ML/y.
- There is a possibility of upward leakage from the confined aquifer in the vicinity of the Blue Lake. It is currently unknown whether there are any other occurrences of upward leakage to the unconfined aquifer in the study area.
- It is estimated that the volume of stormwater draining to the unconfined aquifer via drainage bores is about 3200 ML.
- There is a net loss of water from the Blue Lake via evaporation of ~440 ML/y.
- The total ground water extraction for irrigation use, other volumetric allocations, and stock and domestic use is assumed to be 28 800 ML/y in the study area.
- Groundwater discharge from springs at the coast is estimated to be ~98 000 ML/y.
- Total water inputs to the unconfined aquifer in Zone 1A are estimated to be ~120 000 ML/y, with total outputs estimated to be 161 730 ML/y. This indicates a net loss of ~41 730 ML/y from storage in the aquifer, equivalent to a hydraulic head drop of the order of 0.4 m. Considering the broad scale and approximate nature of the water balance, this compares well with measured head declines of up to 0.4 m/y and suggests that the conceptual model derived here is a reasonable approximation of the unconfined aquifer in Zone 1A.

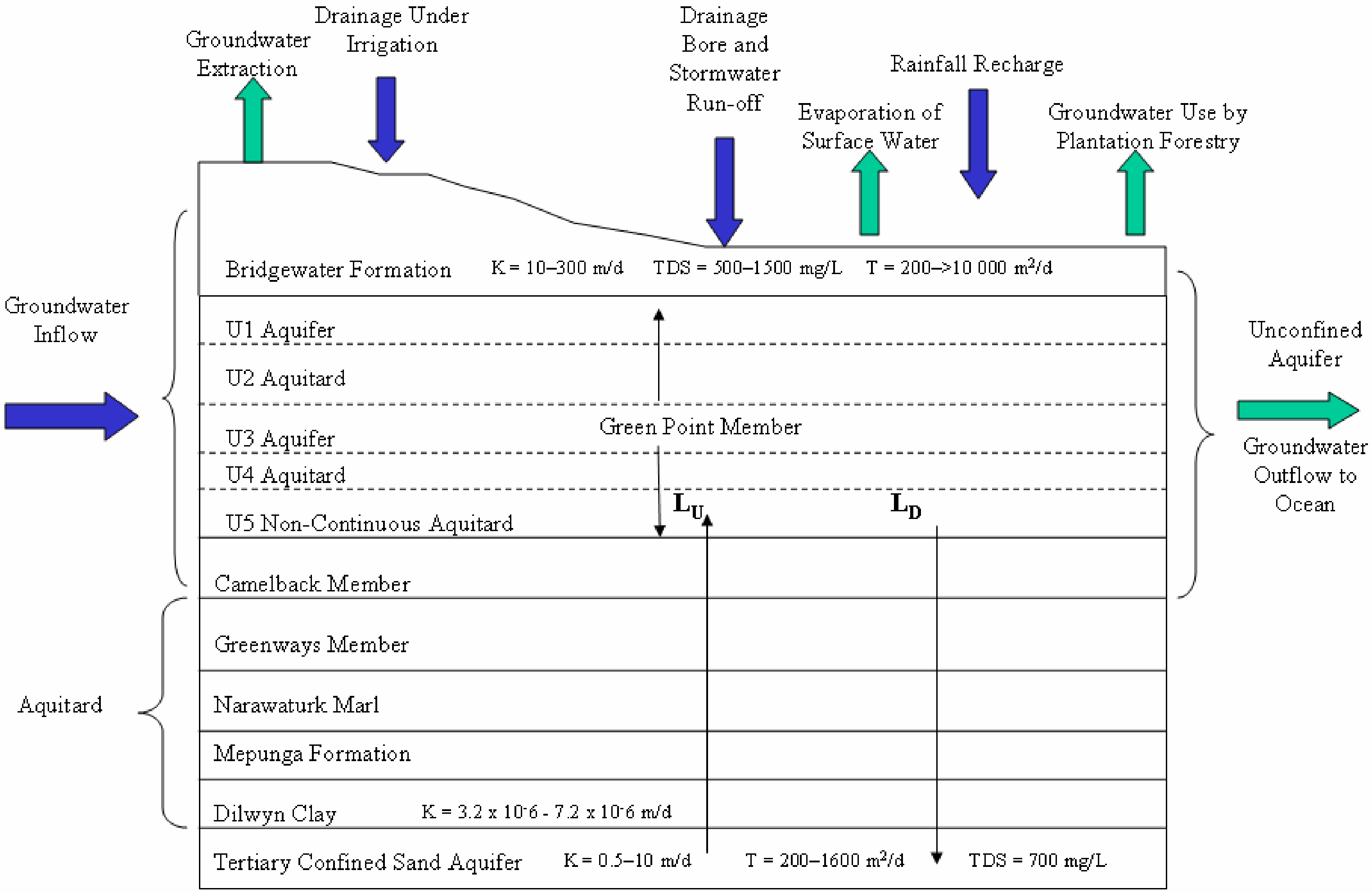
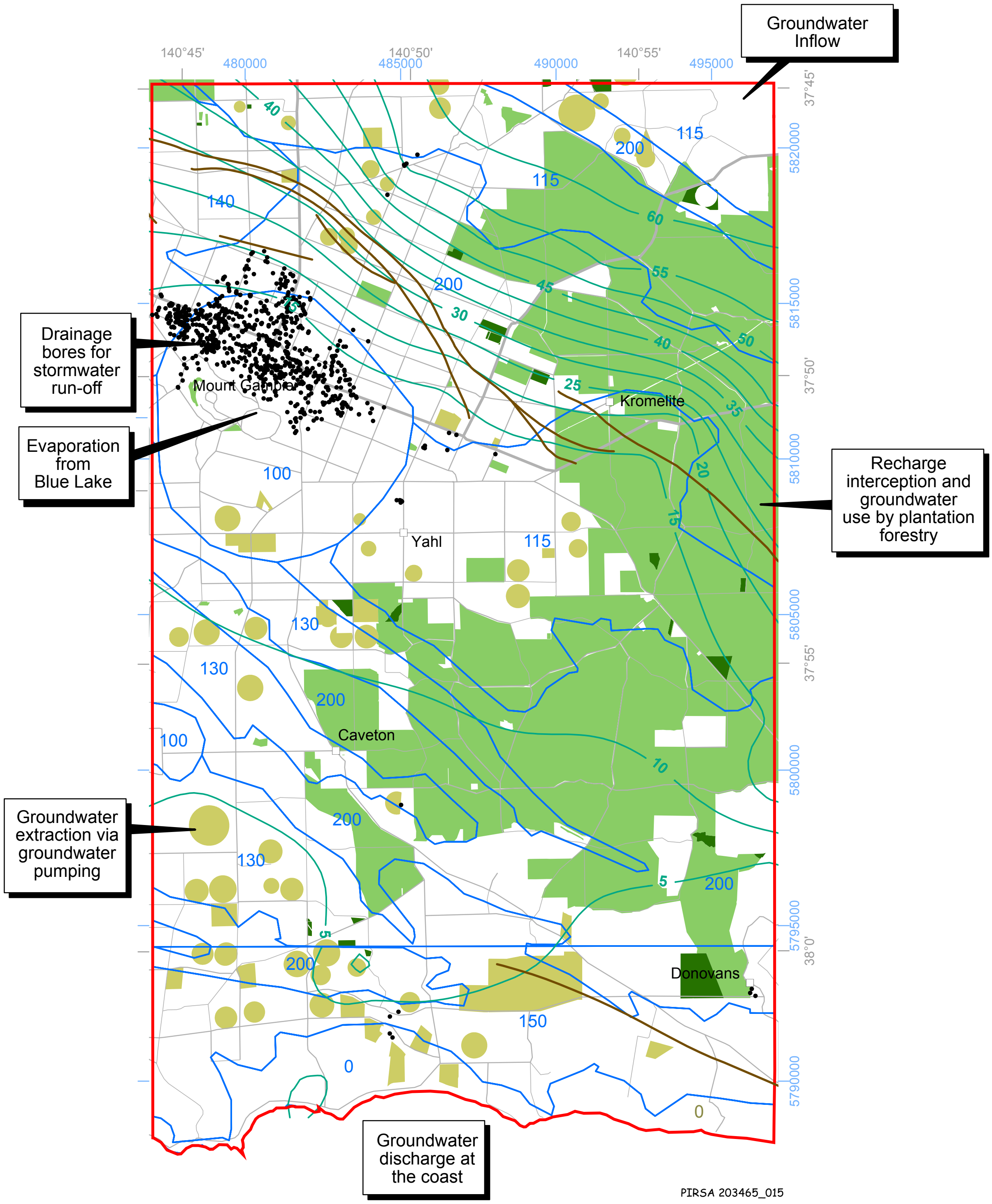


Figure 14. Cross sectional conceptual model for groundwater flow in Zone 1A.



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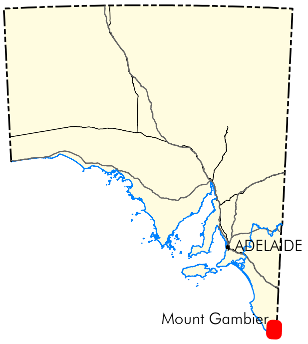

0 2.5 5 Kilometers

Projection:	MGA Zone 54 Transverse Mercator
Datum:	Geocentric Datum of Australia 1994
Produced by:	Publishing Services Primary Industries and Resources SA
Date:	December 2006

🟩 Hardwood plantation

🟩 Softwood plantation

🟨 Irrigated sown grasses

● Drainage bores

— Potentiometric head (m) – March 2006

— Fault

🟥 Zone 1A study area

— 200 Recharge rate (mm/yr)

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Zone 1A Numerical Modelling Study: Conceptual Model Development

SPATIAL VIEW OF CONCEPTUAL MODEL FOR GROUNDWATER FLOW IN ZONE 1A

Figure 15

5.5 PLIO-PLEISTOCENE SANDS AQUIFER (BRIDGEWATER FORMATION)

5.5.1 GENERAL CHARACTERISTICS

The Bridgewater Formation is part of the Quaternary/Upper Tertiary Limestone Aquifer and overlies and is hydraulically interconnected with the underlying Gambier Limestone. The formation forms part of the unconfined aquifer, along with the Gambier Limestone and most areas of Bridgewater Formation in Zone 1A, particularly to the south of Mount Gambier are unsaturated.

Marine transgressions and regressions over time have resulted in the Bridgewater Formation creating stranded coastal dune ridges and topographic highs, which are orientated in a northwest to southeast direction, and unconformably overlie the Gambier Limestone (Lawson et al., 1993). The Bridgewater Formation is comprised of calcareous sandstone, is highly fossiliferous in parts and can range from being consolidated to highly indurated.

5.5.2 WATER SOURCES

The Bridgewater Formation and the Gambier Limestone are hydraulically interconnected and form the unconfined aquifer in the regions where the Bridgewater Formation is present. The information for the Gambier Limestone provided above also applies to the Bridgewater Formation.

5.5.3 RAINFALL RECHARGE

Recharge to the Bridgewater Formation occurs through infiltration of rainfall through the unsaturated zone and due to low evapotranspiration rates and highly permeable soil conditions (Leaney and Herczeg, 1995). Recharge to the unconfined aquifer is typically of low salinity. The recharge zones of Figure 10 apply in areas where the Bridgewater Formation is present.

5.5.4 GROUNDWATER FLOW

Regional groundwater flow in the Bridgewater Formation is in a south to south-westerly direction towards the coast. Due to the occurrence of karstic terrains and stranded dune ridges, local flow paths are potentially difficult to predict (Lawson et al., 1993). Local groundwater flows have been recognised in areas where a reversal of the flow direction has occurred, as a result of the karstic terrain.

To the south of Mount Gambier, transmissivity values increase on the interdunal flats and result in flat hydraulic gradients. Local flow patterns occur as a result of dune ridges and slightly higher water tables beneath these local recharge zones.

5.5.5 AQUIFER PROPERTIES

The Bridgewater Formation is known to have a dual porosity, with both a primary porosity and secondarily developed karstic features (Lawson et al., 1993). Waterhouse (1977) and Stadter (1989) determined that transmissivity values from aquifer pump tests range between 200–>10 000 m^2/d within karstic features. Porosity in the Bridgewater Formation was estimated to range between 30–50% from borehole geophysics and from 49–61% from measurements on outcrops (Andrews, 1974; Love, 1991).

5.5.6 GROUNDWATER SALINITY

Groundwater salinity in the Bridgewater Formation is generally low due to low evapotranspiration rates and highly permeable soil conditions. Salinity ranges between 300–600 mg/L.

5.5.7 SUMMARY OF BRIDGEWATER FORMATION CONCEPTUAL MODEL

- The Bridgewater Formation is part of the Quaternary/Upper Tertiary unconfined aquifer system and overlies and is hydraulically interconnected with the underlying Gambier Limestone.
- Most parts of the Bridgewater Formation in Zone 1A, particularly to the south of Mount Gambier are unsaturated.
- Karstic terrains and stranded dune ridges of the Bridgewater Formation cause local flow paths that are potentially difficult to predict on flat gradients.
- Transmissivity values determined from aquifer pump tests range between 200–>10 000 m^2/d within karstic features.
- Groundwater salinity ranges between 300–600 mg/L.

6. APPLICATION OF THE CONCEPTUAL MODEL TO DEVELOPING THE NUMERICAL MODEL AND ITS LIMITATIONS

6.1 SUMMARY

A summary of the information provided in Chapter 5 is shown on Figures 14–15. This information, along with the discussion in Chapter 5, will be used to guide the development of the three dimensional numerical model of Zone 1A, to be presented in a subsequent report. For example, the estimates of aquifer properties and recharge rates described will be used to guide the application of such parameters in the numerical model. Additionally, both the quantitative and qualitative information on inflows, outflows and inter-aquifer groundwater flow can be compared with model results to ensure that the final model best represents the real system.

6.2 LIMITATIONS OF THE CONCEPTUAL MODEL

The accuracy and hence conclusions and outcomes from a numerical model are limited by the accuracy and completeness of the conceptual model. In modelling natural systems in which limited data is available, a number of assumptions must be made and the effect of these assumptions on the outcomes of a numerical model must be assessed and understood. The limitations of the current conceptual model of Zone 1A and their likely impacts on the outcomes of the numerical model are described in Table 4. The actual impacts of these limitations will be assessed during the numerical modelling process. For example, it may be shown that some limitations have more impact than others, or that some have a negligible effect on the final outcome.

Table 4. Limitations of the existing conceptual model, with the suggested approach for addressing these in the numerical modelling process and likely impacts on outcomes of the numerical model.

Limitation	Approach for Addressing This in the Numerical Model	Likely Impact on Outcomes of Numerical Model
(1) Lack of information on the occurrence of inter-aquifer leakage between the confined and unconfined aquifer.	This is expected to be a small part of the water balance. Hence upward and downward leakage between the two aquifers assumed to be 0.	The impact of this limitation on the groundwater flow model is likely to be small. It may limit the accuracy of water quality predictions in localised areas of the contaminant transport model.
(2) Lack of information on diffuse groundwater discharge at the coast.	As the water balance for the unconfined aquifer appears to represent observations of groundwater level changes in the aquifer relatively accurately, this component is currently considered to be negligible, with the only outflow being that estimated for creeks and springs (98 000 ML/y).	This may have minor impacts on our representation of diffuse contaminant transport and our understanding of the potential for contamination by pollutants at the coast.

Limitation	Approach for Addressing This in the Numerical Model	Likely Impact on Outcomes of Numerical Model
(3) Poor knowledge of and reliability of information regarding aquifer properties, particularly for the unconfined aquifer where spatial variability is large.	Use of approximate average transmissivity and hydraulic conductivity estimates and optimisation of these parameters during the model calibration process.	This is likely to have the largest impact on the results of both the groundwater flow and contaminant transport models. An inability to accurately model the preferential flow of contaminants is likely to greatly limit the accuracy of predictions of contaminant fate.

7. CONCLUSIONS AND RECOMMENDATIONS

The overall objective of the “Primary Production to Mitigate Water Quality Threats” Project is to create a numerical groundwater flow and contaminant transport model that could be used to (1) assess the risk of contamination of water resources in the South East (2) quantify the sources of diffuse pollution, and (3) decrease the risk of contamination of water resources in the South East.

This report contains details of a conceptual model of Zone 1A, which could be then used as a basis for the numerical groundwater flow and solute transport model, and for future groundwater projects in Zone 1A.

In order to construct the conceptual model, a comprehensive review of available data and past studies was carried out. The resulting water balance for the unconfined aquifer in Zone 1A suggests a net loss of water from storage in the aquifer of 41 710 ML/y, which represents an approximate decline in hydraulic head of 0.63 m/y over the entire study area. Despite the simplicity of the conceptual model and the uncertainty in each of the inputs and outputs, this estimate agrees reasonably well with measured declines in hydraulic head, which can be up to 0.4 m (Brown et al., 2006). This suggests that the conceptual model derived here is a reasonable representation of the real system.

However, some limitations exist in applying this information to a detailed numerical model (Table 4). These limitations include a lack of knowledge of inter-aquifer leakage between the confined and unconfined aquifers, and the lack of information on the magnitude of groundwater discharge at the coast. These factors may contribute to the accuracy of the water balance in Zone 1A. In particular, a lack of ability to accurately represent the large spatial variability in unconfined aquifer properties is likely to have a large impact on the accuracy of predictions of contaminant transport.

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

δD	hydrogen isotope composition
$\delta^{18}O$	oxygen isotope composition
^{14}C	carbon-14 isotope (percent modern carbon)
CFC	chlorofluorocarbon (parts per trillion volume)
EC	electrical conductivity (µS/cm)
pH	acidity
ppm	parts per million
ppb	parts per billion
TDS	total dissolved solids (mg/L)
~	approximately equal to

GLOSSARY

Act (the). In this document, refers to The *Natural Resources Management Act* (South Australia) 2004.

Aquifer. An underground layer of rock or sediment which holds water and allows water to percolate through.

Aquifer, confined. Aquifer in which the upper surface is impervious and the water is held at greater than atmospheric pressure. Water in a penetrating well will rise above the surface of the aquifer.

Aquifer, storage and recovery (ASR). The process of recharging water into an aquifer for the purpose of storage and subsequent withdrawal.

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. Under pressure such that when wells penetrate the aquifer water will rise to the ground surface without the need for pumping.

Artificial recharge. The process of artificially diverting water from the surface to an aquifer. Artificial recharge can reduce evaporation losses and increase aquifer yield. *(See recharge, natural recharge, aquifer.)*

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

Catchment. A catchment is that area of land determined by topographic features within which rainfall will contribute to runoff at a particular point.

Catchment water management board. A statutory body established under Part 6, Division 3, s. 53 of the Act whose prime function under Division 2, s. 61 is to implement a catchment water management

Cone of depression. An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction which exceeds the rate of recharge. Continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality.

CWMB. Catchment Water Management Board.

Diffuse source pollution. Pollution from sources such as an eroding paddock, urban or suburban lands and forests; spread out, and often not easily identified or managed.

DWLBC. Department of Water, Land and Biodiversity Conservation. Government of South Australia.

EC. Abbreviation for electrical conductivity. 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25 degrees Celsius. Commonly used to indicate the salinity of water.

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

Effluent. Domestic wastewater and industrial wastewater.

Environmental water requirements. The water regimes needed to sustain the ecological values of aquatic ecosystems, including their processes and biological diversity, at a low level of risk.

Erosion. Natural breakdown and movement of soil and rock by water, wind or ice. The process may be accelerated by human activities.

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

Gigalitre (GL). One thousand million litres (1 000 000 000).

Geological features. Include geological monuments, landscape amenity and the substrate of land systems and ecosystems.

Heavy metal. Any metal with a high atomic weight (usually, although not exclusively, greater than 100), for example mercury, lead and chromium. Heavy metals have a widespread industrial use, and many are released into the biosphere via air, water and solids pollution. Usually these metals are toxic at low concentrations to most plant and animal life.

Hydrogeology. The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers. *(See 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 hydrogeology.)*

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

Lake. A natural lake, pond, lagoon, wetland or spring (whether modified or not) and includes: part of a lake; and a body of water declared by regulation to be a lake; a reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land. Whether under water or not and includes an interest in land and any building or structure fixed to the land.

Leaching. Removal of material in solution such as minerals, nutrients and salts through soil.

Megalitre (ML). One million litres (1 000 000).

Model. A conceptual or mathematical means of understanding elements of the real world which allows for predictions of outcomes given certain conditions. Examples include estimating storm runoff, assessing the impacts of dams or predicting ecological response to environmental change.

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

Natural Resources. Soil; water resources; geological features and landscapes; native vegetation, native animals and other native organisms; ecosystems.

Natural Resources Management (NRM). All activities that involve the use or development of natural resources and/or that impact on the state and condition of natural resources, whether positively or negatively.

Occupier of land. A person who has, or is entitled to, possession or control of the land.

Palaeochannels. Ancient buried river channels in arid areas of the state. Aquifers in palaeochannels can yield useful quantities of groundwater or be suitable for ASR.

Pasture. Grassland used for the production of grazing animals such as sheep and cattle.

Permeability. A measure of the ease with which water flows through an aquifer or aquitard.

PIRSA. (Department of) Primary Industries and Resources South Australia.

Pollution, diffuse source. Pollution from sources that are spread out and not easily identified or managed (e.g. an eroding paddock, urban or suburban lands and forests).

Pollution, point source. A localised source of pollution.

Potentiometric head. The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer.

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 Water Resources Act 1997.

PWA. Prescribed Wells Area.

Recharge area. The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. *(See artificial recharge, natural recharge.)*

Riparian zone. That part of the landscape adjacent to a water body, that influences and is influenced by watercourse processes. This can include landform, hydrological or vegetation definitions. It is commonly used to include the in-stream habitats, bed, banks and sometimes floodplains of watercourses.

Stock Use. The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act).

Stormwater. Runoff in an urban area.

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.

Transfer. A transfer of a licence (including its water allocation) to another person, or the whole or part of the water allocation of a licence to another licensee or the Minister under Part 5, Division 3, s. 38 of the Act. The transfer may be absolute or for a limited period.

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

Volumetric allocation. An allocation of water expressed on a water licence as a volume (e.g. kilolitres) to be used over a specified period of time, usually per water use year (as distinct from any other sort of allocation).

Water affecting activities. Activities referred to in Part 4, Division 1, s. 9 of the Act.

Water allocation. (a) in respect of a water licence means the quantity of water that the licensee is entitled to take and use pursuant to the licence; (b) 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.

Water allocation plan (WAP). A plan prepared by a CWMB or water resources planning committee and adopted by the Minister in accordance with Division 3 of Part 7 of the Act.

Water licence. A licence granted under the Act entitling the holder to take water from a prescribed watercourse, lake or well or to take surface water from a surface water prescribed area. This grants the licensee a right to take an allocation of water specified on the licence, which may also include conditions on the taking and use of that water. A water licence confers a property right on the holder of the licence and this right is separate from land title.

Waterbody. Waterbodies include watercourses, riparian zones, floodplains, wetlands, estuaries, lakes and groundwater aquifers.

Watercourse. A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; and a lake through which water flows; and a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse.

Water-dependent ecosystems. Those parts of the environment, the species composition and natural ecological processes, which 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.

Well. (a) an opening in the ground excavated for the purpose of obtaining access to underground water; (b) an opening in the ground excavated for some other purpose but that gives access to underground water; (c) a natural opening in the ground that gives access to underground water.

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/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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